



8th International Conference on Optical Angular Momentum

Graz, June 15-19, 2026

Digital Conference Booklet



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General Information

1 Venue & Wi-Fi

The conference is held at the Alte Universität Graz, located in the historic center of Graz, Austria.

Venue Address:

Alte Universität Graz
Hofgasse 14, 8010 Graz, Austria

Wireless internet access is available throughout the venue for all conference participants.

- **SSID:** Not available in webpage version, check the version you got via Email.
- **Password:** Not available in webpage version, check the version you got via Email.

2 Getting There And Around

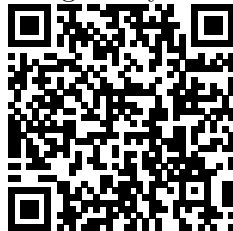
Graz has an excellent and easy-to-navigate public transport network consisting of trams and buses operated by *Holding Graz*.

You received your personalized transportation ticket for use within the city of Graz during the ICOAM 2026 conference per Email.

The ticket is valid for the entire duration of the conference and permits unlimited travel on Graz's public transportation network, including buses, trams, and local trains within the city area. Please note that the ticket is only valid when presented together with an official photo ID. You may either print the ticket or present it digitally on your mobile device. You do not need to present the ticket when boarding public transportation. However, in the event of a ticket inspection, please be prepared to present both the ticket and a valid photo ID upon request.

You can plan your trips online via BusBahnBim or download the GrazMobil app:

Google Play store



App store



Getting to the Venue

The Alte Universität is located near the Hauptplatz (Main Square).

- **From Main Train Station (Hauptbahnhof):** Take tram lines 1, 4, 6, or 7 directly to the *Hauptplatz* stop. From there, it is a scenic 5-minute walk up past the Graz Cathedral.
- **From Graz Airport (GRZ):** Take the S-Bahn train (S5) to the Hauptbahnhof, or catch bus 630/631 directly to the city center.

3 Green Event

As organizers, we are taking concrete steps to ensure a sustainable experience, but a "Green Event" is a collaborative effort. Therefore, we invite all participants to join us in these initiatives.

Green Venue

The conference takes place at the Alte Universität Graz, a venue that holds the distinction of being the first certified "Green Location" in Styria. In addition to its historic charm, the building operates with high energy efficiency and modern waste management systems. Please [click here](#) to learn more.

Climate-Friendly Travel

Graz is excellently connected to the European railroad network. We encourage all attendees to choose train rides over short-haul flights whenever possible.

The venue is located in the heart of the city, and it is easily accessible by foot or via the local public transport system. We provide every participant with a ticket for public transportation, which is valid in the core tariff zone of Graz.

Regional & Conscious Catering

Food and beverages are a major part of any conference, and we are committed to making them sustainable.

Local & Organic: Our catering partners prioritize seasonal products from the Styrian region.

Waste Reduction: We have eliminated single-use plastics and are striving for a "zero-waste" catering approach.

Water: We encourage the use of Graz's high-quality tap water to reduce bottled waste.

Resource Management

We are moving away from traditional conference "swag" and heavy paper usage.

Going Digital: All programs and abstracts will be available via our mobile-friendly website.

Eco-Badges: Conference badges and lanyards will be made from recycled or biodegradable materials rather than standard plastics.

Your Contribution Matters

You can help us by opting for environmentally friendly travel, using our digital program, and properly separating waste at the venue. If you must fly, please consider contributing to a CO₂ compensation project.

4 Food

Complimentary coffee, tea, and light refreshments and snacks will be served during all scheduled coffee breaks. Lunches are provided daily for registered attendees in the exhibition area.

Recommended Nearby Restaurants

If you wish to explore local Styrian cuisine or international dining options during your stay, here are a few highly recommended spots within walking distance of the venue:

- **Glöckl Bräu** (Glockenspielplatz 2-3) – Casual restaurant in a 17th-century building with traditional Styrian food & craft beer.
- **Die Herzl Weinstube** (Prokopigasse 12 | Mehlplatz) – Excellent traditional Styrian dishes and local wines.
- **Landhauskeller** (Schmiedgasse 9) – Classic Austrian dining in a historic renaissance courtyard setting.
- **Aiola upstairs** (Schlossberg) – Modern dining with a panoramic terrace view overlooking the roofs of Graz (accessible via lift or stairs).
- **Café Freiblick** (Sackstraße 7-13) – Located on top of the Kastner & Öhler department store, offering light bites, drinks, and a stunning view of the Schlossberg.
- **Pizzaiolo** (Karmeliterplatz 1) – Outstanding, authentic Neapolitan wood-fired pizzas in a vibrant, casual square setting.
- **Operncafé** (Opernring 22) – A historic and iconic Graz café ideal for premium coffee, classic Austrian pastries, breakfast, or a light lunch near the Opera House.
- **Kunsthauscafé** (Südtiroler Platz 2) – Vibrant, casual spot for burgers, salads, and vegetarian options.
- **Café Greenhouse** (Herrengasse 7) – Freshly prepared food, quality coffee, and a focus on sustainable, plant-based, and locally sourced ingredients.
- **Café Parkhouse** (Stadtpark 2) – A relaxed, iconic pavilion nestled right inside the Stadtpark, perfect for outdoor drinks, casual snacks, and a lively atmosphere.

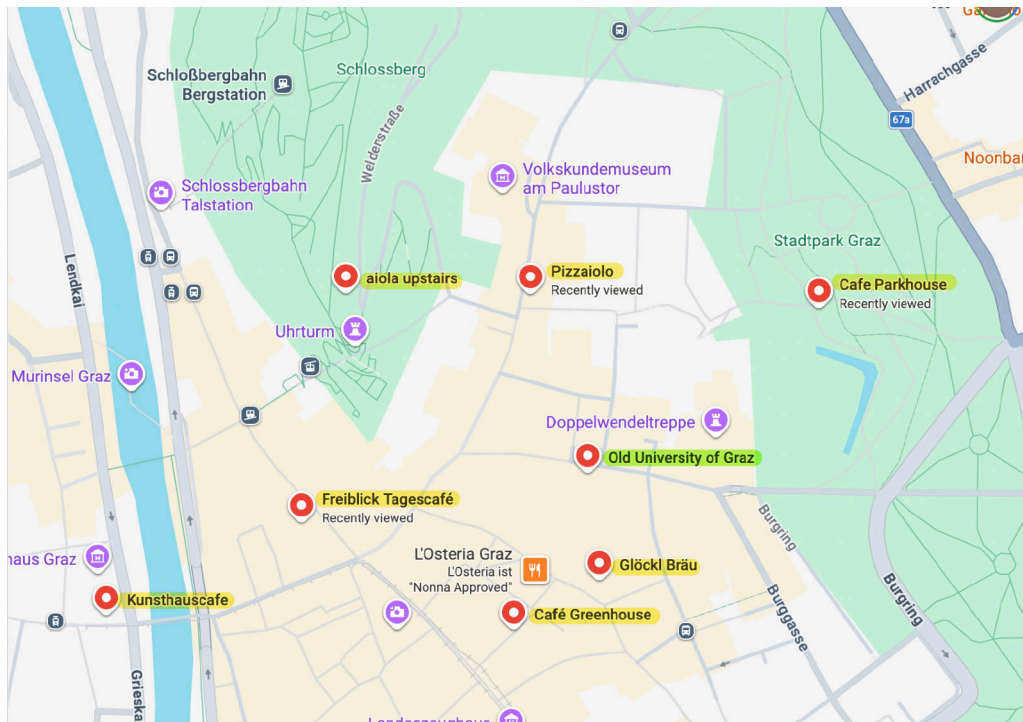


Figure 1: Map of recommended restaurants.

5 Ideas for the Free Afternoon in Graz

Please note, that there is no group experience scheduled for the free Wednesday afternoon. However, we compiled a list of interesting and fun things to do. Graz offers a variety of cultural, historical, and recreational attractions that can easily be explored within a few hours.

- **Explore the Historic City Centre**

Stroll through Graz's UNESCO World Heritage old town, with its charming courtyards, Renaissance architecture, and lively squares.

- **Visit the Schlossberg**

Take the funicular, glass lift, or a pleasant walk up the city's landmark hill to enjoy panoramic views and see the famous Clock Tower (*Uhrturm*). **The price for the funicular is included in your public transport ticket!**

- **Ride the Schlossberg Slide**

For a more adventurous descent from the Schlossberg, try the Schlossberggrutsche, the world's longest underground slide. Stretching approximately 170 metres through the hill, it offers a fun and unique way to return from the Clock Tower area to the city below. Tickets can be bought

- **Discover Kunsthaus Graz**

The city's striking contemporary art museum, affectionately known as the "Friendly Alien," hosts changing exhibitions of international artists.

- **Cross the Murinsel**

Designed by artist Vito Acconci, this floating island on the River Mur combines architecture, art, and a café in a unique setting.

- **Visit Eggenberg Palace**

A short tram ride from the city centre leads to this magnificent Baroque palace – a UNESCO World Heritage Site – and its extensive gardens and beautiful peacocks.

- **Experience the Schöckl**

Take a trip to Graz's local mountain and enjoy spectacular views over the city and the surrounding Styrian countryside. The Schöckl can be reached conveniently by Bus and cable car and offers hiking trails, mountain huts, and opportunities to experience nature just outside the city. Take the hourly bus 250 from Jakominiplatz to Schöckl-Talstation (about 30min). A part of the bus fare is included in your public transport ticket, you just have to top off the rest. The funicular from the bus stop to the top costs € 10,40.

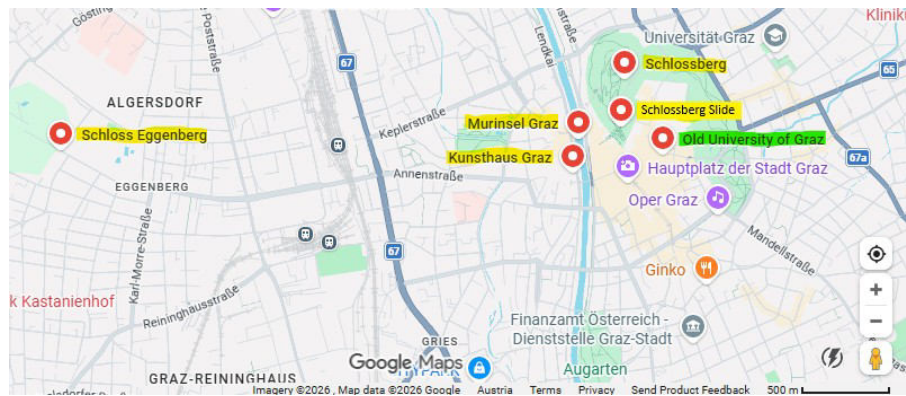


Figure 2: Map of recommended sights within city boundaries.

6 Conference Organizers

We are thrilled to welcome you to Graz for ICOAM 2026.

If you have any questions regarding the program, sessions, or the venue, please do not hesitate to reach out to any of us listed below.



Peter Banzer



Sarah Lindner



Marko Šimić

7 Conference Helpers

A conference of this scale would not be possible without the commitment and hard work of our support staff.

They are happy to help you with directions, Wi-Fi access, or any logistics at the Alte Universität.



Christoph Stockinger



Light Mkhumbuza



Shyamal Guchhait



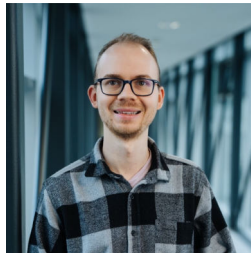
Gabriele Maschera



Jacob Reynvaan



Michael Lamprecht



Philipp Werhounig

8 Scientific Program

A mobile-friendly version of this program can be found below, at the beginning of each day.

Monday, the 15th	Tuesday, the 16th	Wednesday, the 17th	Thursday, the 18th	Friday, the 19th
Chair: Sonja Franke-Arnold	Chair: Karen Patricia Volke Sepulveda	Chair: Allison Yao	Chair: Robert Fickler	Chair: Ebrahim Karimi
09:00-09:25 Welcome Address	09:00-09:25 Halina Rubinsztein-Dunlop Optical Angular Momentum in Optical Micromanipulation and Quantum Sensing	09:00-09:25 Berenice Sephton Structuring light into interferometers for three-dimensional imaging	09:00-09:25 Michael Berry Newton	09:00-09:25 Stephen Barnett Optical torques in the focusing of light
09:25-09:50 Cade Peters / Andrew Forbes Leveraging optical topologies to see and communicate through random channels	09:25-09:50 Andrea Aiello Counterfactual reasoning does not affect Bell's theorem	09:25-09:50 Carmelo Rosales-Guzman Structured light-based optical metrology	09:25-09:50 Ebrahim Karimi Structured Quantum Light for High-Dimensional Quantum Information	09:25-09:50 Mark Dennis Euler-top Gaussian beams: Structured Modes Beyond Separation of Variables
09:50-10:15 Natalia Litchinitser Optical Skyrmions Across Scales: From Spatiotemporal Structured Light to Nanoscale Topological Fields	09:50-10:15 Qiwen Zhan Topology with Spatiotemporally Sculptured Light	09:50-10:15 Takahige Omatu Materials manipulation with optical skyrmions	09:50-10:15 Lorenzo Marrucci Superscillations and conservation laws in structured light	09:50-10:15 Mark Main Structured Light for Multi-Scale Sensing
10:15-10:40 Yijie Shen Meta-photonics topologies for multidimensional communications	10:15-10:40 David Andrews Optical Angular Momentum and a Multiplicity of Multipoles	10:15-10:40 Charles Roques-Carnes Separating partially coherent light	10:15-10:40 Francisco J. Rodriguez-Forcello Electromagnetic bispinor in different bases and the energy symmetry sphere	10:15-10:40 Filippo Romanato Metasurfaces for Structured Light: Generation, Sorting, and Topological Control of Vector Beams
10:40-11:10 Coffee Break	10:40-11:10 Coffee Break	10:40-11:10 Coffee Break	10:40-11:10 Coffee Break	10:40-11:10 Coffee Break
Chair: Andrew Forbes	Chair: Monika Ritsch-Marte	Chair: Marko Šimić	Chair: Lorenzo Marrucci	Chair: Jonathan Leach
11:10-11:35 Monika Ritsch-Marte A stroll down DAM lane: From Acoustics to Optics and back again	11:10-11:35 Gerd Leuchs A clear operational distinction between quantum and classical entanglement	11:10-11:35 Eileen Otte Revealing micro- and nano-dynamics through the spatiotemporal structure of light	11:10-11:35 Jörg Götte Bounds on Delocalization in the Angular Talbot Effect	11:10-11:35 Mehul Malik Programming quantum measurements of time inside a multi-mode fibre
11:35-12:00 Kostya Bliokh Topological waveforms and manipulation of particles: From nanoparticles to ocean waves	11:35-12:00 Robert W. Boyd TBA	11:35-12:00 Yuri Gorodetski Spatio-Temporal Weak Measurement of Structured Pulses	11:35-12:00 Oliver Heckl Towards Probing New Physics in the Mid-Infrared	11:35-12:00 Kiki Dekkers Observing High-Dimensional Nonlocality Bell Inequality Violations using Multi-Outcome Spectral Measurements
12:00-12:25 Etienne Brasselet Agile light-matter topological interplay using self-engineered liquid crystals textures	12:00-12:25 Alan Willner Longitudinally Structured Beams for Communications and Sensing	12:00-12:25 Thomas Juffmann Optical Near-field Electron Microscopy (ONEM): Damage-free, label-free super-resolution imaging of interfaces	12:00-12:25 Marco Origonetti Geometric Aspects of Vector Beams and Jones Calculus	12:00-12:25 Stefan Rotter Structured Waves for Micro-Manipulation and Information Flow
12:25-12:50 Kelsey Everts Metasurface-generated spatiotemporal vector beams and their invariance in complex media	12:25-12:50 Robert Fickler Volumetric Processing of Structured Light Integrated in Glass	12:25-12:50 Ulrich Hohenester The workbench of optofluidic force induction	12:25-12:50 Enrique Galvez Laboratory Astrophysics with Complex Light: Gravitational lensing diffraction of gravitational waves	12:25-12:50 Harald Gießen / Julian Schwab Discovery of phonon-polaritonic skyrmions: Transition from bubble- to Néel-type
13:00-14:00 Lunch Break	13:00-14:00 Lunch Break	13:00-14:00 Group Photo / Lunch Break	13:00-14:00 Lunch Break	13:00-13:20 Closing, Awards
Chair: Eileen Otte	Chair: Jian Wang	14:00-20:00 Free Afternoon – Exploring Graz	Chair: Kayn Forbes	13:20-14:00 Lunch Break
14:00-14:25 Carlos Hernández-García Attosecond Structured Light: From Angular Momentum Engineering to Topological Harmonic Spectroscopy	14:00-14:25 Siddharth Ramachandran Topologically complex light transported by topological confinement		14:00-14:20 Fazliah Nothhawa Measuring relativistic motion using orbital angular momentum of entangled photons	
14:25-14:50 Kayn Forbes Spin from spinless light: Topological and non-paraxial generation of optical spin	14:25-14:50 Christian Schmiegolow Super rotational Doppler shifts measured with single ion probe		14:20-14:40 Andrei Alanaev Three-Dimensional Optical Spin in Vacuum and in Chiral Matter	
14:50-15:15 Antonio Khoury Informationally complete orbital angular momentum tomography with intensity measurements	14:50-15:15 Vincenzo D'Ambrosio Tailoring photonic correlations with quantum interference		14:40-15:00 Linqiao Gan Spin-angular-momentum-multiplexed optoacoustic light storage	
15:15-15:50 Jian Wang Towards Robust Structured Light Communications	15:15-15:50 Mohamed Babiker Quantum optics in phase-front-controlled Poincaré modes		15:00-15:20 Koel Murali A quantum topological switch for entangled and single-photon skyrmions	
15:50-16:20 Coffee Break	15:50-16:20 Coffee Break		15:20-15:40 Tareq Jassal Full-Field Mode Sorter for Optical Knots	
Chair: Yijie Shen	Chair: Berenice Sephton		15:40-16:00 Coffee Break	
16:20-16:45 Karen Patricia Volke Sepulveda Engineering wave structure for acoustic manipulation	16:20-16:45 Allison Yao Novel Petal Beams for Control of Light & Ultracold Atoms		Chair: Sarah Lindner	
16:45-17:10 Miguel Alonso Commensurate harmonic oscillators: bichromatic polarization and modal distributions	16:45-17:10 Sonja Franke-Arnold Optical activity of atomic vapours in topological light		16:00-16:20 Margarita Khokhlova Chiral Stark shift – tweezing molecules in an enantiofashion	
17:10-17:35 Filippo Cardano Free-space photonic circuits for spatially structured light	17:10-17:35 Gabriel Molina-Terriza Improving optical trapping with angular momentum and helicity beams		16:20-16:40 Dmitry Karlovets Generation and manipulation of relativistic vortex particles at accelerator facilities	
			16:40-17:00 Riaan Schmidt Probing the isolated vector magnetic field of structured laser beams by atoms	
			17:00-17:20 Alex Vernon Novel topological and geometric features of light's electric-magnetic space	
			17:20-17:40 Michael de-Oliveira Programming Nonlinear Optical Responses with Structured Light	
18:30-20:00 Poster Session I Poster Session and Best Poster Award Sponsored by AIP			18:30-20:00 Poster Session II Best Poster Award Sponsored by WILEY	

9 Poster Session Assignment

Poster Session I (Monday)	Poster Session II (Thursday)
Rojan Abolhassani	Shiyao Fu
Hammad Ahmed	Rodrigo Martín-Hernández
Darby Paez Amaya	Anuj Maurya
Maria Ammendola	Nicola Mayer
Cord Arnold	Emma Minarelli
Hassan Asgharzadeh	Niladri Modak
Alejandro V. Arzola	Lukas Montenegro-Ferreira
Monika Bahl	Jaime Moreno
Altilano Barbosa	Jeeban Nayak
Rafael Barros	Alexander Neuhaus
Richard Bernecker	Seraphine Oakley
Susheel Bhardwaj	Pedro Ornelas
Patrick Cameron	Zihao Pang
Carlos Cardoso-Isidoro	Ilia Pavlov
Mufeeduzaman Chavilkadan	Christophe Pin
Swapnil Chitriv	Danilo Pires
Claire Cisowski	Emilio Pisanty
Simon Darveau	Radhika Prasad
Francesco Di Colandrea	Pranay Mohta
Nazanin Dehghan	Przemyslaw Litwin
Alessio D'Errico	Laurence Pruvost
Sneha Dey	Pedro Quinto
Ritwik Dhara	Shreyas Ramakrishna
Matias Eriksson	Melvin Redon
Hossein Fathi	Corina Revora
Manuel Ferrer	Valeria Rodriguez-Fajardo
Gabriela Flores-Cova	Sahil Sahoo
Amanda Fritsch	Lukas Scarfe
Mairi Gilmour	Carlo Schiano
Neelan Gounden	Julian Schwab
Edgar Alonso Guzman	Finlay Scott
Sabrina Hammel	Nilakshi Senapati
Masoud Hamidi	Souvik Sil
Ricardo Heras	Oliver Street
James Hubble	Sophia Strnat
Naoki Ichiji	Miroslav Sulc
André Junior	Sphinx Svensson
Suman Karan	Mateusz Szatkowski
Daria Kargina	Rakhi Thomas
Tatjana Kleine	Guy Tshuva
Aleksandra Korzeniewska	Vartika Vishnoi
Georgios Koutentakis	Zhey Wang
Girish Kulkarni	Jakub Wronski
Vijay Kumar	Xiangdong Xie
Renata Loberto	Iuliia Zalesskaia
Daijun Luo	Zhamila Kulchukova
David Marco	Jan Enenkel
Gabriele Maschera, Christoph Stockinger	Philipp Werhounig
Marko Šimić	

Monday Sessions

Monday, the 15th
Chair: Sonja Franke-Arnold
09:00–09:25 Welcome Address
09:25–09:50 Cade Peters / Andrew Forbes Leveraging optical topologies to see and communicate through random channels
09:50–10:15 Natalia Litvinchev Optical Skyrmions Across Scales: From Spatiotemporal Structured Light to Nanoscale Topological Fields
10:15–10:40 Yijie Shen Meta-photonics topologies for multidimensional communications
10:40–11:10 Coffee Break
Chair: Andrew Forbes
11:10–11:35 Monika Ritsch-Marte A stroll down OAM lane: From Acoustics to Optics and back again
11:35–12:00 Kostya Bliokh Topological waveforms and manipulation of particles: From nanooptics to ocean waves
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Chair: Yijie Shen
16:20–16:45 Karen Patricia Volke Sepulveda Engineering wave structure for acoustic manipulation
16:45–17:10 Miguel Alonso Commensurate harmonic oscillators: bichromatic polarization and modal distributions
17:10–17:35 Filippo Cardano Free-space photonic circuits for spatially structured light
18:30–20:00 Poster Session I Poster Session and Best Poster Award Sponsored by AIP

Leveraging optical topologies to see and communicate through random channels

C. Peters^{1*}, K. Everts¹, T. Kleine¹, P. Ornelas¹, A. Forbes¹

¹ University of the Witwatersrand, South Africa

*presenting author, 1843828@students.wits.ac.za

The ability to transmit information through complex channels is vital for many applications. Structured light offers improved imaging resolution and communication bandwidths [1], but is highly susceptible to medium-induced distortions, typically requiring adaptive optics or sophisticated numerical techniques [2]. Here, we exploit the embedded skyrmionic topology of light [3] to overcome these effects without mitigation strategies, demonstrated through three experiments [4].

First, we establish the robustness of skyrmions both theoretically and in controlled laboratory conditions (Fig. 1a), revealing resilience to amplitude and phase distortions and identifying when channel-induced changes remain smooth deformations of the topology. Second, we test optical topologies in real-world channels using biological samples and inorganic scatterers (Fig. 1b), showing topology preservation in all cases. Third, we demonstrate robust information transmission by encoding data in a topological alphabet (Fig. 1c), achieving up to 97.0% accuracy through highly distorting, time-varying media without pre- or post-compensation and significantly outperforming orbital angular momentum (OAM) encoding (25.1%). Overall, this work establishes optical skyrmions as a powerful tool for robust information encoding through complex media, with applications spanning classical and quantum communication as well as imaging.

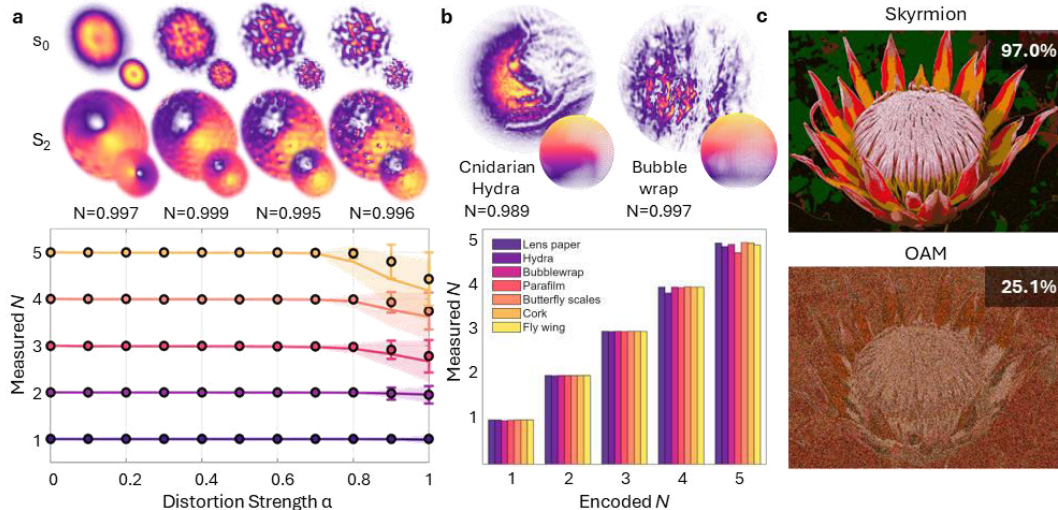


Figure 1. **a** The measured skyrmion number N of various fields after passing through an amplitude distorting channel ($\alpha=0$ no absorption, $\alpha=1$ full absorption), showing robustness throughout. **b** The encoded and measured N through various physical samples. **c** Reconstructed images after information transmission through complex channels using skyrmion encoding and OAM encoding.

References:

- [1] A. Forbes, et al, 2021. *Nat. Phot.*, **15**(4), pp. 253-262.
- [2] S. Gigan, et al, 2017. *Rev. Mod. Phys.*, **89**(1), 015005.
- [3] S. Gao, et al, 2021. *Phys. Rev. A*, **104**, 049901.
- [4] Peters *et al*, 2025. *arXiv:2508.12305*

Optical Skyrmions Across Scales: From Spatiotemporal Structured Light to Nanoscale Topological Fields

Danilo Gomes Pires¹, Jiaren Tan¹, Hooman Barati Sedeh¹, Wenhao Li¹, Jacob LaMountain², Evan Simmons², Takashige Omatsu^{3,4}, Viktor A Podolskiy², Natalia M. Litchinitser^{1*}

¹ Duke University, USA

² University of Massachusetts Lowell, USA

³ Chiba University, Japan

⁴ National Yang Ming Chiao Tung University, Taiwan

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Structured light with engineered spatial, temporal, and polarization degrees of freedom offers powerful opportunities to control light–matter interactions and encode information in optical fields. Our recent studies focused on the role of optical skyrmions and related topological polarization textures as a framework for connecting structured-light phenomena across space, time, and length scales. These studies link spatiotemporal field structuring, nanoscale photonic platforms, and the propagation of topological light fields in realistic environments.

Here, we first introduce a new class of spatiotemporal polarization states described by a generalized spatiotemporal higher-order Poincaré sphere. These states arise from the superposition of two orthogonal circular-polarization components that carry spatiotemporal optical vortices, enabling simultaneous control over the spatial and temporal structure of the electromagnetic field. Using ultrafast femtosecond pulses, we experimentally reconstruct the evolving vector fields and demonstrate the formation of spatiotemporal skyrmionic polarization textures.

We then show how such topologically structured fields can be compressed to the nanoscale using a hypergrating platform based on a multilayer hyperbolic metastructure. This approach enables subdiffraction focusing of orbital angular momentum beams to spots as small as $\lambda/3$ and supports optical skyrmion spin textures with characteristic sizes down to $\lambda/250$, providing a pathway for coupling structured light to nanoscale systems and quantum emitters.

Finally, we discuss the behavior of optical skyrmions in realistic propagation environments. Through turbulence-emulation experiments, numerical simulations, and full-Stokes-field reconstruction, we independently track the global and local topology of the polarization texture. While the global skyrmion number remains remarkably robust, local texture parameters, including polarity, vorticity, and helicity, degrade significantly under turbulence, revealing a hierarchy of robustness with important implications for topological information encoding.

Together, these results highlight optical skyrmions as a versatile platform for structuring light across space, time, and scale, opening new directions for optical communication, imaging, and nanoscale light–matter interactions.

This work was supported by the Army Research Office Award No. W911NF2310057, DMR 2004298, JSPS KAKENHI Grants-in-Aid (Grant Nos. JP22H05131, JP22H05138, JP23H00270) and JST-CREST (Grant No. JPMJCR1903).

Meta-photonic topologies for multidimensional communications

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Optical metamaterials and the topologies of light have both matured into vibrant sub-disciplines of photonics, yet their intersection—the meta-generator, manipulation and detection of topological optical textures—remains largely uncharted. Here, we provide a forward-looking talk on “meta-topological photonics”, an emerging platform that integrates ultrathin meta-devices with higher-dimensional topologies of light, ranging from two-dimensional skyrmions to four-dimensional knot fields. By surveying the latest advances in meta-generators, we outline a technological roadmap that miniaturizes bulky optical set-ups into chip-scale architectures while simultaneously extending the accessible topological complexity. Particular emphasis is placed on dynamically tunable, fiber-embedded metasurfaces, and alignment-free architectures based on bound-states-in-the-continuum. We conclude by charting an interdisciplinary pathway toward quantum-compatible topological photonic networks.

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A stroll down OAM lane: From Acoustics to Optics and back again.

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Over the years, various experimental realizations of optical as well as acoustical vortex fields have been created and applied to biomedical questions at our institute in Innsbruck.

A selection of these will be briefly discussed and put into perspective. The talk will start with opto-acoustically generated helical sound waves. Next, a concise overview will be given on holographic optical trapping and imaging that utilizes the features of OAM-carrying beams [1]. Finally, coming back to Acoustics, it will be demonstrated how acoustic vortex fields enable multi-view imaging, e.g. for optical tomography with high and isotropic resolution (cf. Fig.1) [2]. Throughout the talk, analogies and differences between optical and acoustic vortex fields will be highlighted [3].

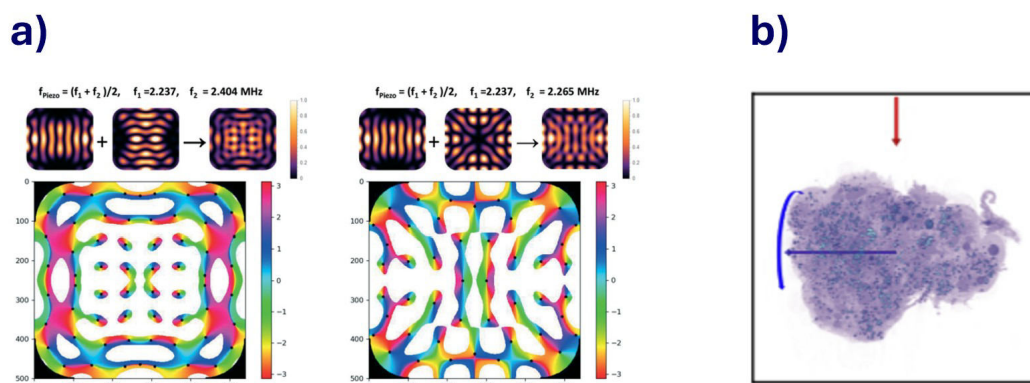


Fig.1 a) Acoustic modes with phase vortices, suitable to transfer angular momentum (and thus apply acoustic torque) to a levitated sample. b) Optical reconstruction of a 60 μm large cancer spheroid enabled by sustained acoustic rotation around 2 orthogonal axes.

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Topological waveforms and manipulation of particles: From nanooptics to ocean waves

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I will present recent theoretical and experimental results on several topics related to topologically structured waves. First, I will describe *type-II wave vortices* in 2D wave systems [1]. These vortices appear around ‘holes’ in the system, such as islands in ocean waves or perforations in surfaces supporting surface waves, see Fig. 1(a). A prominent example is provided by ocean tides circulating around New Zealand. Second, I will describe the generation of various topological wave structures, previously studied in optics (*vortices*, *skyrmions*, and *polarization Möbius strips*), in water waves [2,3]. Third, I will show that structured water waves can be employed for *manipulation of floating particles*, in a manner analogous to optical and acoustic tweezers [3,4], see Fig. 1(b,c).

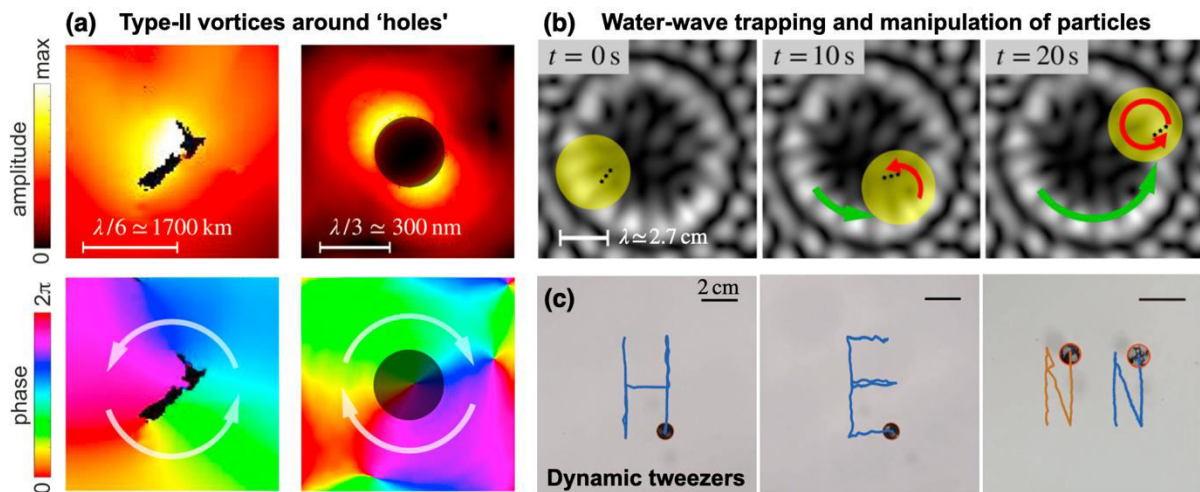


Fig. 1. (a) Amplitude and phase distributions in type-II wave vortices around ‘holes’ in a 2D plane. Shown are: ocean tides around New Zealand (left) and the vertical electric-field component around a nanohole in a phonon-polariton surface (right). (b) Radial trapping, orbital motion, and spinning of a ping-pong ball in a Bessel-type water-wave vortex with topological charge $\ell = 8$. (c) Dynamic water-wave tweezers enabling controllable transport of trapped floating particles along arbitrary trajectories.

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Agile light-matter topological interplay using self-engineered liquid crystals textures

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Liquid crystals underpin key optical technologies, most notably in display applications, where their orientational order is harnessed in highly optimized devices to generate dynamic distributions of light intensity over space and time, namely sequences of two-dimensional frames forming what is commonly perceived as video. Yet, this widespread use relies on a restricted view of light, limited to intensity modulation. Optical fields, however, carry additional degrees of freedom, such as phase and polarization, whose structuring enables a far richer landscape of control. This expanded perspective has driven the emergence of structured light and spin-orbit photonics, now a mature field where polarization (spin angular momentum) and spatial modes (orbital angular momentum) are intrinsically coupled. In this context, liquid crystals have enabled the development of geometric-phase optical elements that are now widely used as turnkey components, often without explicit consideration of their underlying liquid-crystal physics.

This technological success, however, only scratches the surface of what liquid crystals can offer. Beyond their maturity as a platform, they possess a defining feature: their ability to host a wide variety of topological structures, together with an exceptional sensitivity to broken symmetries across multiple length scales. This combination makes them particularly well suited for harnessing the topology of optical fields in a deterministic and reconfigurable manner.

In this talk, I will illustrate, through a set of recent experiments [1-4], how the self-adaptive and tunable response of liquid crystals to the angular momentum degrees of freedom of the light point to a regime where the intrinsic topological richness and self-organizing capabilities of liquid crystals can be fully leveraged.

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Metasurface-generated spatiotemporal vector beams and their invariance in complex media

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Simultaneous shaping of multiple of light's degrees of freedom has yielded spatiotemporal optical vortices (STOVs) with transverse orbital angular momentum and recently exotic 4D spatiotemporal vectorial beams (STVBs). Unfortunately, current generation methods rely on bulky, complex 4f shapers [1], prohibiting compact and on-chip applications. Additionally, the physics of how STVBs evolve in complex media remains unexplored, lacking quantitative basis independent methods for quantifying the space-time non-separability characterizing such vectorial light [2].

Here we demonstrate a novel, single-step metasurface generating STVBs by leveraging a symmetry-broken birefringent grating design [3] shown in figure 1(a,b). Next, we investigate STVB dynamics in complex channels using a customized basis independent quantitative measurement toolkit. We use this to show that the measured space-time non-separability remains the same through free-space and random phase distorting channels, even when other degrees of freedom are distorted, see figure 1(c). Our work thus represents a key step towards understanding STVBs by introducing new methods for both their experimental generation and their theoretical analysis, crucial for robust communication applications in noisy channels.

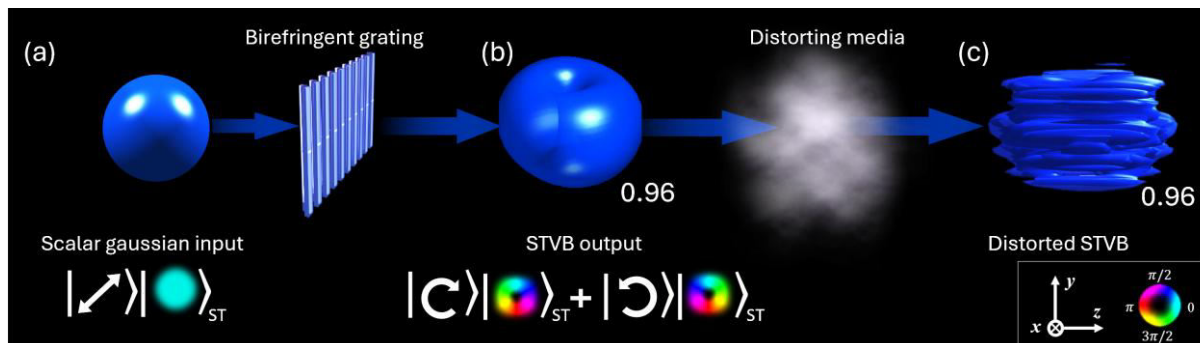


Figure 1: (a) Iso-intensity plots of a linearly polarized gaussian ST pulse sent through a symmetry-broken birefringent grating, generating an STVB shown in (b) consisting of orthogonally polarized STOVs with measured space-time non-separability of 0.96. After a random phase channel, the space-time non-separability emerges unchanged, still 0.96, despite the distortion in the STVB pulse profile shown in (c). Gradient colors indicate 2π phase variation, brightness indicates intensity and the non-separability value is shown at bottom right of (b,c).

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Attosecond Structured Light: From Angular Momentum Engineering to Topological Harmonic Spectroscopy

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Ultrafast laser technology has transformed our ability to observe and control matter on femtosecond and attosecond timescales. High-harmonic generation (HHG) has established attosecond science as a unique platform for applications in photonics, nanotechnology, spectroscopy, and imaging, as well as for fundamental research in physics, chemistry, and biology. A relevant development in this field is the structuring of ultrafast light fields in their spatial, temporal, and polarization degrees of freedom—in particular through the control of spin and orbital angular momentum (SAM and OAM)—opening avenues for time-resolved studies of ultrafast electronic and spin dynamics with unprecedented selectivity and sensitivity.

We review recent advances in the emerging area of structured light at the attosecond timescale. We discuss strategies to tailor the angular-momentum content of attosecond pulses, with emphasis on how the topology of extreme-ultraviolet (EUV) and soft-x-ray wavefronts, as well as polarization textures, can be engineered on ultrafast timescales. Building on the first demonstrations of HHG driven by vortex beams [1], the use of driving fields with engineered OAM has enabled precise control of the spatiotemporal properties of high harmonics, including attosecond vortices with controlled polarization [2], self-torqued waveforms carrying time-dependent OAM [3], EUV vector beams and attosecond vortex pulse trains [4], and EUV spatiotemporal and spatio-spectral optical vortices [5]. We present our latest results on attosecond spatiotemporal optical-vortex pulses [6] and on generalized attosecond polarization textures, including the first theoretical proposal for attosecond pulse skyrmions [7].

Finally, we outline emerging opportunities at the intersection of structured attosecond light and solid-state HHG. We highlight topological harmonic spectroscopy [8] as a powerful new approach for characterizing the nonlinear anisotropic response of quantum materials, with direct applications to the study of polycrystals and heterostructures of relevance to the semiconductor industry.

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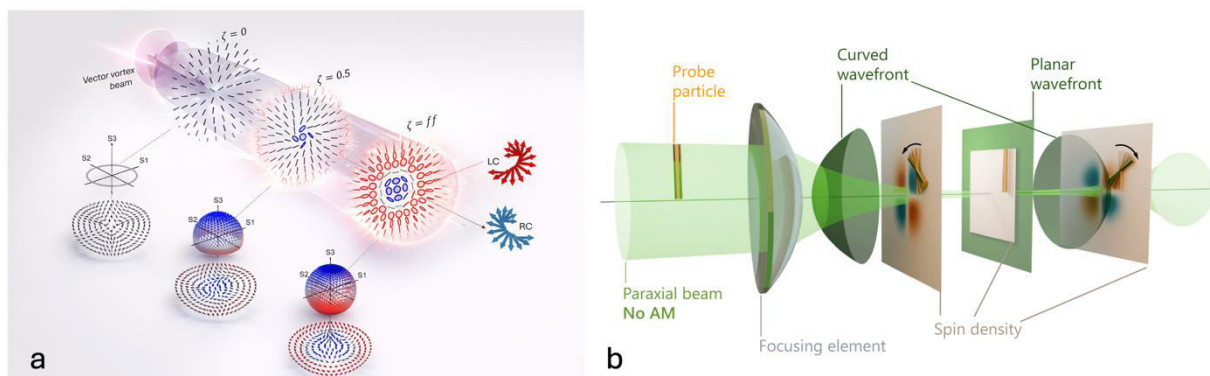
Spin from spinless light: Topological and non-paraxial generation of optical spin

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Structured light has revealed that the angular momentum of optical fields extends far beyond the simple distinction between spin and orbital contributions associated with polarisation and wavefront helicity [1,2]. In this talk I present recent work demonstrating that optical spin can emerge even from beams that are globally spinless. The first part focuses on a topological mechanism based on the Pancharatnam charge of vectorial fields, where spatially varying polarization structures give rise to well-defined topological character that enables the controlled emergence and manipulation of optical chirality and spin density, even when the overall beam carries no net spin [3]. This framework provides a new route for controlling the chiral features of light through topology, opening possibilities for structured-light-based sensing and light-matter interactions [1,2]. The second part addresses a complementary mechanism arising from strong non-paraxial focusing, showing that tightly focused linearly polarised Gaussian and Laguerre-Gaussian beams generate transverse field components that lead to local longitudinal spin in and around the focal region despite the incident beam being spinless. Together, these results illustrate how optical spin can be generated through both topological structuring and non-paraxial field formation, revealing new ways to engineer the angular momentum and chiral properties of light [1,2].



Spin from spinless light: (a) A vector vortex beam with controllable Pancharatnam charge generates spin density, optical chirality, and skyrmion-like structures upon propagation; (b) a spinless paraxial Gaussian beam produces spin density near the focal plane when tightly focused due to wavefront curvature.

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Informationally complete orbital angular momentum tomography with intensity measurements

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We study the tomography of spatial qudits encoded on structured light photons in the space of fixed order transverse modes. While direct position measurements with cameras do not provide an informationally complete Positive Operator Valued Measure (POVM), this property is achieved with the use of astigmatic transformation, allowing full characterization of the spatial quantum state from simple intensity measurements in both the intense and in the low photocount regimes. These methods are useful for classical and quantum communication with structured light. Here we deal with two regimes: in the first, we treat intense beams, which are equivalent to measurements on many copies of a quantum system and, therefore, one has reliable estimates for the probabilities of each experimental outcome. Then, we explore the low photocount regime, which is more subtle, as one cannot determine with certainty the state being observed. This fact is considered by some tomographic techniques, such as maximum likelihood [1,2] or the variational tomography method [3,4]. Here we will employ Bayesian inference [5,6], where one assigns a probability for each possible state. This probability is updated with each new observation, being initially broad when one has performed a low number of measurements, and then concentrating around a particular state as more and more data is used to update our knowledge. We will discuss the perspectives for quantum communication with structured light in free space and fiber links in the Rio de Janeiro Network.

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Towards Robust Structured Light Communications (Invited Talk)

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Optical vortices carrying orbital angular momentum (OAM) possess a helical phase front. More generally, structured light with spatially varying amplitude, phase, and polarization distributions makes full use of the spatial dimension of light waves. Structured light not only enables sustainable capacity scaling in optical communications, but also leverages its unique spatial structure to achieve robust optical communications with high immunity to interference and obstacles [1]. In this talk, we report recent advances in high-capacity and robust structured light communications in diverse scenarios [2-5], including free space, fiber, underwater, etc. After introducing Petabit-per-second high-capacity structured light enabled multi-dimensional multiplexing communications [1], we show our efforts in finding the superior mode basis for mode-division multiplexing communications by a comparison of various spatial modes in air-core fiber [3]. We also present robust free-space and underwater structured light communications in complex media environments, such as rain, fog, wind, and turbulence [1, 4, 5].

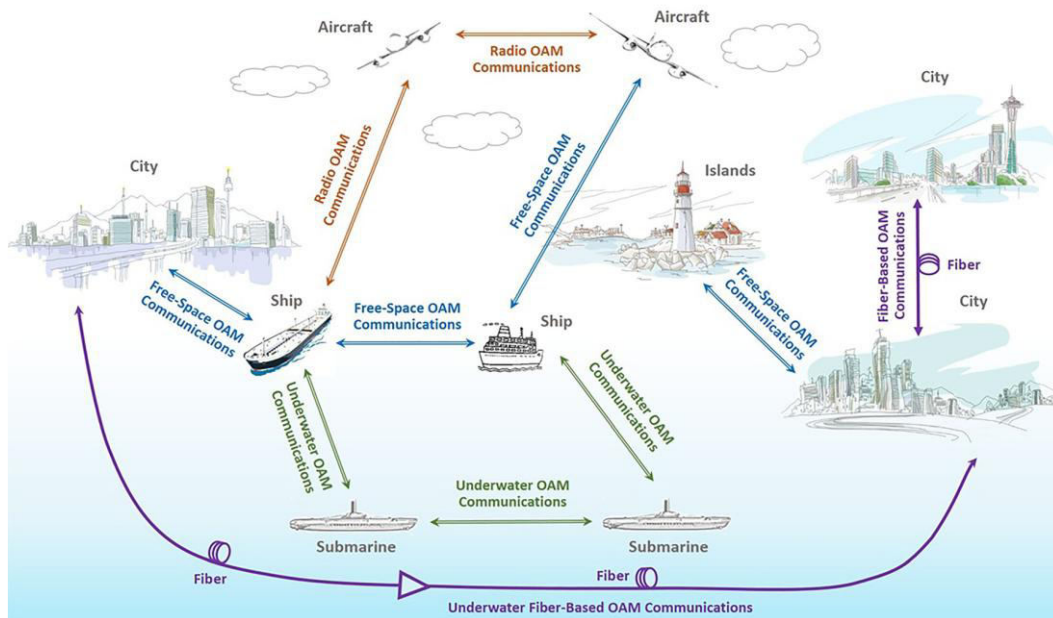


Figure 1. OAM communications in diverse scenarios (free space, fiber, underwater) [1].

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Engineering wave structure for acoustic manipulation

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In this work, we investigate two systems in which structured acoustic waves exhibit enhanced and unconventional capabilities for manipulating matter across very different length scales.

On the one hand, we introduce the use of high-order transverse modes in standing-wave acoustic levitation and demonstrate their ability to trap larger objects than those achievable with standard focused standing-wave levitators. By selecting appropriate transverse modes, we further show that irregular objects can be stably trapped and rotationally locked. We also examine the role of acoustic resonances in determining trapping behavior. In all cases, we support our findings with numerical calculations of acoustic radiation forces and experimental measurements.



Figure 1. Trapping of objects with different shapes and sizes (a) and multiple particle trapping (b) in high-order transverse modes in standing-wave acoustic levitators.

On the other hand, we present a fully controllable optical platform for generating spiral shock fronts. Combined with ultrafast shadowgraphy and streak-camera measurements, this platform enables real-time tracking of shock propagation and particle dynamics. Beyond introducing a new class of structured shock waves, our results reveal a previously unexplored regime of ballistic, angular-momentum-driven particle motion in liquids. These findings extend concepts originally developed for optical and acoustic vortices into the domain of nonlinear hydrodynamics. The ability to imprint and measure angular momentum in shock-driven flows opens new opportunities for microfluidic manipulation, cavitation control, and shock–matter interaction studies under extreme yet highly controllable conditions. Numerical simulations and analytical modeling are used to quantify pressure fields and angular momentum transfer.

Commensurate harmonic oscillators: bichromatic polarization and modal distributions

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Both the polarization state of coherent bichromatic fields produced by harmonic generation and a class of anisotropic paraxial optical cavities and waveguides are examples of commensurate two-dimensional harmonic oscillators. The geometric phase for these systems is discussed here, both in the classical/ray and quantum/wave regimes. The quantum geometric phase is described in terms of the coherent states of the system, for which recursive expressions are derived that yield the exact result and are numerically stable even for high modal orders. The ray/classical description of modes for the waveguides and cavities helps explain the geometry of the recently observed Boyer-Wolf modes that are separable in parabolic coordinates.

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Free-space photonic circuits for spatially structured light

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Free-space photonic circuits are emerging as a promising platform for the processing of structured light in both classical and quantum regimes. More generally, photonic circuits are designed to implement prescribed couplings among optical modes, and therefore act as processors for optical information encoded in multiple degrees of freedom. To date, the most developed implementations have relied on integrated photonics, typically based on meshes of beam splitters and phase shifters. However, free-space approaches offer an attractive complementary route, with direct access to large families of co-propagating spatial and polarization modes, broad optical bandwidth, and the possibility of low-loss high-dimensional transformations [1].

In this talk, I will present our recent advances in the development of a free-space photonic circuit technology based on patterned liquid-crystal elements. These devices implement spatially varying polarization transformations and, through them, controlled coupling between polarization and transverse spatial modes of light. This provides a powerful and flexible framework for the manipulation of structured light and for the realization of high-dimensional optical transformations in compact free-space architectures. Our recent work demonstrates scalable mode processing in both one-dimensional and two-dimensional configurations, including schemes that redistribute a single optical input across large sets of output modes and more general programmable manipulations of structured light [2,3,4].

Beyond their classical functionality, these free-space circuits are naturally suited to quantum optical applications [5]. They offer new opportunities for manipulating multi-photon states, controlling high-dimensional interference, and implementing photonic protocols that benefit from large mode spaces. I will finally discuss ongoing efforts toward more general and ultimately universal free-space photonic circuits, based on the combined use of near-field and far-field transformations.

These results highlight the potential of liquid crystal based free-space photonics as a versatile platform for structured-light processing, quantum simulation, and high-dimensional quantum information processing.

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Tuesday Sessions

Tuesday, the 16th
Chair: Karen Patricia Volke Sepulveda
09:00–09:25 Halina Rubinsztein-Dunlop Optical Angular Momentum in Optical Micromanipulation and Quantum Sensing
09:25–09:50 Andrea Aiello Counterfactual reasoning does not affect Bell's theorem
09:50–10:15 Qiwen Zhan Topology with Spatiotemporally Sculptured Light
10:15–10:40 David Andrews Optical Angular Momentum and a Multiplicity of Multipoles
10:40–11:10 Coffee Break
Chair: Monika Ritsch-Marte
11:10–11:35 Gerd Leuchs A clear operational distinction between quantum and classical entanglement
11:35–12:00 Robert W. Boyd TBA
12:00–12:25 Alan Willner Longitudinally Structured Beams for Communications and Sensing
12:25–12:50 Robert Fickler Volumetric Processing of Structured Light Integrated in Glass
13:00–14:00 Lunch Break
Chair: Jian Wang
14:00–14:25 Siddharth Ramachandran Topologically complex light transported by topological confinement
14:25–14:50 Christian Schmiegelow Super rotational Doppler shifts measured with single ion probe
14:50–15:15 Vincenzo D'Ambrosio Tailoring photonic correlations with quantum interference
15:15–15:50 Mohamed Babiker Quantum optics in phase-front-controlled Poincaré modes
15:50–16:20 Coffee Break
Chair: Bereneice Sephton
16:20–16:45 Alison Yao Novel Petal Beams for Control of Light & Ultracold Atoms
16:45–17:10 Sonja Franke-Arnold Optical activity of atomic vapours in topological light
17:10–17:35 Gabriel Molina-Terriza Improving optical trapping with angular momentum and helicity beams

Optical Angular Momentum in Optical Micromanipulation and Quantum Sensing.

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Optical angular momentum interacting with matter has been extensively used in applications such as optical micromanipulation, quantum sensing, quantum communication, superresolution and quantum imaging. In optical trapping the OAM is used for introducing rotation and torque to the system enabling application such as nano- and microviscoelasticity and production of all optically driven nano and micromachines.

Nanodiamonds (NDs) containing nitrogen- vacancy (NV) centers have raised interest as multifunctional probes for their unique possibility of being fluorescent scanning probes, combining spin optical read-out that makes them unique quantum sensors.

Combining optical micromanipulation and NV centres in nanodiamonds (NDs) focuses on the advantages and achievements in controlling the NDs positioning that enables precise magnetic sensing and measurements of other highly relevant parameters of the environment that they are in such as minute temperature changes and pH. The measurements combine force, position and torque determination with fluorescence detection and optically detected magnetic resonance, ODMR. For high precision measurements of this type it is essential to be able to control precisely the position of the nanodiamonds. We are developing methods that combine rotational optical tweezers and quantum sensing with FNDs to achieve this goal.

Counterfactual reasoning does not affect Bell's theorem

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Bell's theorem proves the incompatibility between quantum mechanics and local realistic hidden-variable theories. In this talk I will show that, contrary to a common belief, the theoretical proof of Bell's theorem is not affected by counterfactual reasoning [1, 2]. By analyzing the standard two-photon polarization-correlation experiment by means of ordinary random variables theory, I will show that all the physical quantities entering Bell's inequality are perfectly measurable, and they do not need to be known simultaneously [3].

This work possibly lays the groundwork for a critical rethinking of Bell's theorem and its consequences.

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Topology with Spatiotemporally Sculptured Light

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With the rapid advances in laser technology, optical fields with various topological features have attracted increasing attentions. Recent developments in spatiotemporal light field manipulation [1, 2] offer us the ability to directly sculpt optical fields in the spatiotemporal domain and produce optical fields with various topological features (figure 1). The generation of novel spatiotemporal wavepackets with various topological structures, including spatiotemporal optical vortex [3], spatiotemporal optical vortex ring [4], optical hopfion [5] and spatiotemporal optical skyrmion [6], etc. will be shown to illustrate the power of this approach. Wavepackets with these complicated topological structures exhibit many unique properties and may find important applications when interact with matters, opening tremendous potential opportunities for sculptured complex spatiotemporal wavepackets.

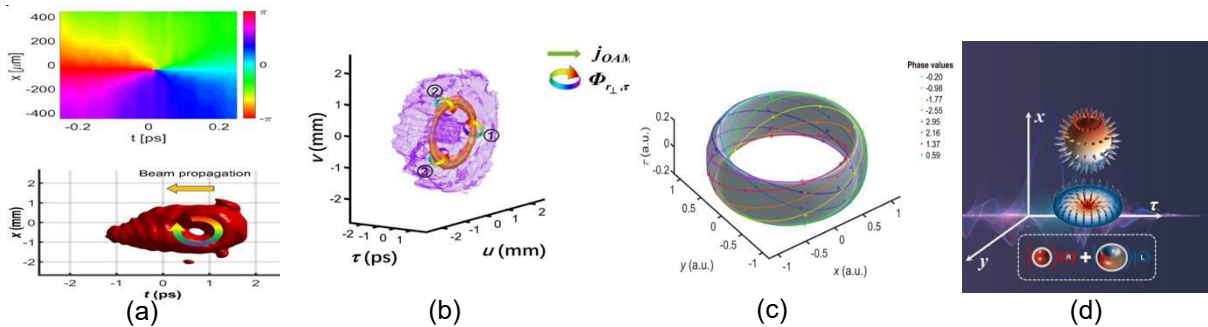


Fig. 1: Various topological structures formed with spatiotemporal optical wavepackets. (a) Spatiotemporal optical vortex; (b) Optical vortex ring; (c) Scalar optical hopfion; (d) Spatiotemporal optical skyrmion.

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Optical Angular Momentum and a Multiplicity of Multipoles

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There is a surprisingly wide, multifaceted range of technical meanings associated with the term ‘multipole’ in optical physics, extending well beyond the original electrostatic concept – and often significantly at variance with it. Especially in connection with optical angular momentum, ambiguities or misunderstandings can often arise. This talk discusses the different connotations with particular reference to their fundamental symmetry basis, examining the extent of connection between various kinds of material multipole and their propensity to engage forms of optical angular momentum.

A clear operational distinction between quantum and classical entanglement

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Quantum entanglement describes superposition states in multi-dimensional systems with at least two partitions, the wave functions, density matrices or Wigner functions of which cannot be factorized. These states are thus non-separable. This is a mathematical property which one finds not only in quantum models, but which exist also in classical theories involving e. g. vector spaces. In all cases, it is possible to violate a Bell-like inequality. This has led to controversial discussions, which were resolved by identifying a clear operational distinction between the classical and quantum cases [1].

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TBA

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Longitudinally Structured Beams for Communications and Sensing

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A category of structured light involves beam tailoring along the longitudinal propagation (z) direction. Controlling the longitudinal wavenumber, k_z , helps tailor the beam's spatial evolution as it propagates. By the judicious combination of complex-weighted modes at a transmitter, many beam properties can be engineered such that the constructive and destructive interference patterns can create a wide range of spatial structures that vary along the propagation path.

This paper will discuss various examples of longitudinal beam tailoring and their applications, including the following [1-5]:

(a) **Tailor Beam Size:** The beam width can be designed at the transmitter to vary with z for the following uses: (i) a low-divergence “pin-like” beam can maintain a relatively small beam size over a certain distance; (ii) a smaller beam might have less interaction with turbulence than a larger beam with the potential for link resilience; (iii) a series of differently designed beams that are narrower at different distances can be sequentially transmitted to probe turbulence along z ; and (iv) a link can be created such that a data beam can only be readily recovered at a specific distance for a desired receiver by transmitting a data beam along with a co-propagating “pseudo-noise” beam. In this last scenario, the noise beam's energy density can drop dramatically at the desired receiver's location.

(b) **Tailor Transverse Phase and Amplitude Distribution:** Tailorable transverse features that change with z include: (i) a “petal-like” transverse intensity profile that rotates with propagation distance can be used for ranging and can be created by combining two beams with different k_z values and orbital angular momentum (OAM) orders; (ii) a beam can exhibit different OAM orders at different distances within a beam's central region – thus enabling distance-dependent data channel recovery.

(c) **Tailor Polarization:** A longitudinal polarization evolution can be induced by the interference between two orthogonal polarization components with different k_z values. Measuring such a beam's z -dependent polarization can be used for ranging.

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Volumetric Processing of Structured Light Integrated in Glass

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Advances in the research of structured light are commonly based on the development of novel methods to increase modulation capabilities. A multi-plane light conversion (MPLC) is one popular example that has attracted a lot of attention over the last years. Commonly MPLCs allow performing complex multi-mode transformations of scalar light fields through multiple phase modulations and free space propagation [1,2]. However, practical limitations of most MPLC systems, such as challenges in alignment, increased losses due to multiple planes, and the lack of polarization control, limit their applicability.

In this work, we present a novel method for MPLC systems based on a compact, low-loss, transmissive silica glass substrate ($\sim\text{mm}^3$), in which the light's polarization is locally modulated thereby enabling full control over the vectorial light field, i.e. its polarization, phase, and amplitude [3]. The modulations are physically implemented through laser-written nanogratings inducing form-birefringence with a locally varying orientation of the optical axis (see Fig.1 a) and b)).

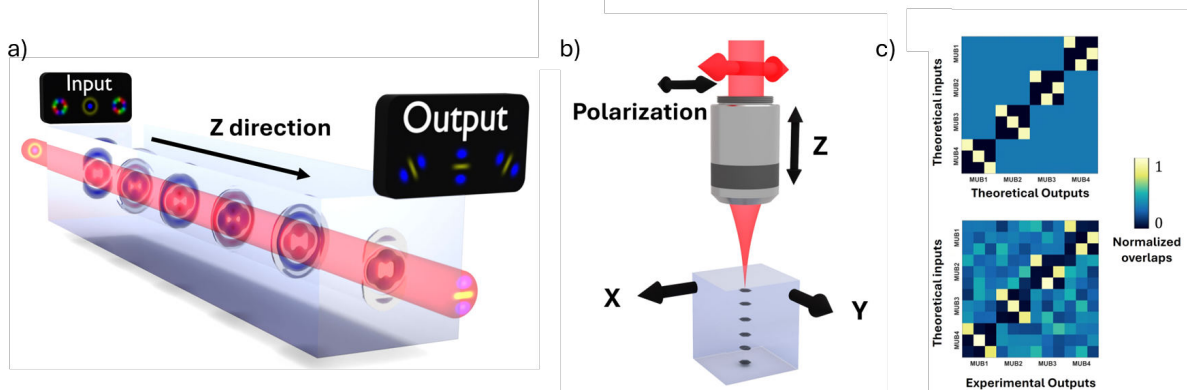


Figure 1: a) Concept of a volumetric modulation of light through MPLCs in glass. b) Schematic of the femtosecond laser-writing process. c) Laser-written 3D Hadamard quantum gate with ideal (top) and measured (bottom) crosstalk matrices obtained by probing all mutually unbiased basis states.

We obtained a spatial resolution of around 1-2 μm per pixel and an efficiency of around $>90\%$ transmission per plane. Using this technique, we implemented various scalar light field operations at 810 nm, incl. high-dimensional quantum gates (see Fig.1 c) as an example), multimode beam splitting, and an unconventional waveguiding scheme. We further implement full polarization-controlled spatial mode transformations and the transformation of the topology of an optical Skyrmion. Finally, demonstrate wavelength scalability and realize a spatial mode and polarization demultiplexer operating at the telecom wavelength of 1550 nm. Our scheme of using laser-written MPLC modulations will be a beneficial tool in all applications requiring advanced control over the full vectorial light.

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Topologically complex light transported by topological confinement

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Recently, a new regime of light guidance in waveguides, that relies on optical centrifugal forces rather than total-internal reflection, was elucidated. This regime of light guidance called topological confinement, enables distortion-free state transport of a record number of select eigenstates of light [1]. However, while topological confinement solves the modal crosstalk problem, transporting coherent superpositions of light's eigenstates remains susceptible to the environment.

In this talk, we describe recent experiments [2] that demonstrate a topological invariant that remains robust to ambient perturbations even for coherent combinations of eigenmodes in an optical fiber. We discuss the implications of these results for systems relying on light's coherence, such as quantum superpositions as well as classical coherent communications.

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Super rotational Doppler shifts measured with single ion probe

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We present a position-resolved measurement of the azimuthal Doppler shift of a structured beam¹, demonstrating that it can exceed the standard Doppler limit. The experiment employs two copropagating vortex laser beams in a configuration that isolates azimuthal field gradients while suppressing longitudinal and curvature effects.

A single ion is deterministically positioned across the beams, and fluorescence spectra exhibiting sharp “dark resonances” are measured. The spectral features depend on the ion’s angular velocity and on the difference in optical orbital angular momentum between the beams.

The results reveal the characteristic divergence of the rotational Doppler shift near the beam center and its scale-invariant nature, in agreement with numerical simulations and a simplified analytical model.

Furthermore, we demonstrate that the azimuthal shift can exceed the standard Doppler shift for a plane wave, providing, to our knowledge, the first observation of a super-Doppler effect. These findings open a route toward exploring its elusive counterpart: superkicks.

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Tailoring photonic correlations with quantum interference

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Photon correlations represent a central resource in quantum optics, with applications ranging from quantum information protocols to sensing. However, engineering such correlations is often challenging, especially beyond the two-photon regime. Structured light forms another hallmark of photonics, achieved by manipulating the degrees of freedom of light, and enables a multitude of applications in both classical and quantum regimes. Here, we combine these concepts and demonstrate a simple and robust scheme to tailor photon correlations directly in the transverse plane. The method relies on locally tuning the distinguishability of photon pairs through spatially structured polarization in a quantum interference setup [1][2]. Our approach offers an easy extension to multiphoton regimes and provides new opportunities for high-dimensional quantum information encoding and manipulation, with potential applications in quantum communication and imaging.

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Quantum optics in phase-front-controlled Poincare` modes

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The interaction of matter with vector twisted light (Poincare`) modes of higher order [1] is discussed, with special focus on the quantum optics of near-resonance dipole and quadrupole interactions. The main quantum processes involve angular momentum exchange, optical trapping in optical Ferris wheels, optical forces and torques and, more generally, opto-mechanics.

We also highlight the consequences of the realization that such modes are amenable to significant changes in their `twistedness' by judicious application of the q-plate technology [2,3] resulting in enhanced or diminished `twistedness'. We discuss how this leads, not only to modified properties of the original Poincare` modes [4], but also to their interaction with matter in the form of atoms, molecules and small particles.

These developments promise further advances in the areas of quantum and atom optics in highly focused structured light, especially in view of recent reports on nanoscale vectorial electric and magnetic field measurements [5].

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Novel Petal Beams for Control of Light & Ultracold Atoms

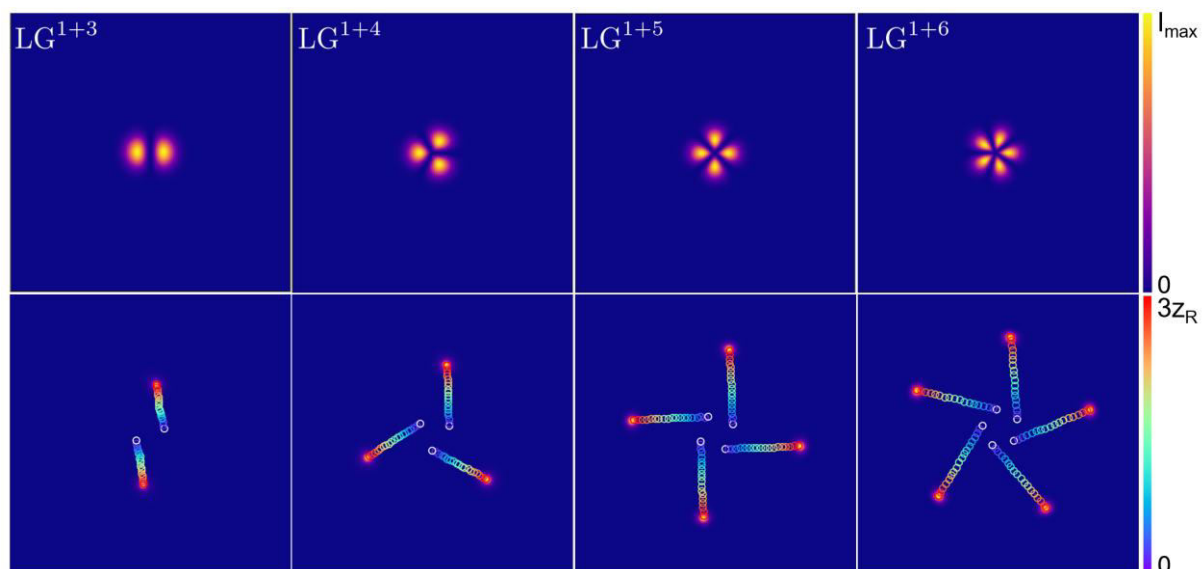
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The ability to spatially structure light can have significant implications in how it interacts with matter and opens new possibilities in engineering light distributions for particular applications. For example, spatial optical solitons – spatial structures that can propagate without a significant change to their spatial profile – are of interest for modern optical technologies. These form when the spreading due to linear diffraction is carefully balanced by a narrowing due to a self-focusing (Kerr) nonlinearity.

Light carrying orbital angular momentum (OAM), ℓ , has a ring-shaped intensity profile and an azimuthal phase distribution. In Kerr media, this fragments into a number $(2|\ell|)$ of solitons due to an azimuthal modulational instability, with angular momentum transferred to the solitons [1, 2]. Here we demonstrate a novel class of OAM-carrying beams with petal-shaped intensity distributions that result from a scalar superposition of two OAM beams, ℓ_1 and ℓ_2 . These allow us to engineer the azimuthal phase to determine both the net OAM and the number of solitons, providing a more robust method of controlling both the number and the dynamics of the resultant solitons. These have potential applications in communications systems and information processing and may be used as a novel method of controllable atomic transport in ultracold atoms when the light is far red-detuned from the atomic transition [3].



Top: Intensity distribution of petal beams consisting of a scalar superposition of OAM modes $\ell_1 + \ell_2$ where $\ell_1=1$ and $\ell_2 = 3, 4, 5$ & 6 (left to right) showing the robust formation of 2, 3, 4 and 5 solitons, respectively (bottom) over 3 Rayleigh ranges.

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Optical activity of atomic vapours in topological light

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We can shape and twist the structure of light, generating phase and polarisation vortices within the 3D electromagnetic vector field. Atoms are ideal in sensing and responding to such light via their dipole interaction. We have imprinted optical polarisation textures onto atomic spin structures in cold rubidium vapours, with promising applications in magnetometry and quantum sensing [1,2], and vice versa used the spectroscopy of strongly focused, structured light to visualise 3D light configurations [3]. More recently we have used the characteristic frequency response of circular birefringence and dichroism of an optically pumped rubidium vapour to generate correlations in frequency, polarisation and the spatial degrees of freedom, allowing us to perform spatially resolved polarisation spectroscopy. We have demonstrated the translation of frequency shifts into an image rotation, observing on resonance a rotation in the order of 9 degree per MHz. These findings may find applications in high-precision spectroscopy, magnetometry, and the generation of hybrid entanglement.

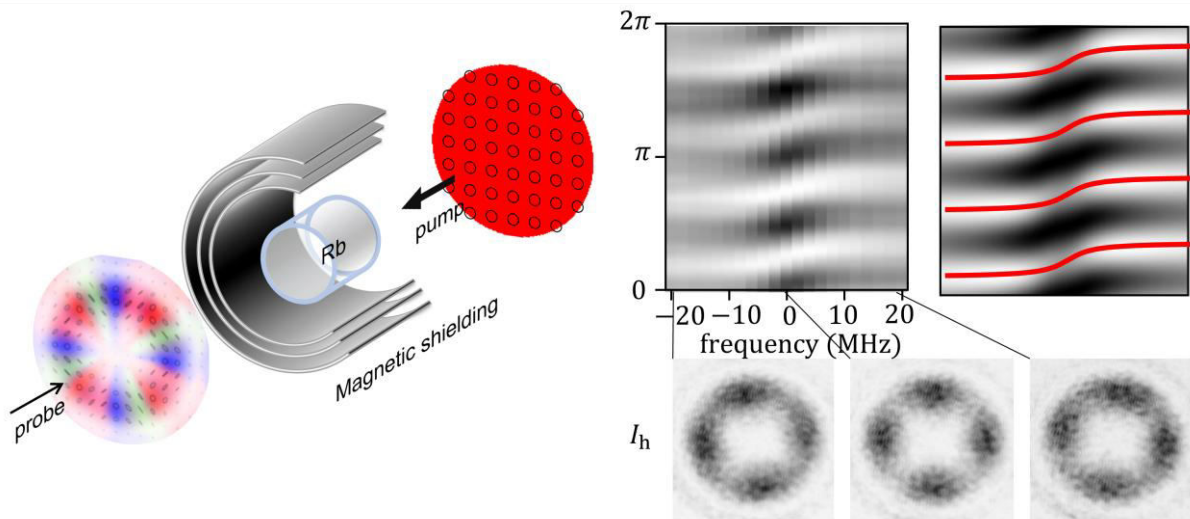


Fig.: Left: Sketch of experimental setup for measuring spatially resolved optical activity. Right: Visualising frequency shifts as rotations.

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- [3] Svensson et al, Optica 12 1553 (2025)

Improving optical trapping with angular momentum and helicity beams

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In this talk I will present our recent work studying both experimentally and theoretically complex optical traps using vortex beams with circular polarization. These beams typically present a dark spot in the centre of symmetry and an annular intensity pattern in the transverse plane. In the small particle regime, it is commonly assumed that the particle will not be trapped at the centre and will be confined to the ring of the particle in a non-stationary trap, as the particle will be moving around the beam centre due to what is commonly addressed as orbital angular momentum transfer of light. On the other hand, for larger particles, a stable and stationary trap can be found at the intensity minimum of the optical trap. Surprisingly, this trapping condition can offer higher forces in some situations than the usual Gaussian beam trapping.

I will show an analytical, numerical and experimental analysis of this kind of traps, which shows that this unusual trapping conditions are due to the multipolar modes that large particles can support. Our model is based on a non-traditional expansion of electromagnetic fields using helicity multipolar modes. We will show that this kind of expansion is better suited to the typical experimental conditions and also, that it can provide useful physical insight in all optical trapping regimes. In this way, we can explain the higher optical forces that can be obtained with higher order optical vortex beams. Moreover, we predict new experimental regimes that can be of interest to the optical trapping community.

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Wednesday Sessions

Wednesday, the 17th
Chair: Allison Yao
09:00–09:25 Bereneice Sephton Structuring light into interferometers for three-dimensional imaging
09:25–09:50 Carmelo Rosales-Guzman Structured light-based optical metrology
09:50–10:15 Takashige Omatsu Materials manipulation with optical skyrmions
10:15–10:40 Charles Roques-Carnes Separating partially coherent light
10:40–11:10 Coffee Break
Chair: Marko Šimić
11:10–11:35 Elleen Otte Revealing micro- and nano-dynamics through the spatiotemporal structure of light
11:35–12:00 Yuri Gorodetski Spatio-Temporal Weak Measurement of Structured Pulses
12:00–12:25 Thomas Juffmann Optical Near-field Electron Microscopy (ONEM): Damage-free, label-free super resolution imaging of interfaces
12:25–12:50 Ulrich Hohenester The workbench of optofluidic force induction
13:00–14:00 Group Photo / Lunch Break
14:00–20:00 Free Afternoon – Exploring Graz

Structuring light into interferometers for three-dimensional imaging

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The inherent insensitivity of conventional detectors to optical phase has long motivated interferometric techniques that map phase onto intensity. While multipath interferometers enable this, they typically suffer from instability and require active stabilization [1, 2], whereas common-path approaches [3] improve robustness at the cost of reconciling varying tradeoffs such as experimental complexity, computational overhead, or resolution constraints. Here, we show how to harness the properties of structured light modes to create a common-path interferometer, providing a versatile alternative [4]. By exploiting the spatial separation of different modes during propagation, collinear measurement and reference channels are formed that are readily generated and recombined. The scheme is fully general, enabling direct use of the rich landscape of structured light, supported by mature generation techniques and a wide range of well-studied modal bases. We experimentally demonstrate it using several different optical modes and reconstruct surface topographies of an array of physical samples, showing very good agreement alongside atomic force microscopy benchmarks. Our scheme presents a simple, compact, robust, and versatile approach to phase imaging that requires minimal post-processing or computation with direct applications to phase-sensitive metrology in biology, material science and industry.

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Structured light-based optical metrology (Invited Talk)

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The ability to tailor the fundamental degrees of freedom of light—phase, amplitude, or polarization—has become a defining capability of modern photonics. Precise, on-demand control over these properties is not only enabling the development of new optical technologies, but also reshaping and extending the performance of existing ones. As a result, structured light has emerged as a unifying framework driving innovation across both classical and quantum domains, with applications ranging from optical communications and trapping to imaging and precision metrology.

Within this broad landscape, optical metrology occupies a particularly central role. As a discipline built upon the use of light as a measurement probe, it underpins a vast range of scientific and technological applications. Its advantages over conventional approaches—non-contact operation, high precision, fast acquisition rates, and adaptability—make it an indispensable tool in modern research and industry.

In recent years, the incorporation of structured light into metrological schemes has opened new and exciting directions. In particular, optical fields engineered to exhibit nonseparability between spatial and polarization degrees of freedom provide access to richer forms of light–matter interaction. These vectorial and higher-order modes enable new strategies for encoding and retrieving information, ultimately allowing measurements that are more sensitive, robust, and adaptable than those achievable with conventional beams.

In this invited talk, I will present our recent advances in leveraging structured light for optical metrology. I will show how tailored spatial–polarization structures can be exploited to enable novel sensing capabilities, with representative examples in remote sensing, optical activity, and surface profilometry. These results illustrate how the structured nature of light can be harnessed to expand the scope and performance of modern measurement techniques.

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Materials manipulation with optical skyrmions

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To date, structured light encompasses a particle-like optical wave-packet, so-called an optical quasiparticle, with topologically protected wavefront or polarization textures in two- or three-dimensional real space. An optical skyrmion is the most remarkable optical quasiparticle, and it possesses an orbital angular momentum (OAM) associated from its Möbius strip shaped polarization textures, and it is rapidly finding utility in fundamentals and innovative applications as an optical counterpart of a magnetic spin skyrmion, such as free space optical and quantum communications under strong turbulence.

In this presentation, we introduce the generation and applications of the optical skyrmion towards exotic nanomanipulation and nanofabrication of materials.

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Separating partially coherent light

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Classical and quantum optical fields are naturally described in terms of modes. Modal decompositions underpin our understanding of the generation, propagation, and measurement of multimode light. Important examples of such modal decompositions include the Karhunen-Loève expansion for partially coherent fields [1], density-matrix eigendecompositions [1], Schmidt decompositions of bipartite states [2], and the Bloch-Messiah reduction of Gaussian states [3]. Conventional approaches rely on tomographic measurements and projections onto predefined modal bases, which scale poorly with dimension and require prior knowledge of the underlying structure.

Here, we introduce a general framework for modal decomposition based on “variational optical processors” [1-4]: self-configuring interferometric networks whose internal parameters are optimized to maximize selected output signals. Implemented with meshes of Mach-Zehnder interferometers, this approach physically separates an unknown optical field into mutually orthogonal components corresponding to the eigenmodes or singular modes of the relevant correlation operator – whether the coherency matrix, a bipartite density matrix, or a Gaussian covariance matrix – without requiring prior modal information. By sequentially training the processor on the largest eigenvalues or singular values, the device automatically performs decompositions such as Karhunen-Loève, Schmidt, or Bloch-Messiah directly in hardware.

We experimentally demonstrate this concept in a silicon photonic circuit designed for spatial coherence processing, which enables us to physically separate light into its mutually incoherent components. Our circuit also allows us to measure the coherency matrix eigenvalues and eigenvectors while preserving the state after optimization. These results establish variational optical processing as a scalable paradigm for programmable modal analysis and control in imaging, communication, sensing, and quantum photonics.

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Revealing micro- and nano-dynamics through the spatiotemporal structure of light

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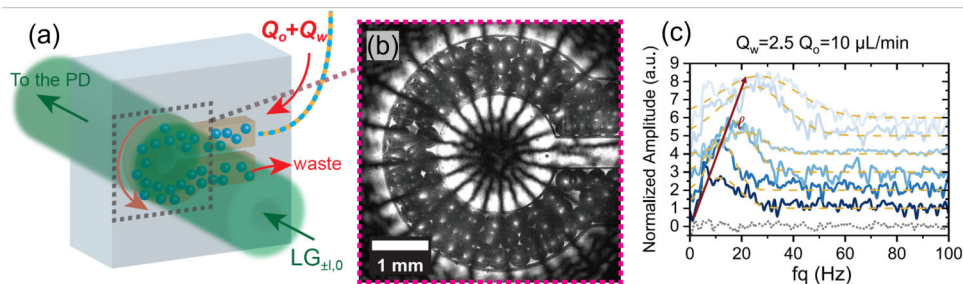
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The spatial and spatiotemporal structure of light serves as a rich carrier of information. When light interacts with a medium, its amplitude, phase, and polarization may be structured, capturing both static and dynamic properties of the system. These effects occur across a wide range of length scales, from macroscopic phenomena such as polarization patterns in the sky to nanoscale processes like the orientation- and motion-dependent emission of dipolar fluorescent molecules.

Fig. 1: OAM-based analysis of microfluidic emulsions. (a) Experimental concept; (b) exemplary channel/sample and (c) data [1].
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Here, we demonstrate that analyzing the spatiotemporal structure of light enables access to otherwise hidden information in dynamic media, and that engineering the probing field plays a major role in this capability. We first show that the orbital angular momentum of light can be exploited to retrieve microfluidic parameters in flowing droplet emulsions (Fig. 1) [1]. Further, we introduce a framework based on paraxial two-dimensional and non-paraxial three-dimensional coherence matrices [2] in cylindrical basis paving the way to probing nanoscale dynamics of dipolar emitters or scatterers in microscopic environments [3].

These results highlight structured light as a versatile tool for quantitatively characterizing complex, dynamic media across scales.

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Spatio-Temporal Weak Measurement of Structured Pulses

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Weak Measurement (WM) has been presented as a technique capable of resolving severely mixed quantum states¹. In particular it has been proved as an efficient way to detect subwavelength polarization-dependent shifts in light beams reflected or refracted by a plane surfaces² or coupled to plasmonic fields³. Here we demonstrate a combined effect of the spatial and temporal confinement resulting in a “spatio-temporal WM”. A femtosecond linearly polarized laser pulse is transmitted through a birefringent medium where temporal splitting into ordinary and extraordinary eigenstates occurs.

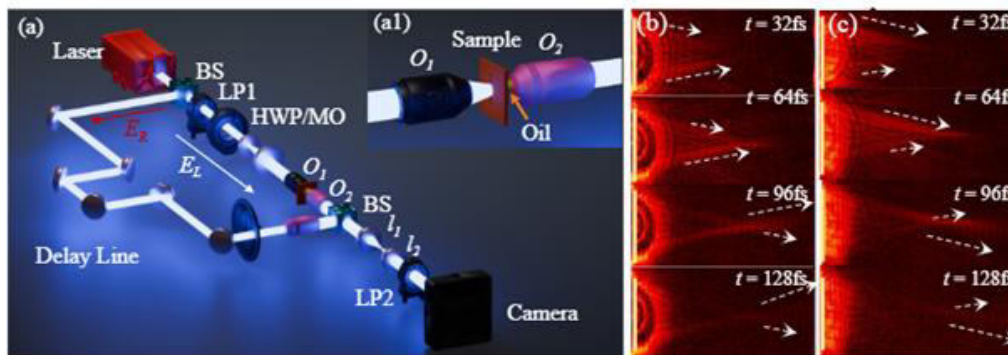


Fig. 1. Experimental Setup and the results. (a) Schematic diagram of the experimental setup with BS - beam splitter, LP - linear polarizer, O1 and O2 - objectives and L1 and L2 lenses. (a1) Leakage radiation microscopy setup. Measured plasmonic distribution in time launched by a beam emerged from a HWP (b) at $+45^\circ$ and (c) at -45° .

The emerging mixed-state time-evolution is then tightly focused by a high numerical-aperture objective (see Fig. 1a) on a plasmonic slit which provokes a spin-orbit interaction in analogy to our earlier work [3]. However, the time varying polarization state caused by the birefringence can be regarded as a time-dependent weak-value (WV). The slit then plays a role of the spatial post-selection while the evolution of the states is tracked by our time-resolved leakage radiation microscopy (TRLRM) system, presented in Fig. 1a. Positive or negative time delay between the eigenstates is obtained by placing a half-wave plate (HWP) at $\pm 45^\circ$ with respect to the incident polarization. Figure 1b,c shows the plasmonic waves measured in different times during the pulse propagation. The beam shifts are clearly observed in our system thanks to the high sensitivity of the WM method and the time resolution proposed by the TLRM. We experimentally measure the WV across the whole complex plane for the time-shifts of the order of 1% of the pulse duration.

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Optical Near-field Electron Microscopy (ONEM): Damage-free, label-free super-resolution imaging of interfaces

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How can we see nanoscale light–matter interactions and fast dynamics at interfaces without damaging fragile samples? In this colloquium, I will introduce Optical Near-field Electron Microscopy (ONEM), a new imaging approach that combines the non-invasiveness of light optics with high spatial resolution enabled by electron optics. The core idea is simple [1]: a specimen is illuminated with light, and the resulting near-field intensity patterns are converted into photoelectrons using a thin photocathode. Those photoelectrons are then imaged with a low-energy electron microscope, providing access to sub-diffraction near-field contrast with minimal invasiveness.

I will explain the underlying theory [1,2] and demonstrate that our prototype achieves a spatial resolution of ~ 30 nm at Hz frame rates [3]. I will then present three illustrative applications: mapping polarization-dependent plasmon modes in nanostructures, live imaging of *E. coli* in a liquid cell, and real-time visualization of copper electrodeposition. These examples demonstrate ONEM's unique combination of high spatial resolution, fast temporal response, and compatibility with liquid and electrochemical environments. I will finish by discussing technical challenges, expected improvements, and potential future directions in biology, electrochemistry, and nanophotonics.

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The workbench of optofluidic force induction

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Optofluidic force induction (OF2i) is an optical nanoparticle characterization scheme that exploits the optical tweezers principle, however, with a weakly focused laser beam and for trapping only in the transverse directions [1]. In OF2i, particles to be analyzed are pumped through a microfluidic capillary, and the laser beam propagating in the same direction as the particle flow exerts optical forces on the particles, which lead to size-dependent velocity enhancements that can be measured and used to infer the size of single particles or the size distributions of particle ensembles.

In this paper, we introduce to the basic principles of OF2i and demonstrate its working principle at the example of standardized particle distributions and industry relevant samples. We will also discuss the nanobem software which has been adapted for the simulation of optical tweezers and OF2i. Finally, we will show that OF2i can serve as a process analytical technology and can be combined with complementary techniques, such as Raman scattering or inductively coupled plasma–mass spectrometry in order to obtain detailed information about the analytes.

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Thursday Sessions

Thursday, the 18th
Chair: Robert Fickler
09:00–09:25 Michael Berry Wave trajectories, quantum potential, superoscillations: Madelung, de Broglie, Newton
09:25–09:50 Ebrahim Karimi Structured Quantum Light for High-Dimensional Quantum Information
09:50–10:15 Lorenzo Marrucci Superoscillations and conservation laws in structured light
10:15–10:40 Francisco J. Rodríguez-Fortuño Electromagnetic bispinor in different bases and the energy symmetry sphere
10:40–11:10 Coffee Break
Chair: Lorenzo Marrucci
11:10–11:35 Jörg Götze Bounds on Delocalisation in the Angular Talbot Effect
11:35–12:00 Oliver Heckl Towards Probing New Physics in the Mid-Infrared
12:00–12:25 Marco Ornigotti Geometric Aspects of Vector Beams and Jones Calculus
12:25–12:50 Enrique Galvez Laboratory Astrophysics with Complex Light: Gravitational lensing diffraction of gravitational waves
13:00–14:00 Lunch Break
Chair: Kayn Forbes
14:00–14:20 Fazliah Nothlawala Measuring relativistic motion using orbital angular momentum of entangled photons
14:20–14:40 Andrei Afanasev Three-Dimensional Optical Spin in Vacuum and in Chiral Matter
14:40–15:00 Linqiao Gan Spin-angular-momentum-multiplexed optoacoustic light storage
15:00–15:20 Koni Mwezi A quantum topological switch for entangled and single-photon skyrmions
15:20–15:40 Tareq Jaouni Full-Field Mode Sorter for Optical Knots
15:40–16:00 Coffee Break
Chair: Sarah Lindner
16:00–16:20 Margarita Khokhlova Chiral Stark shift – tweezing molecules in an enantiofashion
16:20–16:40 Dmitry Karlovets Generation and manipulation of relativistic vortex particles at accelerator facilities
16:40–17:00 Riaan Schmidt Probing the isolated vector magnetic field of structured laser beams by atoms
17:00–17:20 Alex Vernon Novel topological and geometric features of light's electric-magnetic space
17:20–17:40 Michael de-Oliveira Programming Nonlinear Optical Responses with Structured Light
18:30–20:00 Poster Session II Best Poster Award Sponsored by WILEY

Wave trajectories, quantum potential, superoscillations: Madelung, de Broglie, Newton

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The wave counterparts of classical particle paths and geometrical-optics rays are families of trajectories – patterns of streamlines – modified by a ‘wave (e.g. quantum) potential’. Wave interference corresponds to undulations in these trajectories, as envisaged in optics by Isaac Newton. Streamline patterns are dominated by singularities at wave vortices and stagnation points. The local momentum (phase gradient of the wave), can exceed the values classically allowed. Regions of such ‘superoscillations’ are bounded by manifolds where the quantum potential is zero. Some classical ‘curl forces’ – not the gradient of a potential – are associated with Hamiltonians (dispersion relations) anisotropic in momentum components, with unusual group velocity field singularities, and eigenfunctions with unfamiliar classical counterparts. For simple dispersion relations, some singularities coincide; for general dispersion, they are separate.

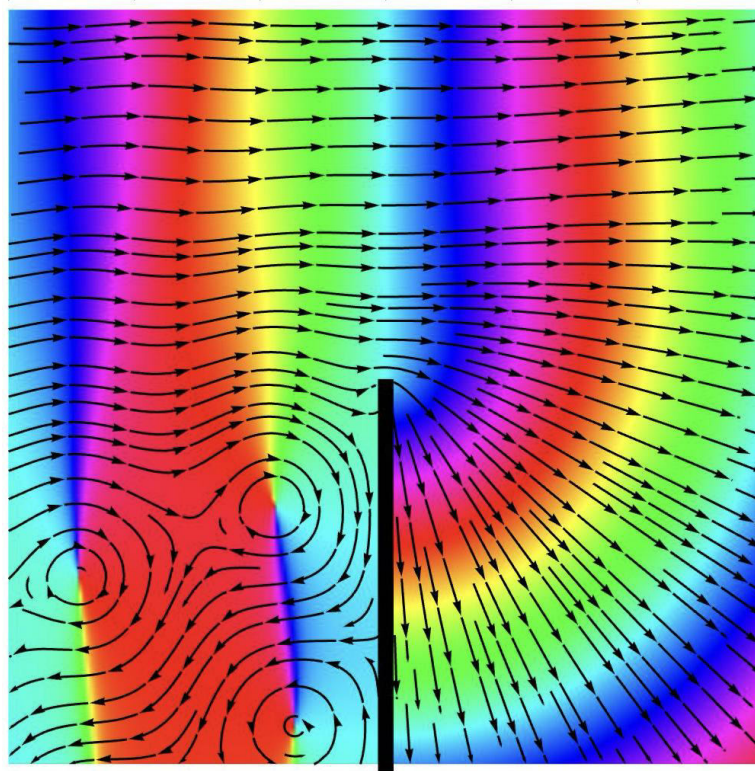


Figure. Madelung trajectories and phase in edge diffraction (Newton's eels)

Reference. <https://michaelberryphysics.wordpress.com>

Structured Quantum Light for High-Dimensional Quantum Information

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Structured waves have become an important resource across a wide range of modern technologies, including imaging, sensing, fabrication, communications, and quantum information science [1]. Their ability to carry tailored spatial, temporal, and polarisation structures provides new ways to control both classical and quantum waves.

Here, I will present several of our recent efforts in the generation, characterisation, and application of structured, high-dimensional, entangled photons for quantum information processing, including quantum key distribution and quantum simulation. I will first discuss our recent work on optimal wavefront shaping for achieving maximal focusing of matter and light waves within the paraxial regime [2]. I will then introduce multi-photon digital holography, which extends holographic techniques into the quantum domain and enables efficient reconstruction of high-dimensional entangled states [3], together with a biphoton phase-retrieval protocol that reconstructs quantum states from correlation measurements in only two propagation planes without requiring an external reference state [4].

Finally, I will highlight several applications of these techniques, including high-dimensional quantum key distribution [5,6], programmable free-space photonic processors [7], and photonic quantum simulators with nontrivial lattice topologies such as cyclic, toroidal, and cylindrical geometries [8].

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Superoscillations and conservation laws in structured light

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Superoscillations are intriguing classical or quantum wave phenomena in which spatial or temporal features may appear on scales that are not represented in the corresponding Fourier spectrum [1,2]. In the case of structured light, superoscillations are often associated with local phase gradients occurring on spatial scales that are not proportionally represented in the global spatial Fourier spectrum, at least for the observed amplitudes. This has motivated the introduction of several generalized definitions of local momenta [3], some of which are, in certain respects, related to weak values in quantum measurements and do not necessarily obey standard conservation laws [4–6]. In this talk, I will present some theoretical and experimental results we have recently obtained on this topic and briefly discuss the possible foundational implications of our findings, particularly in the context of quantum physics [4–7].

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Electromagnetic bispinor in different bases and the energy symmetry sphere

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The mathematical framework of electromagnetism was established by James Clerk Maxwell over 150 years ago. Later developments refined its notation, often bringing intuition, but without changing the physics: vector notation simplified the equations, relativistic notation unified electric $\mathbf{E}$ and magnetic $\mathbf{H}$ fields as frame-dependent projections of a single field, and later compact forms include Silberstein's $\boldsymbol{\Psi} = \mathbf{E} + i\mathbf{H}$ [1] and the equivalent bi-spinor form $\boldsymbol{\Psi} = (\mathbf{E}, \mathbf{H})$ [2], recently used effectively by Bliokh et al. to bring clarity and intuition to absorption, optical forces and torques [3].

In this work we explore the fascinating consequences of changing the basis of the electromagnetic bispinor. The electromagnetic bispinor has two coefficients (each of them vector-valued in three-dimensional space) in a two dimensional electric-magnetic space. We use $\boldsymbol{\Psi} = \frac{1}{2}(\sqrt{\epsilon}\mathbf{E}, \sqrt{\mu}\mathbf{H}) \equiv (\mathbf{F}_e, \mathbf{F}_m)$ in SI units. Like any other vector space, this vector may be expressed in different bases, as long as the basis vectors span the electric-magnetic vector space spanned by the unit vectors $\{\hat{\mathbf{e}}, \hat{\mathbf{m}}\}$:

$$\boldsymbol{\Psi} = \mathbf{F}_e \hat{\mathbf{e}} + \mathbf{F}_m \hat{\mathbf{m}} = \mathbf{F}_p \hat{\mathbf{p}} + \mathbf{F}_a \hat{\mathbf{a}} = \mathbf{F}_R \hat{\mathbf{R}} + \mathbf{F}_L \hat{\mathbf{L}} \quad \text{with} \quad \begin{cases} \hat{\mathbf{p}}, \hat{\mathbf{a}} = (\hat{\mathbf{e}} \pm \hat{\mathbf{m}})/\sqrt{2} \\ \hat{\mathbf{R}}, \hat{\mathbf{L}} = (\hat{\mathbf{e}} \mp i\hat{\mathbf{m}})/\sqrt{2} \end{cases}$$

This leads to novel vector-field components of the bi-spinor: parallel and antiparallel fields $\boldsymbol{\Psi} = (\mathbf{F}_p, \mathbf{F}_a)$ or right and left-handed fields $\boldsymbol{\Psi} = (\mathbf{F}_R, \mathbf{F}_L)$, with each pair describing the full electromagnetic field, as an alternative to electric and magnetic fields. Interestingly, we can define the total energy density W_{tot} , canonical momentum $\mathbf{p}_{\text{tot}}$, and spin $\mathbf{S}_{\text{tot}}$ of the electromagnetic field, in terms of any basis:

$$\begin{aligned} W_{\text{tot}} &= W_e + W_m = W_p + W_a = W_R + W_L & \text{with} & & W_i &= \mathbf{F}_i^* \cdot \mathbf{F}_i, \\ \mathbf{S}_{\text{tot}} &= \mathbf{S}_e + \mathbf{S}_m = \mathbf{S}_p + \mathbf{S}_a = \mathbf{S}_R + \mathbf{S}_L & \text{with} & & \mathbf{S}_i &= \mathcal{I}\{(\mathbf{F}_i^* \times \mathbf{F}_i)/\omega\}, \\ \mathbf{p}_{\text{tot}} &= \mathbf{p}_e + \mathbf{p}_m = \mathbf{p}_p + \mathbf{p}_a = \mathbf{p}_R + \mathbf{p}_L & \text{with} & & \mathbf{p}_i &= \mathcal{I}\{(\mathbf{F}_i^* \cdot (\nabla)\mathbf{F}_i)/\omega\} \end{aligned}$$

This is reminiscent of 2D Jones vectors and Stokes parameters, and indeed a structure mathematically equivalent to the Bloch or Poincare sphere arises on $\{\hat{\mathbf{e}}, \hat{\mathbf{m}}\}$ space [4].

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Bounds on Delocalisation in the Angular Talbot Effect

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The Talbot effect — self-imaging of periodic waves from quadratic dispersion in the Fourier-dual domain — has recently been realised in the azimuthal angle and orbital angular momentum (OAM) degrees of freedom of structured light. In multimode fibres, the whispering gallery modes, high-OAM eigenmodes confined near the core–cladding interface, exhibit the required near-quadratic OAM dispersion [1,2]. A Gaussian beam coupled tangentially into such a fibre generates a rich angular Talbot carpet, with integer and fractional self-images, periodic relocalization, and fractal substructure — providing an analytically tractable platform for exploring angular localisation and delocalisation in the context of the angle–OAM uncertainty relation.

The angle–OAM conjugate pair presents foundational challenges absent from the canonical position–momentum case: 2π -periodicity of the angle forces the OAM to take only integer values, requiring a discretization procedure in the construction of a Hermitian angle operator [3]. We compare three uncertainty frameworks: the Robertson variance-based approach [3] (starting-angle-dependent); the Shannon entropic uncertainty relation [4], which is starting-angle-independent and resolves the fractal self-similarity of the Talbot carpet; and a circular-moment approach [5] that respects the topology of the circle and yields tight bounds with explicitly constructible minimum-uncertainty states.

A key finding concerns the fundamental limits on angular delocalization in this system. Although the intensity profile approaches near-uniform flatness between Talbot revivals, the residual modulation imposed by the Talbot resonance structure prevents the distribution from ever reaching a truly uniform random angular distribution. The deviation from uniformity is quantified by the OAM power spectrum and the specific Talbot phases, establishing a lower bound on the angular entropy that is intrinsic to the fiber geometry. This connects the uncertainty relation directly to the mode structure of the fiber and constrains the use of Talbot dynamics as a generator of angularly random fields.

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Towards Probing New Physics in the Mid-Infrared

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Broadband precision spectroscopy of rovibrational molecular transitions holds promise for tracking periodic variations in fundamental constants — variations that may offer evidence for ultralight dark matter and point towards physics beyond the Standard Model. This talk presents an overview of our efforts towards novel spectroscopy methods in the mid-infrared, pursuing two complementary directions.

First, we are developing broadband saturation spectroscopy [1] enabled by mid-IR low-noise, high-power frequency combs delivering Watt-level output [2] and crystalline supermirrors with a cavity finesse surpassing 400,000 [3], [4]. Together, these tools open the path to Doppler-free interrogation of molecular transitions over broad spectral windows.

Second, we explore the use of structured light to excite dipole-forbidden transitions [5]. Our current focus is on quantifying the orbital angular momentum content of light beams [6] and designing light patterns that enhance coupling to quadrupole transitions, thereby accessing spectroscopic signatures.

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Geometric Aspects of Vector Beams and Jones Calculus

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Geometry and topology are the foundations of modern theoretical physics and, as such, underpin a wide variety of physical theory, from condensed matter physics [1] to quantum field theory [2], and optics [3,4]. The latter offers a unique playground, where topological and geometrical concepts and ideas can be tested, and at the same time exploited to create new kinds of structured light, or new protocols to control its flow in photonic systems. Due to their intrinsic spin-orbit coupling, vector beams possess rich topological features, such as polarisation and phase singularities [5], skyrmionics charges [6,7] and nontrivial topologies [8]. The usual framework used to describe the properties of vector beams is that of the high-order Poincaré sphere [9,10]. Although simple and intuitive, this framework fails to capture the more complicated geometric features carried by vector beams, such as nonabelian geometric phases, and lacks a proper unified classification of the topology of vector beams.

Motivated by all this, in this talk I will present a new perspective on vector beams by going beyond the usual Poincaré sphere description and introducing the paraxial bundle, a principal $SU(2)$ bundle naturally encoding the topological properties of vector beams in the Chern-Simons charge, a topological invariant related to spin-orbit coupling [11]. A careful study of the Chern-Simons charge will also allow a universal topological classification of paraxial vector beams.

With the paraxial bundle established, I will also discuss how Jones calculus fits into this formalism, and how the paraxial bundle gives a simple recipe to design and control the topological properties of paraxial vector beams by means of simple optical components, such as q-plates and wave plates.

Finally, I will discuss how to extend this framework to nonparaxial beams, and what sort of new information can be deduced from it.

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Laboratory Astrophysics with Complex Light: Gravitational lensing diffraction of gravitational waves

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We investigate the diffraction pattern produced by gravitational lensing due to a binary-mass system. We use spatial light modulation to deflect coherent light following the predictions of general relativity, and image the resulting diffraction pattern, as shown in Fig. 1(a). The analog-simulated diffraction of the lensed light exhibits rich patterns. For zero mass separation, the diffraction pattern is a Bessel pattern [1]. For non-zero separations, the patterns consist of interference-decorated caustics. The morphology of patterns depends on the parameters of the problem. The pattern shown in Fig. 1(b) corresponds to a binary-mass separation of the order of the corresponding Einstein lensing-ring radius for the lensing masses. By using scaled parameters, we can correlate laboratory-scale measurements with astrophysical-scale predictions. There is excellent agreement with theoretical calculations of the expected diffraction patterns.

Observing lensing diffraction with electromagnetic waves is not feasible due to a lack of coherence. Diffraction of gravitational waves (GW) may be possible due to more favorable conditions: Earth-sized wavelengths, and point-source emitters, such as black-hole neutron-star mergers. However, the GW observatories (LIGO-Virgo-KAGRA) occupy only a minute region in the pattern. A multi-wavelength study that we performed can inform the expected modulation of gravitational-lensed signals due to the gravitational-wave chirp.

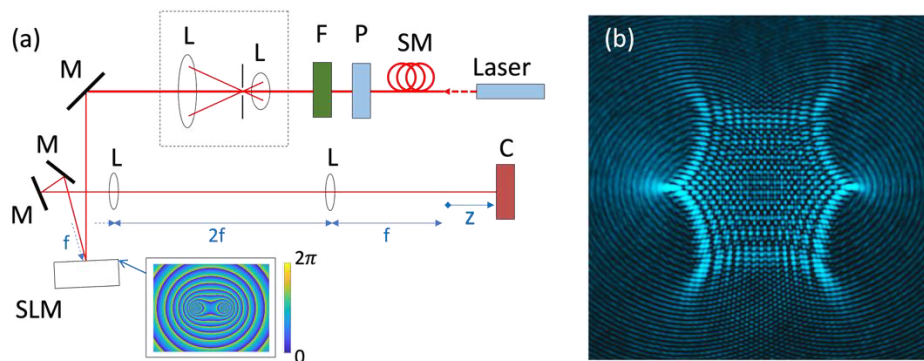


Fig. 1 (a) Apparatus: light from a laser is expanded, deflected with a binary-mass phase mask, and imaged with a camera. (b) A pattern taken with a wavelength of 491 nm.

This work was funded by National Science Foundation grant PHY-2409587.

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Measuring relativistic motion using orbital angular momentum of entangled photons

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Orbital angular momentum (OAM) in both classical and quantum regimes has fueled numerous fundamental studies and application from high-dimensional optical communication [1,2] to enhanced precision in metrology and sensing [3-5]. Here we extend OAM-based metrology to measure relativistic parameters using the OAM spectrum of entangled photons, by exploiting the Lorentz invariance of OAM. We show how the joint OAM spectrum is altered when measured by observers moving at relativistic speeds relative to the OAM-entangled source, with a broadening in the spectrum shown in **Figure 1(a)**. We experimentally simulate the relativistic motion of the observers using length-contracted OAM holograms on spatial light modulators (SLMs), achieving velocities up to 0.99c and confirm the predicted broadening with experimentally measured OAM spectra. Leveraging this broadening, we directly extract the Lorentz factor (γ) using the measured joint probability outcomes, with the experimentally measured γ matching the encoded γ , as shown in **Figure 1(b)**. Our work opens an exciting avenue for harnessing OAM structured light for precise measurements in relativistic scenarios.

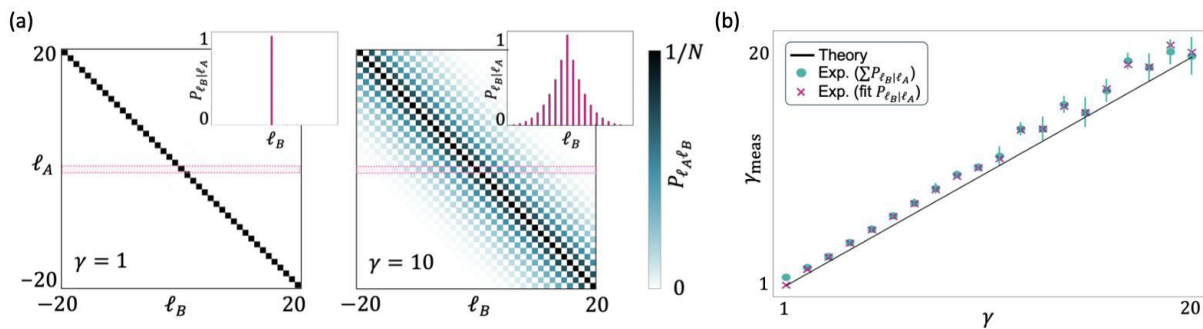


Figure 1 (a) Theoretical joint OAM spectrum for observers at rest ($\gamma = 0$, $v = 0$) and moving at relativistic speeds ($\gamma = 10$, $v = 0.99c$). (b) The encoded Lorentz factor compared with the measured factor with the fitted γ values shown with pink crosses.

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Three-Dimensional Optical Spin in Vacuum and in Chiral Matter

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Phase singularities of electromagnetic fields are often accompanied by topological spin textures. We show that these topologies may be identified as stand-alone sub-wavelength size skyrmions formed by a three-dimensional optical spin [1,2]. Special features of these topological formations include (a) robustness under propagation and (b) particle-like properties in their interaction with matter.

After presenting theoretical background for the photon spin described by a (3x3) density matrix, we analyze physics constraints that make optical spin skyrmions non-diffractive under propagation [3,4]. Next, we show that the spin skyrmions are polarization normal modes in optically active chiral medium and predict evolution of optical spin of structured light in the optically active matter. Figure 1 shows our predictions for evolution of the transverse optical spin for azimuthally-polarized (AP) and radially polarized (RP) cylindrical vectorial beams in optically active medium derived from superposition of individual skyrmionics modes. We find that the beam oscillates between AP and RP modes, accompanied by rotation of the transverse spin component.

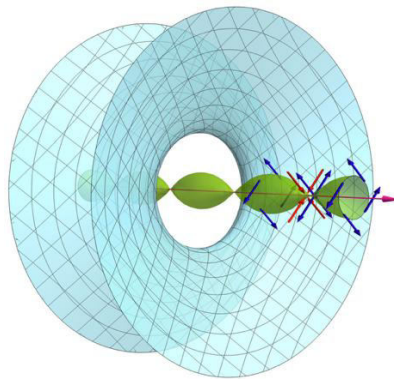


Figure 1. Evolution of transverse optical spin of cylindrical vector Laguerre-Gauss beams in optically active medium. Blue surface is beam's waist; the surface of 3D-spin singularity (C-surface) is shown in green. Spin direction - shown by arrows - is azimuthal for RP mode, becoming radial when approaching AP mode and flipping sign after passing through AP state of polarization. Blue (red) arrows indicate a positive (negative) radial direction.

We draw a comparison between the rotation of photon spin under optical activity and similar rotation of the spin of thermal neutrons due to small-angle scattering on nuclei via parity-violating weak interactions [5]. There are, however, distinct differences that we will outline in this talk.

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Spin-angular-multiplexed optoacoustic light storage

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We report spin angular momentum (SAM) multiplexed light storage in chiral photonic crystal fiber (PCF). This mechanism provides coherent buffering that exploits the SAM space, facilitating high-dimensional storage for all-optical computing. We use a 3-fold rotationally symmetric chiral PCF (Fig. 1(a)) which is designed to carry orbital angular momentum (OAM) with topological charge ℓ and SAM with order s . Fig. 1(a) shows the measured near field distribution of $[0,+1]_1$, $[+1,+1]$ and $[0,+1]_2$ modes. Optoacoustic light storage^[1] leverages stimulated Brillouin scattering (SBS) to store and retrieve optical information in and from acoustic waves, taking advantage of the slow acoustic velocity by five orders of magnitude. Two data channels are encoded with orthogonal spin states (Fig. 1(b)): Each data pulse is counter-propagating a pair of write and read pulses, which are encoded in LCP, RCP and linear polarization (LP) states. When data and write pulses meet in the waveguide, the data information is coherently transferred to the acoustic domain. In the reading process, the stored information is converted back to an optical read-out. According to the cross-spin SBS effect^[2], the data only interacts with control pulses when they are in opposite spin states. The data pulses can be selectively or simultaneously written and readout by appropriately tuning the spin state of each control pulse pair. In Fig. 1(c), we demonstrate the spin-selective storage of LCP and RCP data with efficiency of 12.2% and 10.8%. LP control pulses lead to simultaneous storage and read-out with 9.6% and 9.8% efficiency, respectively.

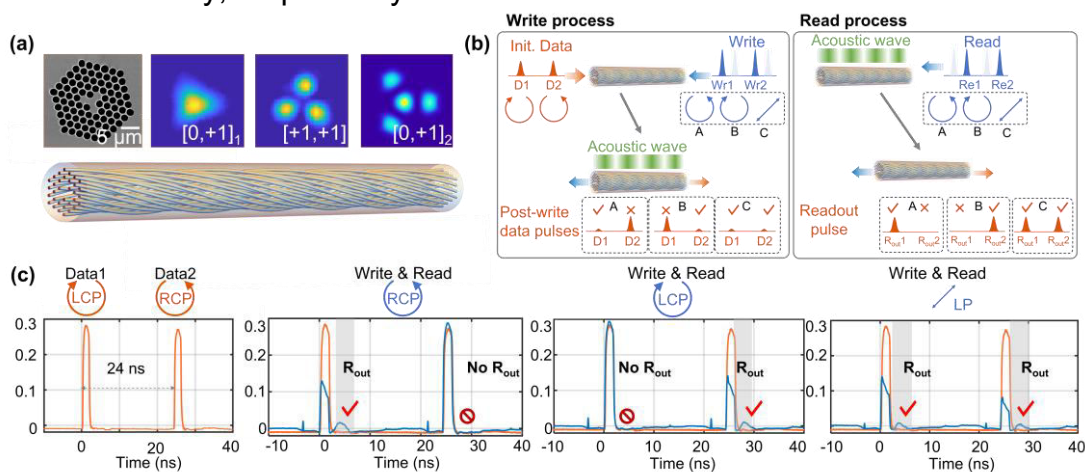


Fig. 1. (a) SEM of fiber cross-section with near field distribution of $[0,+1]_1$, $[+1,+1]$ and $[0,+1]_2$ modes and chiral PCF. (b) Optoacoustic storage and read-out schematic. (c) Measured stored and retrieved data pulses under RCP, LCP, and LP control states.

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A quantum topological switch for entangled and single-photon skyrmions

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Topological structures such as skyrmions have emerged as robust carriers of information across condensed matter [1] and photonics [2]. In optics, skyrmions have been realized in entangled photon pairs [3] and single photons [4] but only in separate implementations [5], leaving no platform capable of switching between quantum topological regimes within the same system. We demonstrate a reconfigurable generator of quantum skyrmions based on a voltage-tunable liquid-crystal topological defect acting as a spin-orbit coupling device. Starting from a dual-wavelength entangled photon pair produced via spontaneous parametric down-conversion, wavelength-dependent coupling between polarization (spin) and orbital angular momentum together with projective measurements enables deterministic preparation of a nonlocal entangled skyrmion, a heralded single-photon skyrmion, or a trivial topology state using the same apparatus. To test robustness, the states were transmitted through a biological specimen (fly wing) and the reconstructed topology remained intact, showing that the encoded topology survives perturbations and indicating potential for noise-resilient communication and minimally invasive quantum imaging. Crucially, wavelength degree of freedom participates non-separably in the state, enabling multicolor topological correlations and suggesting a route toward GHZ-type entanglement across polarization, OAM, and wavelength, establishing liquid-crystal defects as programmable generators of switchable topological entanglement for quantum photonics.

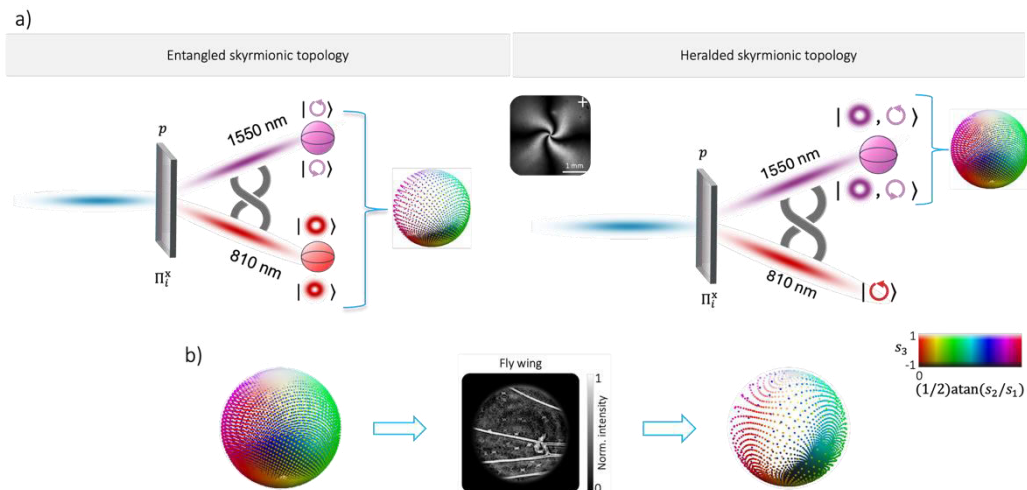


Figure 1 a) Conceptual schematic of the quantum topological switch. A dual-wavelength entangled photon pair passes through a voltage (p) controlled liquid-crystal topological defect that couples polarization and orbital angular momentum. Subsequent projective measurements (Π_i^x) select the output state, enabling switching between a nonlocal entangled skyrmion, a heralded single-photon skyrmion, or a trivial topology. The inset includes cross-polarized image of the liquid-crystal defect used in the experiment. b) The generated topology remains preserved after transmission through a biological sample.

Full-Field Mode Sorter for Optical Knots

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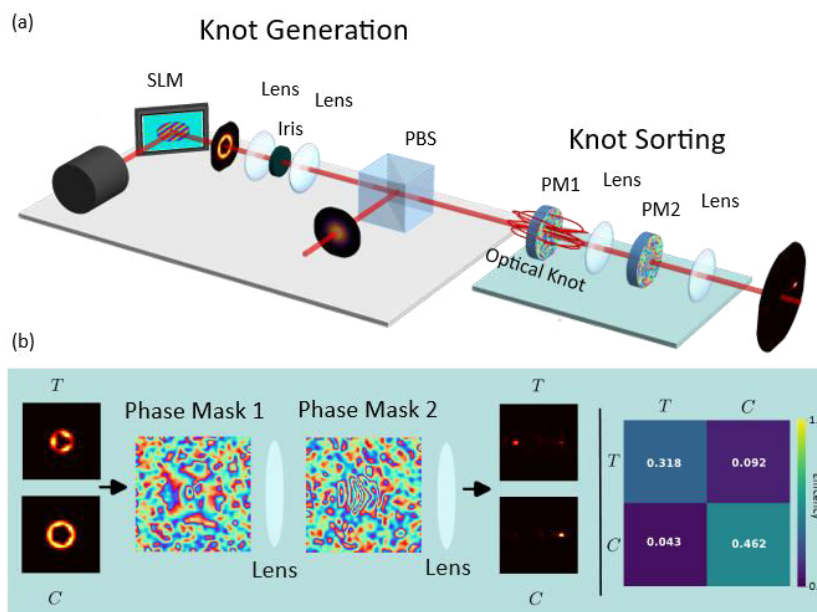
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Optical knots show promise as vectors of classical and quantum information due to their topologically structured field configurations [1] which, inspired by knot theory [2], can exhibit robustness to smooth disturbances [3]. Devices incorporating optical knots into information tasks have not yet been investigated. Here, we demonstrate a proof-of-principle experiment which sorts optical knots. We propose a full-field sorting scheme with up to two phase elements optimized using evolutionary algorithms [4]. Owing to the topological nature of optical knots as well as the knotted fields' non-orthogonality, we further study our sorting scheme's performance under different experimental conditions and suggest a scheme on designing optical knots to achieve optimal sorting performance.



Full-Field Optical Knot Sorter. (a) Experimental concept which generates and sorts optical knots. (b) Sorted output and crosstalk matrix for Trefoil (T) and Cinquefoil (C) knots using two phase masks.

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Chiral Stark shift – tweezing molecules in an enantiofashion

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Chirality plays a vital role in living nature, emphasising its importance across the sciences, with chiral recognition – telling apart right-handed molecules from their mirror, left-handed companions – as a key challenge. This broad effort has recently reached ultrafast physics, with vivid progress in strong-field laser interactions with chiral molecules [1].

We introduce a new effect in ultrafast physics – the chiral Stark shift [2]. We show theoretically that the ordinary Stark shift acquires a chiral counterpart when a chiral molecule is illuminated by synthetic chiral light [3], or more specifically, a tricolour chiral (TRICC) field [2]. This turns Stark-shift-based phenomena into enantiosensitive ones, where molecules of opposite handedness, enantiomers, respond differently to the same synthetic chiral light field.

Optical tweezers are an extremely powerful and versatile tool for trapping and manipulating matter, from atoms to micron-scale objects. One long-lasting dream is the enantiosensitive optical trapping of chiral molecules: an optical trap that captures one enantiomer while rejecting its mirror twin – an optical solution long sought in chemistry and pharmaceuticals. Yet such a chiral optical trap has remained elusive, since linear chiroptical phenomena rely on magnetic-dipole and electric-quadrupole interactions, which are dominated by the much stronger electric-dipole contribution.

Here we leverage recent developments in chiral nonlinear optics, a direct offspring of attosecond and ultrafast science, which permit pure electric-dipole interactions in the ultrafast regime. Our approach is built around synthetic chiral light [3] as the main tool: a multicolour light field that couples to a multi-photon chiral molecular pseudoscalar [4] and exhibits its chirality over time. We construct a tightly focused TRICC beam designed to be globally chiral [2]. We demonstrate how this leads to highly efficient enantio-separation of small molecules using only electric-dipole transitions that give rise to a nonlinear (three-photon) chiral Stark shift.

This chiral Stark shift, the product of a molecular and a light-field pseudoscalar tuned through the relative phases and frequencies of the TRICC field, permits the enantiosensitive optical trapping of a specific enantiomer – a chiral optical tweezer – in the same way that the linear achiral Stark shift enables standard optical tweezers [5]. We analyse the nonlinear susceptibility of the molecule of choice to optimise the TRICC-beam frequencies and show that this results in a realistic trap in the presence of a cold buffer gas.

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Generation and manipulation of relativistic vortex particles at accelerator facilities

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While twisted photons and 300-keV vortex electrons can be generated via diffraction elements, the generation and diagnostics of relativistic vortex electrons, protons, or ions at accelerator facilities require more sophisticated techniques. We review the status of the project of developing a source of several-MeV vortex electrons based on a photo-cathode combined with a twisted UV laser at the Joint Institute for Nuclear Research in Dubna [1, 2], as well the possible diagnostic techniques for phase retrieval of the relativistic electron wave function. In particular, we argue that diffraction of vortex electrons by a triangular aperture can also be used as a diagnostic tool for energies of a few MeV [3].

We also review the recent theoretical studies of relativistic vortex particles in accelerators. In particular, losses of the orbital angular momentum (OAM) by particles due to emission of twisted photons are mostly negligible for realistic setups [4]. The non-radiative OAM dynamics turns out to be drastically different from that of spin: the OAM precession frequency can become both lower and higher than the spin precession frequency, depending on the energy. This results in non-radiative resonances occurring when the OAM precession frequency matches the cyclotron frequency in a circular accelerator. For a spin-unpolarized vortex electron, the resonances are predicted to start at the energy of 3 MeV with a step of 1 MeV [5], whereas the analogous spin resonance due to the anomalous magnetic moment occurs at 440 MeV. While Siberian snakes or spin rotators can be used to manipulate the particle OAM in circular machines making spatio-temporal states on demand, the lack of OAM resonances in a linear accelerator makes it a better choice for accelerating the vortex particles to relativistic energies.

The work was carried out with the support of the Russian Science Foundation Grant No. 23-62-10026.

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Probing the isolated vector magnetic field of structured laser beams by atoms

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Electric and magnetic fields are inherently coupled in an electromagnetic wave. However, structured light beams enable their spatial separation. In particular, the azimuthally polarized beam is distinguished due to the zero electric and non-zero magnetic fields in its center. In the case of a single beam, this “isolated” magnetic field is oriented along the beam axis. On the other hand, the use of two azimuthally polarized beams makes it possible to generate a rotating magnetic field, see Fig. 1,

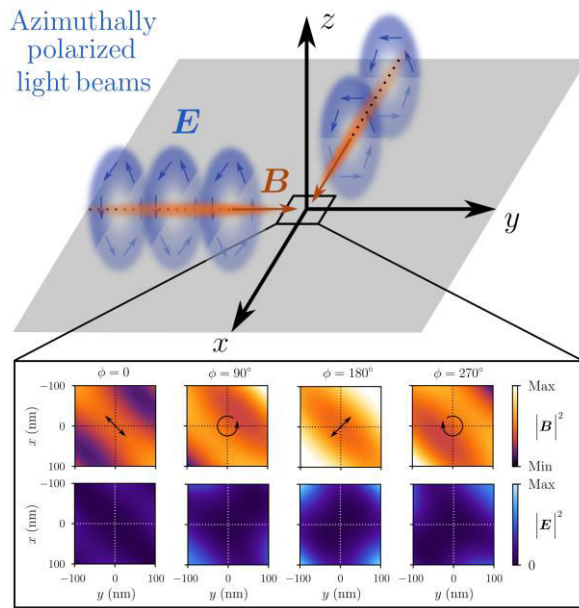


Figure 1: Geometry of two azimuthally polarized beams. The bottom inset shows the squared magnetic (top row) and electric (bottom row) fields. The arrows indicate the orientation of the magnetic field at the origin. Figure modified from Ref. [3].

while keeping the electric field zero [1]. This configuration opens up new opportunities for studies of laser-induced ultrafast magnetization dynamics in solid matter, where suppression of electric-field effects is important [2]. In the present contribution we explore the interaction of a single atom with different superpositions of azimuthally polarized beams. We perform calculations within the framework of the density-matrix formalism. For illustration purposes, we apply our general approach to the $2s^2 2p^2 \ ^3P_0 - 2s^2 2p^2 \ ^3P_1$, the $1s^2 2s^2 \ ^1S_0 - 1s^2 2s2p \ ^3P_2$, and the $2s^2 2p \ ^2P_{1/2} - 2s^2 2p \ ^2P_{3/2}$ transitions in $^{40}\text{Ca}^{14+}$, ^{10}Be , and $^{38}\text{Ar}^{13+}$, respectively. Based on the results of our calculations, we show how the interaction of matter with the isolated magnetic field of two azimuthally polarized beams can be enhanced. It is also demonstrated that observation of atomic population dynamics can be used as a sensor for the relative orientation and phase of the light field components.

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Novel topological and geometric features of light's electric-magnetic space

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Topological structures in light, like optical vortices and skyrmions, are central concepts in modern optics commonly linked to fundamental phenomena such as optical angular momentum and geometric phases. They tend to be studied in electric quantities (e.g., polarisation singularities of $\mathbf{E}$) or their magnetic counterparts *separately*—yet in nonparaxial waves $\mathbf{E}$ and $\mathbf{H}$ have both different polarisation structures and dynamics. Rarely are the features of the $\mathbf{E}$ and $\mathbf{H}$ fields considered simultaneously, in a formalism capturing not only the C^3 space of polarisation, but the relationship between the $\mathbf{E}$ and $\mathbf{H}$ fields in an adjacent C^2 “electric-magnetic” space. This is not just a matter of curiosity—many unusual and highly desirable kinds of local light-matter interactions, such as chiral and magnetoelectric interactions, hinge on delicate relationships between electric and magnetic fields rather than their specific individual polarisation states. I will present a compendium of what we have recently found to be hidden in this C^2 EM space of light: *novel phase singularities* [1] and *particle-like topologies* [2] that relate to local parity, duality and time-reversal symmetries of the six-vector $(\mathbf{E}, \mathbf{H})$, as well as a new kind of optical geometric phase, the *electric-magnetic geometric phase* [3], relating to a Poincaré-like EM sphere and emerging even when the $\mathbf{E}$ and $\mathbf{H}$ polarisation states are unchanging.

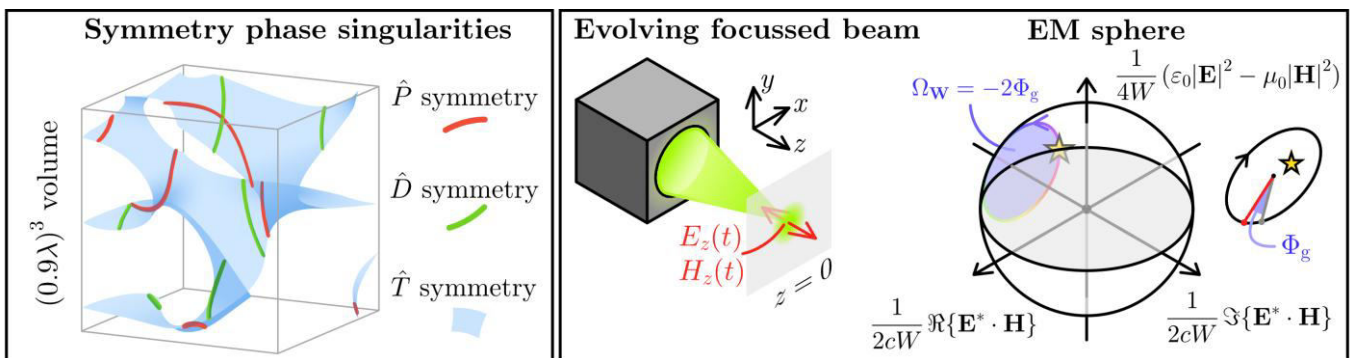


Figure 1 L: Novel optical phase singularities in random waves corresponding to local symmetries [1]. R: EM geometric phase emerging in an evolving, tightly focussed beam, from evolution of $\mathbf{E}$ and $\mathbf{H}$ z-components [3].

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Programming Nonlinear Optical Responses with Structured Light

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Structured light is typically used to probe or encode information, but it can also serve as the mechanism that programs optical interactions themselves. Here, we introduce a reconfigurable nonlinear optical platform in which structured optical fields program the effective nonlinear response of an otherwise unpatterned second-order thin film. By leveraging sum-frequency generation in the thin-film limit, where the generated field is locally proportional to the product of two interacting beams, we demonstrate that complex-valued nonlinear operations can be optically written through the controlled overlap of independently structured inputs. Using a single-modulator, common-path architecture based on transverse-momentum routing, we synthesize co-propagating replicas with independently tailored complex envelopes and isolate the desired nonlinear product by Fourier filtering. By updating a single hologram, we realize a broad library of reconfigurable operations on an encoded input image, including tunable focusing, on-demand vortex generation, and log-polar mapping for rotation- and scale-invariant transformations. Moreover, the same framework supports complex-valued quadratic kernels and their weighted superpositions, which can be composed into matrix-vector operations and other nonlinear primitives relevant to optical inference and next-generation photonic neural-network architectures. Together, these results establish structured light not only as an information carrier, but also as programmable resource for shaping nonlinear optical functionality on demand, beyond conventional Fourier optics.

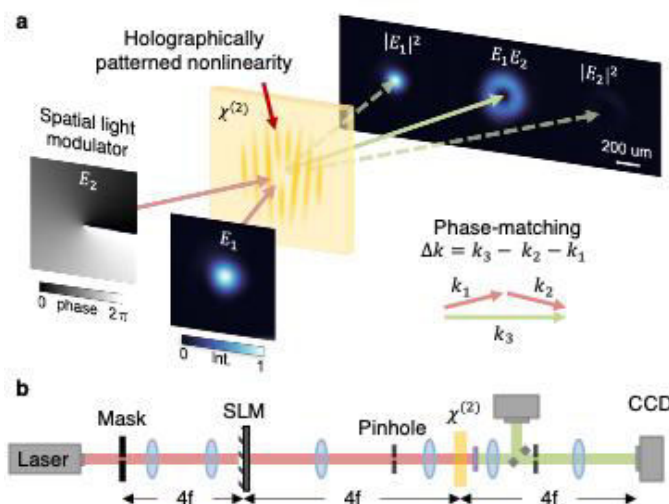


Fig. 1. (a) Structured illumination holographically writes a spatially varying nonlinear polarization in a second-order nonlinear thin film. Momentum routing separates the generated fields in the Fourier plane, allowing the desired cross term to be isolated. (b) Single-modulator, common-path experimental setup, where a phase-only SLM applies a superposition of programmable complex wavefronts to generate two independently programmed field replicas that overlap in a thin [111]-AlGaAs film.

Friday Sessions

Friday, the 19th
Chair: Ebrahim Karimi
09:00–09:25 Stephen Barnett Optical torques in the focusing of light
09:25–09:50 Mark Dennis Euler-top Gaussian beams: Structured Modes Beyond Separation of Variables
09:50–10:15 Mark Main Structured Light for Multi-Scale Sensing
10:15–10:40 Filippo Romanato Metasurfaces for Structured Light: Generation, Sorting, and Topological Control of Vector Beams
10:40–11:10 Coffee Break
Chair: Jonathan Leach
11:10–11:35 Mehul Malik Programming quantum measurements of time inside a multi-mode fibre
11:35–12:00 Kiki Dekkers Observing High-Dimensional Nonlocality Bell Inequality Violations using Multi-Outcome Spectral Measurements
12:00–12:25 Stefan Rotter Structured Waves for Micro-Manipulation and Information Flow
12:25–12:50 Harald Gießen / Julian Schwab Discovery of phonon-polaritonic skyrmions: Transition from bubble- to Néel-type
13:00–13:20 Closing, Awards
13:20–14:00 Lunch Break

Optical torques in the focusing of light

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We address the question of whether the focusing of a c.w. beam of light causes the optical angular momentum to change and thereby to induce a torque on the focusing lens. At first sight there seem to be sensible arguments in favour of both “yes” and “no”. To address the problem we reveal the importance of the fluxes of both the total angular momentum [1,2] and of the helicity [3] as well as the rotational symmetry of the beam. The answer to our question is “it depends ...”.

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Euler-top Gaussian beams: Structured Modes Beyond Separation of Variables

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Structured Gaussian mode families—Hermite-Gaussian (HG), Laguerre-Gaussian (LG), and Ince-Gaussian (IG)—are conventionally understood as arising from separation of variables in the three orthogonal coordinate systems of the 2D quantum harmonic oscillator. As such, each family consists of eigenfunctions of a specific optical operator built from the Stokes–Fradkin parameters (M_+ , M_x , L) on the ray-orbital Poincaré sphere [1,2]: HG modes diagonalise M_+ , LG modes diagonalise L , and IG modes diagonalise $I = L^2 + \ell^2 M_+$, the nonlinear Ince operator. This operator perspective reveals that separable coordinates do not exhaust the natural mode algebra.

We introduce Euler-top Gaussian (EG) modes [3], defined as eigenfunctions of the balanced quadratic operator $K = L^2 - M_+^2$. Although K is not a Gaussian beam separation operator, the resulting EG modes have well-defined mode order N , Gouy phase, and complete the classification of Gaussian eigenmodes under quadratic combinations of Stokes-Fradkin operators, up to $SU(2)$ transformations. On the ray-orbital sphere, contours of K are polhode curves: the trajectories of the angular velocity vector of a tumbling rigid body (the Euler top). Modes with label $\mu > 0$ are LG-like; those with $\mu < 0$ are HG-like, with the $\mu = 0$ separatrix quantising the unstable intermediate-axis rotation familiar from the Dzhanibekov effect (tennis racket theorem). Although nonseparable mode families are familiar for propagation-invariant beams (e.g. pendulum beams [4]); EG modes are such a family for Gaussian beams, demonstrating that the operator algebra of structured Gaussian beams extends fundamentally beyond coordinate separation, inspired by classical angular momentum.

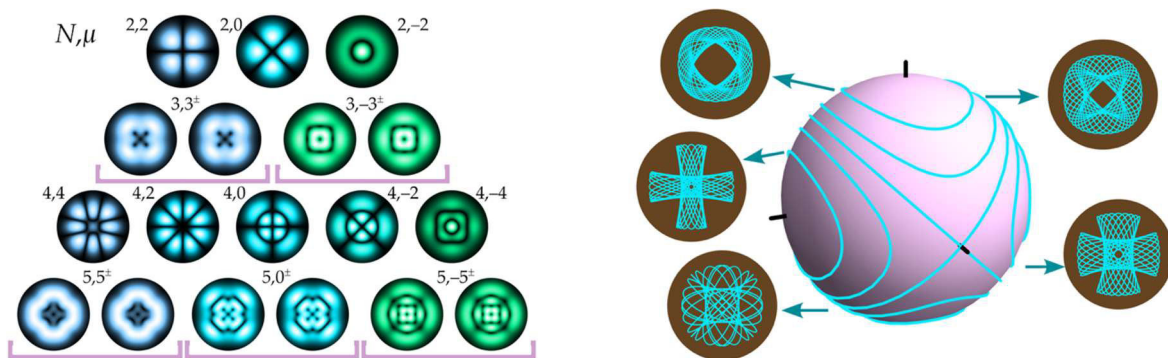


Figure: Euler-top Gaussian modes. Left: Modes labelled by N and μ , $-N \leq \mu \leq N$. Right: Polhode Poincaré paths on ray-orbital sphere, ray-ellipse families which are LG-like (squircular), HG-like (Maltese cross) and the intermediate separatrix mode.

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Structured Light for Multi-Scale Sensing

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Physical perturbations to a structured optical field produce characteristic redistributions of power across the modal basis, an effect more commonly corrected for than exploited. Treating shifts in modal distributions as a signal rather than noise provides a reconfigurable sensing approach spanning many orders of magnitude in physical scale.

We present work related to four sensing modalities. Acoustic pressure wavefront orientation is resolved from relative modal weight changes within a two-mode LG superposition. Optically trapped red blood cells are classified by morphological state, with cell geometry changes encoded in the scattered field of a structured probe. A two-stage Singular Value Decomposition (SVD) framework extracts deformation-specific modal bases from bent multimode fibre and reorients them into a common coordinate system, recovering bend state without rotational ambiguity. Finally, through exploiting the geometric similarity between atmospheric eddies and OAM vortices, the OAM spectrum through a CFD-calibrated turbulence chamber enables path-integrated recovery of wind speed and temperature, outperforming conventional scintillometry in measurement precision. This work establishes structured light as a sensing framework spanning many orders of magnitude, from single-cell scale to kilometre-scale atmospheric channels.

Metasurfaces for Structured Light: Generation, Sorting, and Topological Control of Vector Beams

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We report on spin-decoupled metasurfaces (SDMS) enabling compact generation, manipulation, and topological control of multidimensional vector beams. By independently controlling left- and right-handed circular polarizations within a single dielectric metasurface, non-separable spin-orbit optical fields spanning the full Hybrid-Order Poincaré spheres can be engineered. This approach overcomes the limitations of conventional bulk optical systems, providing a scalable and integrated platform for structured light.

The proposed devices are based on anisotropic dielectric meta-atoms designed through a combined numerical-experimental workflow and fabricated using CMOS-compatible nanofabrication processes. Wafer-scale metalenses up to 2 inch in diameter are realized with high uniformity and efficiency. The platform is further extended to dual-functional meta-doublets, enabling the integration of multiple optical functionalities within a compact architecture.

Exploiting independent phase encoding for orthogonal polarization components, SDMS enable the generation of Bessel-Gaussian vector beams exhibiting propagation-dependent dynamics such as polarization beating, axial and helical self-healing, and topological transitions. In addition, optical coordinate transformations allow efficient manipulation of orbital angular momentum states, including generation, sorting, multiplication, and division of topological charge.

Within this framework, we demonstrate full Poincaré vector beams and access complex topological states, including skyrmionic polarization textures, with propagation-dependent evolution and tunable control via wavefront shaping.

These results establish spin-decoupled metalenses as a versatile platform for multifunctional structured-light generation and topological beam engineering, opening new opportunities for robust information encoding, optical manipulation, and advanced light-matter interaction in integrated photonic systems.

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Programming quantum measurements of time inside a multi-mode fibre

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The temporal degree-of-freedom of light is incredibly exciting for many quantum technologies, ranging from photonic quantum computing to quantum key distribution. The generalized measurement of large and complex superpositions of the time-of-arrival of a photon presents a unique experimental challenge. A time-bin qubit is usually measured with an unbalanced “Franson-type” interferometer that enables arbitrary measurements of two-dimensional time-bin superpositions. However, generalizing this device to larger dimensions is very challenging, requiring many cascaded interferometers with stringent stabilization requirements. Here we show how the coupling of spatial and temporal information inside a multi-mode fiber (MMF) can be harnessed to program generalized measurements for large photonic time-bin qudits. We experimentally reconstruct the multi-spectral transmission matrix of an MMF and use it to find special sets of spatial modes that are temporally unscattered through the fiber. By exciting coherent superpositions of these spatial modes at the input of the fiber, we engineer arbitrary unbalanced interferometers inside the fiber. We use these interferometers to perform mutually unbiased basis (MUB) measurements of photonic time-bin superpositions in dimensions up to 11. We certify the quality of our measurements via quantum tomography techniques, demonstrating greater than 85% fidelity in $d=11$. The single fiber serves as a scalable, common-path interferometer for time-bin qudits that significantly eases the experimental overheads of standard approaches based on unbalanced Franson-type interferometers.

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Observing High-Dimensional Nonlocality Bell Inequality Violations using Multi-Outcome Spectral Measurements

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Violation of Bell inequalities is an essential requirement for many quantum information and communication protocols. In high-dimensional systems, Bell inequality tests face the challenge of implementing genuinely multi-outcome measurements, since the emulation of these with separate dichotomic projections opens a binarisation loophole that local hidden variable theories can exploit [1]. Here we show that the joint spectral intensity of a two-photon entangled state contains access to the necessary multi-outcome measurements to overcome this obstacle and violate a Bell inequality for high-dimensional states [2]. This result is contrary to the belief that the joint spectral intensity is a phase-insensitive quantity and does not have sufficient information to certify entanglement or Bell-nonlocality. Using this approach, we violate the CGLMP Bell inequality [3] up to dimension $d = 8$, all with negligible p -values, and for the first time close the binarisation loophole in high-dimensional Bell experiments. Guaranteeing Bell-nonlocal correlations using frequency-only measurements removes the technological hurdle of measurements in the temporal domain, thus greatly simplifying any practical implementation of future high-dimensional quantum information protocols.

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Structured Waves for Micro-Manipulation and Information Flow

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Structured waves provide a powerful platform for both controlling matter and extracting information from complex environments. In this contribution, I will establish a direct connection between these two aspects by linking wave-based micro-manipulation and information retrieval through the Wigner-Smith operator [1] and its recently identified relation to the Fisher information operator [2].

Building on this connection, I will show that the same physical mechanisms governing forces exerted by structured waves on microscopic objects also determine the sensitivity with which system parameters can be inferred. This reveals micro-manipulation and metrology as two complementary facets of a unified framework.

I will then introduce the concept of Fisher information flow, in which the information generated in an experiment emerges as a conserved quantity that propagates through space according to a continuity equation, in close analogy to the Poynting theorem for electromagnetic energy flow [3]. Within this framework, sensitivity can be described by spatially resolved information fields that obey a wave equation, allowing for propagation, interference, diffraction, and resonant enhancement.

This perspective shows that Fisher information behaves as a physical resource whose spatial distribution and transport can be engineered. In particular, we demonstrate how material composition, geometry, and environmental design control where information is generated and how it propagates. Plasmonic and dielectric resonances can strongly enhance local information flow, while structured interfaces and gratings enable its directional shaping, in analogy to antennas and metasurfaces for electromagnetic radiation [4]. Remarkably, the information flow also exhibits topological features such as vortices, where the flow circulates around phase singularities, providing a direct connection to singular optics and orbital-angular-momentum-carrying structured wave fields [4].

These results establish a unified viewpoint in which micro-manipulation and wave-based sensing are governed by the same underlying operators and conservation laws. They open the door to designing structured-wave systems that simultaneously optimize control and sensitivity, thereby reframing metrology as an engineering discipline based on shaping information sources and flows, with applications ranging from nanoscale diagnostics to remote sensing and radar technologies.

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Discovery of phonon-polaritonic skyrmions: Transition from bubble- to Néel-type

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Abstract:

We observe for the first time phonon-polariton skyrmions in ultrathin silicon carbide membranes, demonstrating a tunable transition from bubble- to Néel-type skyrmions via wavelength control across the Reststrahlen band. Using scanning near-field microscopy, we reveal highly confined skyrmion lattices, enabling topological tuning [1].

Optical skyrmions constitute an emerging and rapidly developing field in the domains of solid-state physics and photonics, allowing for control over topological light textures through light-matter interactions. However, until now, their practical application has been severely limited by high inherent optical losses in plasmonic materials, resulting in the lack of tunability between different topological properties. Here, we leverage the strong dispersion of silicon carbide (SiC) thin films to realize highly confined surface phonon polariton (SPhP) skyrmion lattices, which we image for the first time via near-field microscopy. We experimentally demonstrate topological tuning between bubble- and Néel-type skyrmions, a unique advantage that polar dielectrics offer over most existing approaches. The ability to control and manipulate these skyrmion lattices through small changes (<10%) in excitation wavelength allows for tailoring the size of individual skyrmions by a factor of 4. We investigate the transition from bubble- to Néel-type skyrmions by analyzing the domain wall size, which depends on the relationship between the in-plane and out-of-plane electric field components of the phononic skyrmion lattice.

Our results expand the tunability of skyrmions in evanescent waves and are a starting point to investigate other topological features in phononic systems such as merons, skyrmion bags, and other complex structured light fields. Furthermore, strong light-matter hybridization and nonlinear effects owed to anharmonicity of the phonons may be observed in the future, possibly leading towards the discovery of polaritonic skyrmion-skyrmion interactions.

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Investigating the Performance of Adaptive Optics on Different Bases of Spatial Modes in Turbulent Channels [1]

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Quantum Key Distribution (QKD) provides a safe platform where two parties can exchange secret encryption keys. The security is guaranteed by the impossibility of cloning unknown quantum states with 100% fidelity. Spatial modes of light, such as those carrying Orbital Angular Momentum (OAM), have been a leading candidate to perform higher dimensional QKD. QKD can be implemented via free-space links over long distances, where other mediums such as fibers are unusable. The prominent factor for loss in these free-space channels is atmospheric turbulence. Adaptive-optics (AO) systems can be employed to overcome these losses.

Here, we investigate and compare the performance of different spatial modes of light in induced turbulence using a fast AO system. The AO system not only reduces the *qudit* error rate for a high-dimensional OAM-based QKD protocol but also improves the fiber coupling efficiency. Our goal is to find the optimal bases in different dimensions that are less affected by turbulence and better corrected by the AO. We generate Laguerre-Gaussian beam modes as our logical basis and proceed to create mutually unbiased bases (MUBs) in dimensions 2, 3, 4, 5, and 8 in a free-space BB-84 QKD protocol and SIC-POVMs in dimensions 2, 3, 4, 6 for the Singapore protocol.

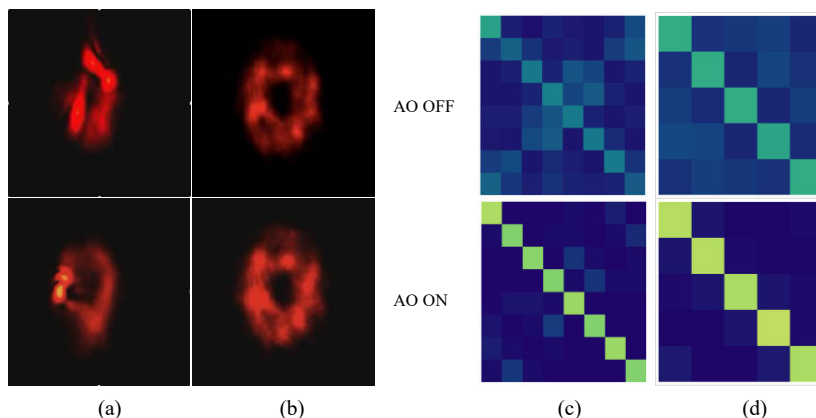


Fig. 1 Intensity of OAM beams with $\ell=2$ in turbulent air with **a)** adaptive optics turned off and **b)** turned on. Crosstalk matrices show measurements of projecting one state on other states with AO on and off in one of the MUBs with **c)** 8 and **d)** 5 dimensions.

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Customizing Multispectral Grafted Vortex Beams and OAM Combs Using a Single Metasurface

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We present a compact metasurface-based flat-optics platform for generating and dynamically controlling multispectral grafted vortex beams (GVB) and azimuthally structured orbital angular momentum (OAM) combs. By coherently superimposing multiple helical phase profiles, the system produces optical fields with tailored topological charges and tunable multispectral OAM distributions. This capability enables new opportunities in optical encryption, advanced communication systems, and particle manipulation.

We introduce a metasurface strategy for the efficient generation and manipulation of multispectral GVBs and grafted perfect vector vortex beams, overcoming the complexity of conventional bulk optical approaches [1,2]. The proposed design allows a single metasurface to synthesize multiple superpositions with different topological charges, resulting in asymmetric phase singularity distributions. Importantly, the positions of these singularities can be flexibly tuned through an initial phase offset, eliminating the need for complex optical alignment. Furthermore, the multifunctional metasurface supports multispectral operation with spatially varying polarization states (Fig. 1(a)), while dynamic modulation is achieved using a rotating half-wave plate for enhanced tunability [3].

Finally, we extend the platform to realize multispectral OAM combs with controllable mode spacing, providing a compact and efficient route for generating structured OAM spectra across multiple wavelengths (Fig. 1(b)) [4]. This significantly enhances the information-carrying capacity of optical systems and supports emerging applications in high-capacity optical communications and information processing technologies.

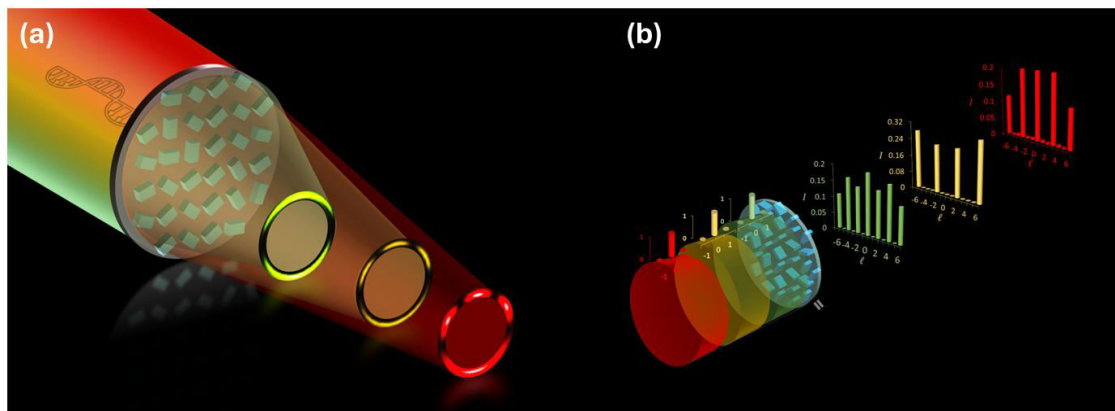


Fig.1. Schematic of a metasurface for realizing multispectral (a) GVBs (b) OAM combs.

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Numerical Study of Controllable Acoustic Vortices Generation for Particle Reorientation Using a Single-Sided Acoustic Emitter

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Cancer spheroids and organoids are promising *in vitro* models, but their sub-millimeter size and optical scattering limit single-view imaging for complete 3D assessment. Contactless acoustic levitation with controlled rotation can provide the multi-angle access required for optical reconstruction without mechanical handling [1].

Conventional resonant chambers typically use three orthogonal transducer-reflector pairs to generate standing bulk acoustic wave (SBAW) fields and acoustic vortices. In this work, we numerically investigate acoustic vortex generation and the resulting radiation forces inside water-filled chambers using a single-sided acoustic emitter based on a square phase grating, as shown in Fig.1(a).

The square phase grating, shown in Fig.1(b), consists of four independently controlled sides. Driving opposite sides 2 and 4 generates an SBAW along the y -axis, while driving sides 1 and 3 generates an SBAW along the x -axis. Superposing these orthogonal fields with a relative phase shift of $\pi/2$ produces a field containing vortices with their axes oriented along the z -axis [2]. Adding an extra acoustic emitter at the center of the square grating, as shown in Fig. 1(c), and driving it with a relative phase shift of $\pi/2$ with respect to the field generated by sides 1 and 3, with sides 2 and 4 inactive, generates vortices with their axes oriented along the y -axis.

Overall, the results show that the proposed acoustic emitter enables field configurations containing vortices with axes aligned along any of the three spatial directions. The numerical evaluation of the acoustic radiation force acting on a subwavelength spherical particle with positive acoustic contrast confirms that the low-pressure cores of these vortices act as trapping regions and may also enable particle rotation through viscous torque. These numerical results provide a route toward future single-sided acoustic emitter prototypes for controlled particle rotation and sample reorientation.

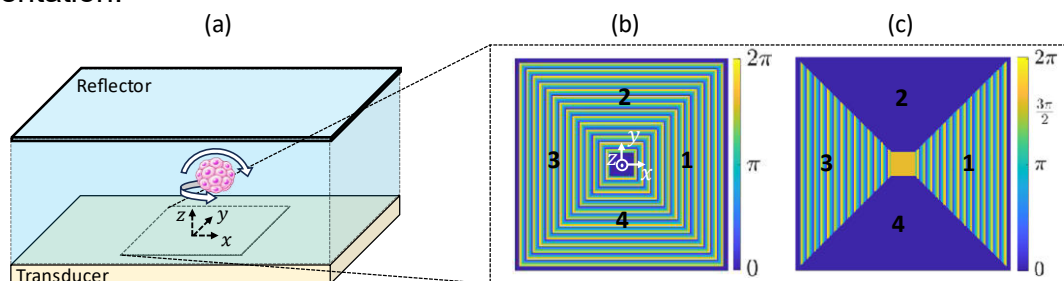


Figure 1: (a) Schematic of the water-filled chamber. Square phase grating configurations for generating acoustic vortices with their axes oriented along the (b) z -axis and (c) y -axis.

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A Programmable Platform for Vectorial Light Control

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Many techniques for manipulating the spatial structure of optical fields rely on scalar wavefront shaping and neglect the vectorial nature of light and its polarization [1]. Here, we present a fully vectorial approach based on local polarization control, in which a spatially-structured anisotropic medium implements a point-wise polarization transformation [2]. A sequence of three patterned birefringent elements is sufficient to realize arbitrary spatially varying polarization transformations [3,4], enabling the generation and manipulation of structured light fields.

We discuss a fully reconfigurable implementation based on liquid-crystal spatial light modulators (LC-SLMs) [5,6]. As a proof of principle, we demonstrate programmable high-dimensional photonic circuits for polarization-momentum modes of light, where the unitary map linking input and output modes has the form of a quantum walk.

Using coincidence detection with a time-tagging camera, we demonstrate compatibility with quantum optics protocols and report quantum walks of heralded single photons. These results establish free-space optical processors as promising platforms for high-dimensional quantum simulation and scalable optical information processing.

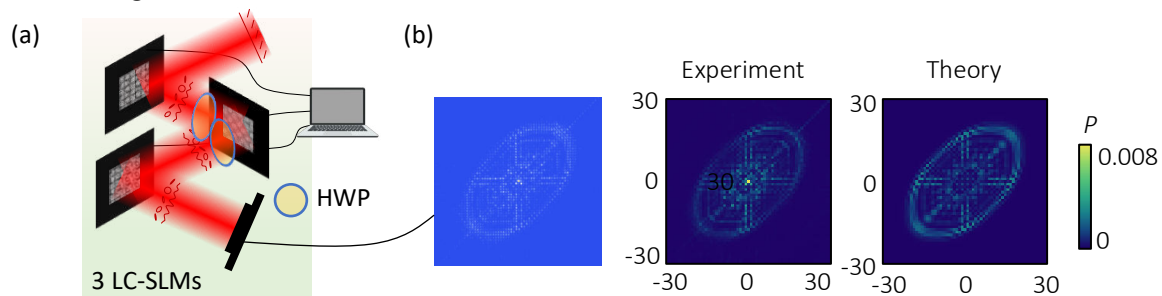


Figure – (a) Experimental scheme. A sequence of three LC-SLMs interleaved with two half-wave plates (HWP). Each SLM is imaged onto the the next one to avoid diffraction (imaging system not shown here). (b) Experimental output image and probability distribution, compared with theoretical expectation for a high-dimensional quantum walk. Each spot is relative to a transverse-momentum mode.

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Spatially-dependent group delay dispersion due to diffraction from a grating

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It is well-known that ultrashort laser pulses, diffracted from a grating, feature angular dispersion and pulse front tilt, which is the underlying principle of one of the most fundamental devices within ultrafast optics, i.e. the grating compressor [1]. It is much less known that diffraction can also introduce large amounts of spatially dependent group delay dispersion (GDD) [2], resulting in a non-uniform pulse duration in any plane not parallel to the grating surface. Using a 4f imaging arrangement, consisting of spherical and cylindrical lenses, we can obtain access to a plane in which the GDD is both positive and negative and in particular crosses zero in the middle of the beam profile.

We demonstrate that the complicated spatiotemporal couplings introduced by the grating can be exploited to make a very compact single-shot ultrashort pulse characterization device based on the dispersion scan (d-scan) principle [3]. The arrangement is illustrated in Fig. 1 (Left side). Depending on the grating parameters, the amount of spatially varying GDD can be massive, enabling the characterization of much longer pulses (Fig. 1, Right) as compared to previous single-shot d-scan implementations. To the best of our knowledge, this is the first practical application of spatially dependent GDD arising from diffraction by a grating [3].

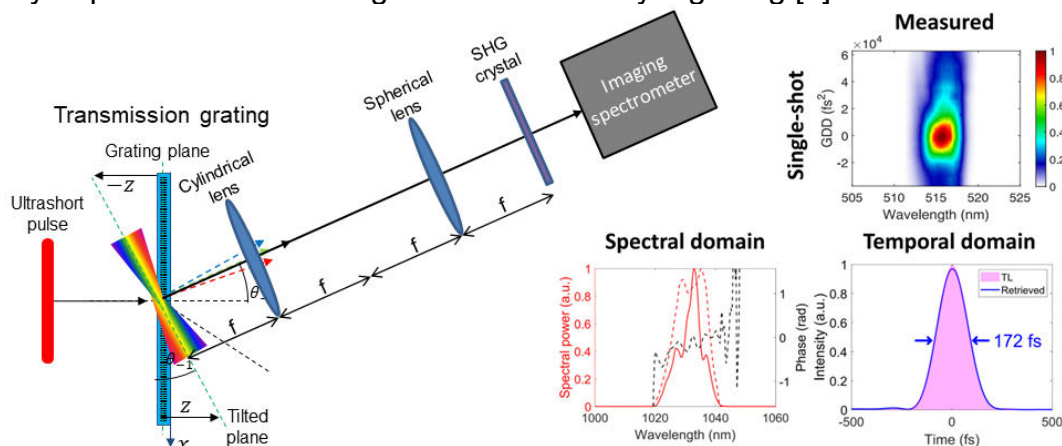


Fig. 1: (Left) – Sketch of a 4f configuration imaging a plane intersecting the grating. (Right) – A measured d-scan trace (top) and retrieved pulse parameters (bottom).

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Propagation of short pulses carrying orbital angular momentum in spun fibers

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While the propagation of short pulses in standard step-index fibers [1] and twisted photonic crystal fibers [2] is well-investigated, the complex dynamics within twisted (spun) fibers remain relatively unexplored. Here, we investigate orbital angular momentum (OAM) pulse evolution in these structures using a full numerical solution of the generalized multimode nonlinear Schrödinger equation (GMMNLSE). Within this framework, we rigorously analyze pulse propagation in twisted fibers over a wide range of input pulse characteristics and nonlinear regimes to examine modulation instability, soliton dynamics, and identify the propagation conditions where fiber twisting offers the greatest advantage. Circularly polarized OAM modes form the natural eigenmode basis in twisted fibers [3]. Moreover, fiber twisting introduces circular birefringence, modifying the propagation constants for orthogonal circular polarization states. We consider self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM), and dispersion effects. Simulation results demonstrate an interesting feature of twisted fibers, which is the topological protection of OAM modes. To evaluate this, we introduce a constant elliptical deformation perturbation to the structure. In untwisted fibers, this perturbation causes significant energy exchange between modes within the same family, leading to unstable transverse field and phase distributions. In the spun case, however, the broken degeneracy minimizes intermodal coupling, allowing the injected OAM modes to propagate with significantly higher stability (See Figure 1).

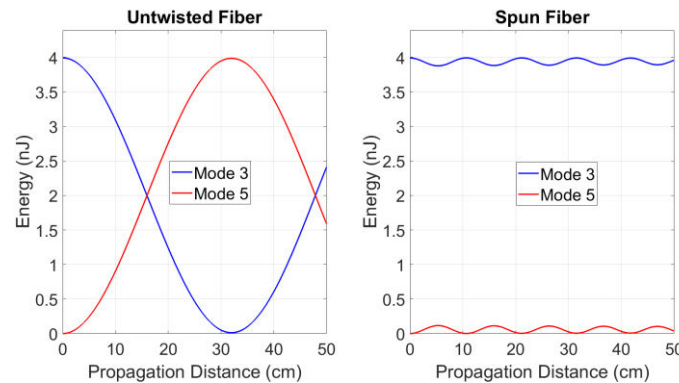


Fig. 1. Evolution of the modal energy of an injected Gaussian mode (duration: 150 fs, energy: 4 nJ) in a standard 6-mode step-index fiber. Both spun and untwisted configurations are evaluated considering identical simulation parameters. For the twisted case, the twist pitch is 20 mm.

Figure 1 illustrates the longitudinal energy transfer between the injected $OAM_{+1,1}^+$ and $OAM_{+1,1}^-$ mode. The numerical results demonstrate that the spun fiber fundamentally preserves the OAM charge over the propagation length. The induced phase mismatch effectively cancels the effect of spatial perturbation, completely disrupting the phase-matching condition.

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Trapping and control of rotation in evanescent optical tweezers

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Evanescent-field patterns provide a way to optically trap, deliver, and sort single nanoscopic particles. In this work, we generate evanescent fields by total internal reflection at a glass-water interface using a Total Internal Reflection (TIR) Objective lens (see Fig. 1) and a Spatial Light Modulator (SLM) [1]. The SLM allows us to sculpt a ring of light with an arbitrary Orbital Angular Momentum (OAM), defined by the topological charge ℓ . At the same time, the Spin Angular Momentum (SAM), given by the circular polarization σ , is controlled by means of a quarter wave plate. We analyze the effect of the SAM and OAM on the trapping and rotational forces exerted on a nanoscopic dielectric particle. We observed a strong coupling between these two variables, surpassing any previous result observed in propagating fields [2-3]. This effect gives rise to an optimal stiffness when the circular polarization and topological charge have equal magnitude, equal to one, and opposite signs (see Fig. 1 (C)). We also show how this setup, together with the configurable variables, allows us to control the rotation and transport of nanoscopic particles in different configurations. Using rigorous electromagnetic theory, we were able to describe the observed phenomenology.

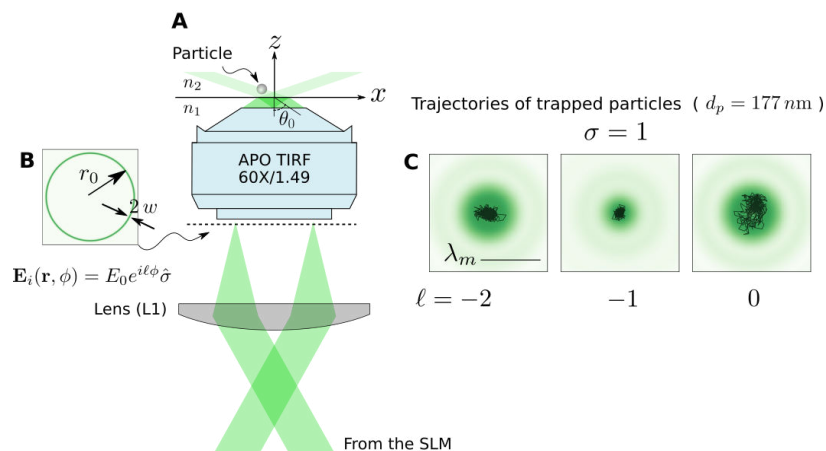


Fig. 1. (A) Schematic of the experimental setup employed to generate evanescent optical tweezers. (B) A ring of light (E_i), circularly polarized and with a topological charge (ℓ), is generated at the entrance pupil of the TIRF objective lens. (C) Examples of the trajectories (solid black lines) of a particle in the evanescent field (depicted in green from simulations) with three different topological charges ($\ell = -2, -1, 0$) and circular polarization ($\sigma = 1$).

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Evaluating OAM content and mode purity in optical fields using the R-Index: Theory and experimental demonstration

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Light fields carrying orbital angular momentum (OAM) enable rotational light-matter interactions and have driven advances in optical manipulation, communications, and quantum science. Recent studies have further highlighted their potential in molecular spectroscopy [1], motivating the need to identify optical fields with optimal OAM for applications such as enhancing quadrupole transitions.

Our recent work on the R-index [2] establishes a theoretical framework as a metric for quantifying the intrinsic OAM content of arbitrary optical fields, from pure Laguerre-Gaussian modes to multi-vortex superpositions.

Beyond measuring total OAM, the R-index also evaluates field purity, providing insight into the fidelity and robustness of OAM generation. Here, we further present its experimental evaluation, demonstrating its practical applicability. By consolidating OAM characterization into a single figure of merit, the R-index enables direct comparison across beam profiles and supports the design of optimal fields for both fundamental and applied photonic systems.

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Gouy phase engineering of self-splitting quantum correlations

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Spatial quantum correlations between photon pairs generated by spontaneous parametric down-conversion (SPDC) are known to inherit properties of the pump beam transverse structure. Most previous studies have focused on transferring the pump angular spectrum to the spatial correlations observed at a fixed detection plane. In this work, we investigate how the propagation dynamics of a structured pump beam can be transferred to the biphoton spatial correlations.

We engineer the pump beam using a coherent superposition of Hermite–Gaussian modes (HG₀₀ and HG₂₀), whose relative phase controls the Gouy phase evolution and produces a self-splitting and recombination of the beam during propagation. Through the well-known transfer of the pump angular spectrum in SPDC, this structured propagation is mapped onto the joint spatial correlations between signal and idler photons. As a result, the two-photon coincidence distribution exhibits a self-splitting behavior analogous to that of the classical pump beam, effectively forming a nonlocal “bottle-like” biphoton structure.

The experiment is implemented using a 405 nm continuous-wave laser structured by a spatial light modulator and imaged onto a PPKTP nonlinear crystal. Photon pairs at 780 nm and 840 nm are detected using fiber-coupled single-photon detectors while the signal detector scans the transverse plane. The measured coincidence distributions agree with theoretical predictions and numerical simulations.

These results demonstrate that Gouy phase engineering enables control not only of the transverse shape but also of the propagation dynamics of quantum spatial correlations, opening new possibilities for structured quantum light and quantum imaging applications.

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Quantum control of light by structured light

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The interaction of light with light mediated by a nonlinear medium is a paramount platform for quantum photonics. For example, in spontaneous parametric downconversion (SPDC), a single pump beam generates pairs of photons entangled in polarization, space or time, enabling entanglement-based quantum communications, quantum-enhanced sensing and more. On the other hand, quantum frequency conversion (QFC) consists of changing the color of a photon before detecting it or interfacing it with another quantum system, by interacting it with a strong laser field in a sum-frequency generation process. QFC allows the detection of entangled photons at wavelengths where direct photodetection is resource intensive, as well as the interfacing between telecom photons and quantum memories.

In this presentation, I will discuss how the spatial and temporal structures of light can be used in the benefit of nonlinear quantum optics. In QFC, I will discuss our recent work [1] on the frequency conversion of entangled photons driven by a vector beam, where we achieved the transduction of quantum information from the polarization of one color to the spatial structure of another color. This experimental work shows how QFC can be modelled by a quantum dynamics that stems from the internal correlations between degrees of freedom of the pump, paving the way for the transduction of entanglement between two high-dimensional state spaces. In SPDC, I will discuss our ongoing theoretical work on the spatio-temporal shaping of the pump field as a tool for the control of temporal correlations between photon pairs, leveraging the Gouy phase effect in the phase-matching problem [2]. Along with these two examples I will present the current projects of my research group, the Quantum Structured Light Laboratory at the University of São Paulo, where we harness the complex structures of light to develop new methods for quantum communications.

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Universal pump shaping scheme for high-dimensional maximally entangled orbital angular momentum states of photons

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Spontaneous parametric down-conversion (SPDC) inherently generates high-dimensional spatial entanglement in orbital angular momentum (OAM) modes. In practice, the resulting two-photon states are typically not maximally entangled due to a highly non-uniform OAM spectrum. Although pump-beam engineering has emerged as an experimentally accessible approach for preparing high-dimensional entangled states, it has been limited to low-dimensional subspaces so far [1,2]. A general framework for generating maximally entangled states (MESs) in arbitrary $d \times d$ -OAM subspaces with dimensionality $d > 2$ is still lacking.

Here, we propose a universal pump-engineering scheme for SPDC that enables the generation of high-dimensional MESs for arbitrary d and is directly compatible with standard laboratory implementations. The central idea of our scheme is to identify the optimal interplay between the spatial structure of the pump beam and a suitable OAM subspace.

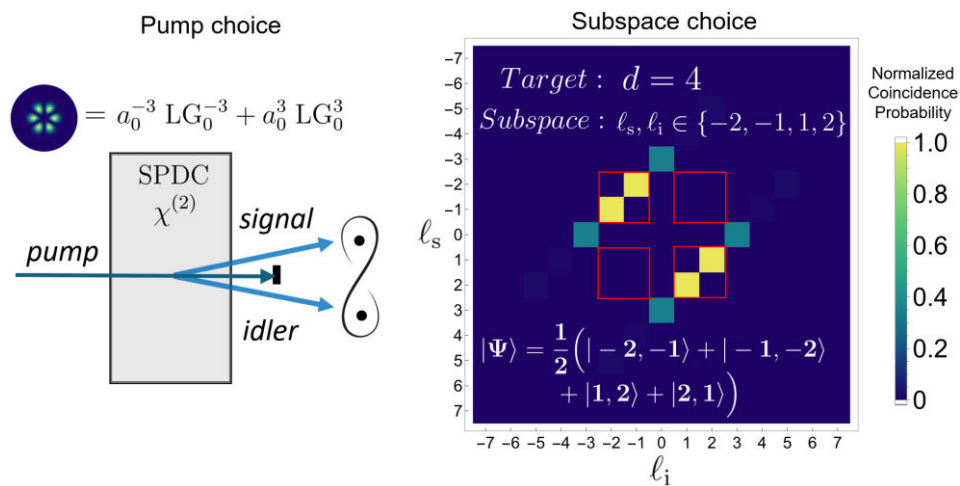


Figure 1: Generation of maximally entangled OAM states via pump engineering. Left: A tailored superposition of Laguerre–Gaussian modes with radial index $p = 0$ and OAM $\ell = \pm 3$ pumps SPDC. Right: The resulting OAM spectrum. Within a selected OAM subspace (red region) for $d = 4$, the state is maximally entangled. Our method enables the direct calculation of suitable pump superpositions and the identification of subspaces compatible with a given pump.

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Experimental mapping of the vector vortex beams on the HOPS

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Here, we represent a simple method to detect vector vortex (VV) beams using a spiral phase plate (SPP) and a linear polarizer only. The number of null points is twice the value of the η index, while their radial and azimuthal positions correspond to the beam's coordinates (2γ , 2χ) on the higher order Poincaré sphere (HOPS). Polarization singularity can be expressed as the superposition of orthogonal spin and orbital angular momentum states:

$$|E_{in}(r, \theta)\rangle = \cos\left(\frac{\pi}{4} - \chi\right) \exp(-i\gamma) r^{|m|} \exp(im\theta) \hat{R} + \sin\left(\frac{\pi}{4} - \chi\right) \exp(i\gamma) r^{|n|} \exp(in\theta) \hat{L}$$

Where m and n are the topological charges of the right and left circularly polarized vortex beams, respectively. For VV beams $|n| = |m|$. The V-point index η of the beam is given by $\eta = (n - m)/2$. Superimposed beams have spatially varying azimuth and constant ellipticity in the polarization distribution. When the test beam is passed through the SPP of order ' t ' and a vertically oriented polarizer, the transmitted beam intensity distribution consists of null points. The number of these null points is twice the index η of the beam, and the coordinates are related to the radial and azimuthal location of null points; $2\gamma = (m-n) \theta_d - 2p\pi$; $2\chi = \frac{\pi}{2} - 2 \tan^{-1}(r_d^{|m+l|-|n+l|})$. Where $0 \leq p < |m-n|$ and θ_d , r_d are azimuthal and radial locations of null points, respectively, and (2γ , 2χ) is the beam's coordinates on HOPS.

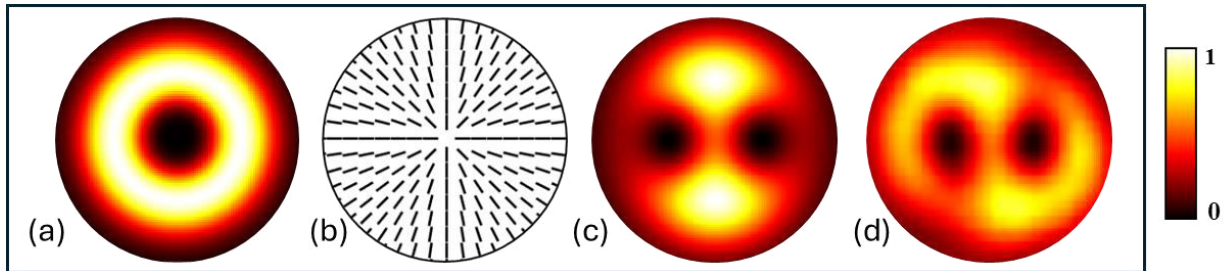


Fig.1 Simulation results of (a) test beam intensity before the SPP and polarizer, (b) polarization distribution of test beam, (c) beam intensity distribution after the SPP and a polarizer, (d) experimental result.

In conclusion, after passing the test beam through the SPP and a linear polarizer, we observed nulls in the intensity distribution. The number of these null points provides information about the index η of the test beam, while their radial and azimuthal positions correspond to the beam's coordinates on the HOPS.

References:

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Tunable Quantum Interference in Free Space with a Liquid-Crystal Metagrating

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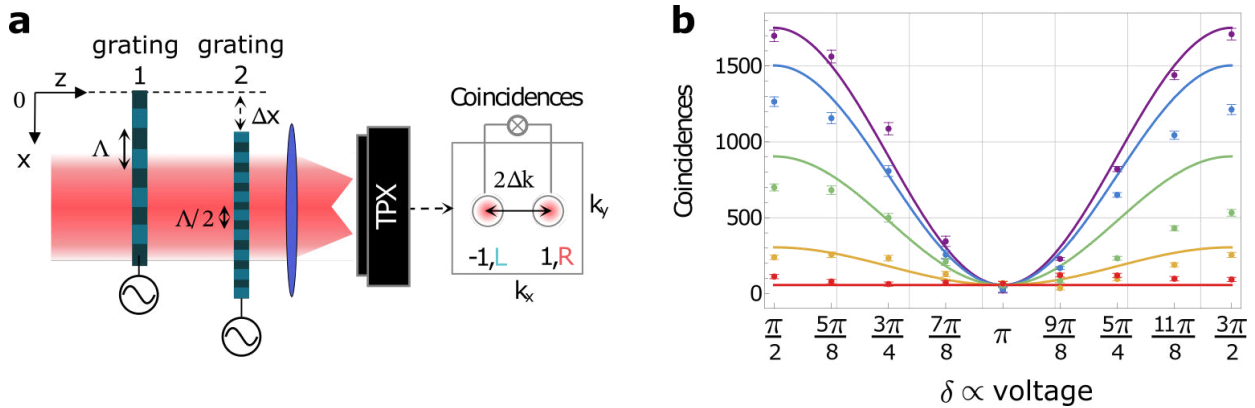


Figure a, Schematic diagram of our experimental setup. A collimated beam illuminates Grating 1 which prepares the target polarisation-transverse momentum input state. Grating 2 acts as a tunable beam splitter in which two-photon interference causes bunching in output mode. Modes are separated using a Fourier lens and resolved as separate spots on a TPX3CAM event-based camera which is used to detect coincidences. **b**, Coincidences between output modes as a function of $\delta(V)$, the tuning of Grating 2, and Δx , the lateral offset of Grating 2.

Abstract: Structured optical materials provide a promising platform for photonic quantum information processing in free space. Beam splitters, a fundamental building block of photonic circuits, have recently been demonstrated in free space using geometric-phase optical elements [1]. These devices coherently mix circularly-polarized transverse modes of freely-propagating optical fields, including modes carrying orbital angular momentum [2]. In this work, we investigate liquid-crystal metagratings as electrically tunable beam splitters for transverse-momentum optical modes. By exploiting the voltage-controlled birefringence of liquid-crystal metasurfaces [3], we experimentally tune the splitting ratio of the device and thereby control the degree of two-photon interference between indistinguishable photons. At the output, photons are spatially resolved on different regions of a time-resolved single-photon-sensitive detector [4], enabling the reconstruction of coincidence maps in the Fourier plane. This approach is readily scalable and enables highly parallel coincidence measurements across a large number of optical modes.

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On the CHSH Violability for a Two Particle System with Arbitrary Measurements

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Clauser–Horne–Shimony–Holt (CHSH) tests [1] with polarization-entangled photons are typically implemented using linear-polarization measurements. While experimentally convenient, this restricts the accessible correlations. We generalize the analysis to arbitrary projective measurements over the full Bloch sphere and show that this broader framework reveals nonlocal correlations hidden in standard linear-polarization settings. In particular, some entangled states, maximally entangled according to the Horodecki criterion [2], do not violate the CHSH inequality when probed only with linear polarizations. However, by optimizing measurement directions, these states can reach violations up to the Tsirelson bound.

Figure 1 shows the experimental S parameter for the Bell state $|\Phi^+\rangle$ under different measurement bases, with violations appearing for linear but not elliptical measurements. Conversely, other maximally entangled states exhibit the opposite behavior, reaching the Tsirelson bound only with elliptical bases. These results demonstrate that Bell violation detectability depends critically on the measurement basis, underscoring the need for full Bloch-sphere control in photonic experiments.

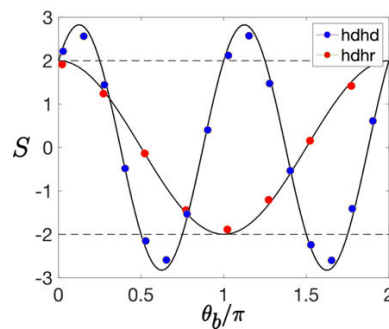


Figure 1. S for Bell state $|\Phi^+\rangle$ under different measurement bases. Dots show experimental measurements while solid line is the theoretical prediction.

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Topologically and spectrally reconfigurable optical skyrmions from liquid crystals

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Recent advances have expanded the idea of skyrmions, topologically stable vector textures, from particle physics to optics, where optical skyrmions denote structured light fields with complex topological features. These configurations provide promising prospects for applications in topological optics, optical communications, and sensing [1]. However, their generation often relies on bulky, costly components such as spatial light modulators, creating challenges for integration and tunability.

Here we report reconfigurable optical skyrmionic waveplates based on self-organized liquid crystal textures exploiting spin-orbit interactions, entirely avoiding lithography or microfabrication. Beyond polarization-driven reconfigurability, we achieve dynamic control of both skyrmion topology and operating wavelength using temperature and external fields. The concept is demonstrated analytically and experimentally with two complementary realizations: sessile droplets, where topology is set by droplet radius and tuned thermally or electrically, and thin films under applied fields, where defect-mediated textures enable simultaneous tuning of topology and wavelength [4]. By combining self-organization, external-field control, and spin-orbit optics, these results establish liquid crystals as a compact, reconfigurable platform for skyrmionic photonics, bridging fundamental topology and practical optical functionality.

References:

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Engineering Polarization Singularities Using a Plasmonic Metasurface Radial Polarizer

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A radial polarizer converts incident light into a spatially varying radial polarization state and plays a crucial role in vortex beam detection and studies of Malus' law[1] in singular optics[2]. In this work, we present a plasmonic metasurface-based radial polarizer capable of converting arbitrary input polarization into a radial vector beam while enabling precise control over polarization states and the generation of polarization singularities.

The proposed metasurface employs anisotropic plasmonic nanoantennas fabricated on a Ti-fused silica substrate, offering subwavelength control and enhanced design flexibility beyond conventional bulk polarizers. The unit cell exhibits strong polarization-dependent response; at an orientation of $\sim 90^\circ$, the s-polarized component is nearly completely absorbed, whereas the p-polarized component is efficiently transmitted, resulting in high polarization selectivity. Furthermore, the metasurface design allows discretization into multiple amplitude levels (20 levels in this work), providing additional control over the output field.

The functionality of the device is demonstrated through the generation and manipulation of polarization singularities. Under left circularly polarized illumination, the metasurface produces a bright C-point singularity. In contrast, an incident azimuthally polarized V-point beam is almost entirely absorbed due to the polarization-selective response. These results highlight the potential of the proposed metasurface as a compact and versatile platform for structured light generation, vortex beam analysis, and singular optics applications.

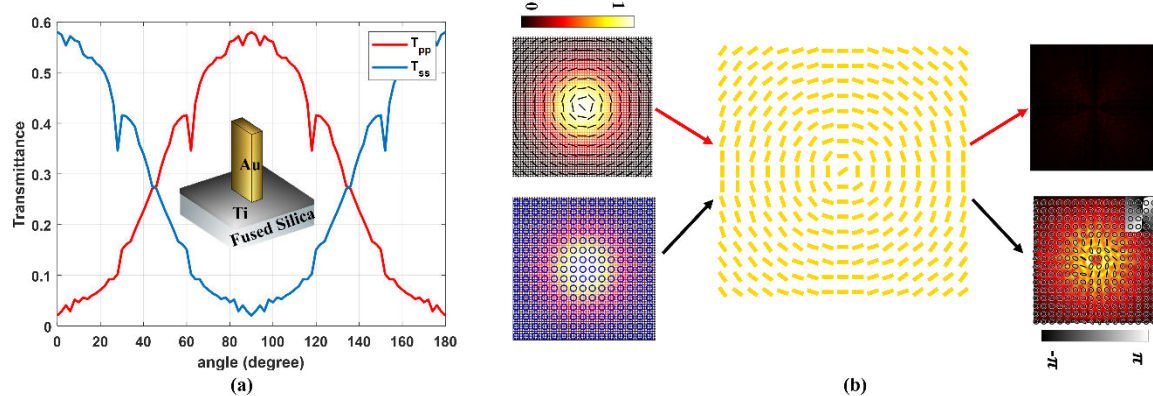


Figure1 (a) Unit cell showing polarization-selective transmission, and (b) shows that LCP incident light generates a bright C-point, while azimuthal beams are absorbed.

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Geometric representation of high order optical modes

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Geometry plays a key role in developing intuition for optical systems. A well-known example is the Poincaré sphere, which maps fully polarised states of light and illustrates the action of common optical elements such as retarders and polarisers [1]. Adding phase information to this picture gives rise to the Hopf fibration, which has proven particularly helpful recently in the context of optical skyrmions [2]. Visualising optical systems beyond qubit systems is notoriously challenging, Poincaré sphere generalizations have been proposed [3,4] but capturing the entire state space requires hyperspheres [5]. Majorana's stellar representation [6] tackles this issue elegantly, its strength residing in the identification of symmetries, and has been applied in the study of nonparaxial light [7,8]. It is shown that relative amplitudes and phase of an optical mode of order two and beyond can be directly encoded in a set of local angle type variables parametrising the state space, providing an intuitive framework for visualising higher order modes. The action of mode converters and mode rotators on these states is also studied geometrically, introducing a complementary approach to the matrix formalism presented in [9].

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Developing a Rotational Quantum Sensor

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We aim to develop an original rotational quantum sensor based on Hong-Ou-Mandel (HOM) interference of photon pairs generated via spontaneous parametric down-conversion (SPDC). By pumping a nonlinear crystal with structured light, we demonstrate that the transverse rotation of the pump beam's spatial mode modulates the HOM coincidence signal, providing information about angular velocity and acceleration. This project lays the groundwork for a quantum inertial sensor capable of measuring position and rotation through HOM signal.

In quantum optics, pairs of correlated photons can be generated by pumping a nonlinear crystal with a laser via SPDC. When these photons enter the two input ports of a beam splitter, they interfere, giving rise to a quantum phenomenon known as HOM interference [1]. In this situation, the symmetry of the biphoton state affects the behavior of the two photons at the output ports of the beam splitter (bunching or antibunching) [2]. By structuring the spatial mode and controlling its spatial parity [3], we demonstrate that a rotation of the transverse profile of the pump beam incident on the nonlinear crystal can modulate the HOM interference signal, measured via the coincidence rate of the two photons detected at the output ports of the beam splitter.

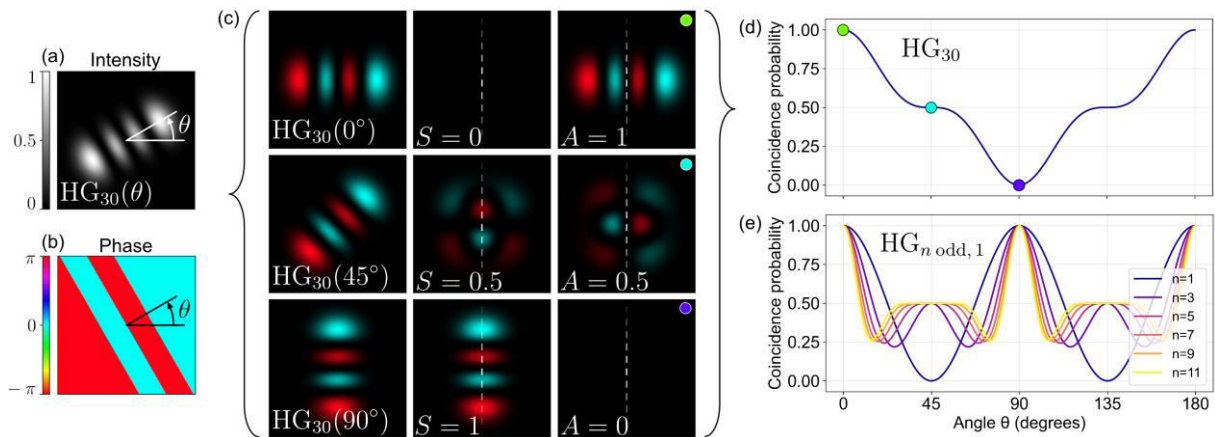


Fig. 1. As an example of this effect, a Hermite-Gaussian (HG) mode with indices $n=3$ and $m=0$ is incident on the nonlinear crystal. The theoretical intensity and phase profiles of this spatial mode are depicted in (a) and (b), respectively. Upon rotation, its transverse spatial parity with respect to the y axis changes (c), modifying the symmetric and antisymmetric parts, quantified by the coefficients S and A . The latter is directly responsible for the coincidence probability curve shown in (d). Finally, we plot the coincidence probability of a few $HG_{n \text{ odd}, 1}$ modes (e).

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Beyond q -plates: Dual-plates and spatially twisted liquid-crystal metasurfaces

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Liquid-crystal devices play a dominant role in generating and manipulating structured light. Among them, q -plates, characterized by an azimuthal pattern of the liquid-crystal molecules, emerge as the prototypical spin-orbit technology, enabling polarization-conditioned wavefront shaping [1,2]. In conventional designs, the front and back alignment layers are patterned identically, i.e., with the same optic-axis orientation, which makes the device a non-programmable optical element. To overcome this limitation, we present the first instance of dual-plates, fabricated by imprinting different patterns on the two alignment layers [3]. This creates an asymmetric device that naturally offers two optical functionalities, depending on the plate orientation. Moreover, the application of a driving field further expands the set of programmable functionalities achievable within a single device, by coupling the in-plane and out-of-plane liquid-crystal orientation [4]. For instance, a dual- q -plate exhibits field-dependent evolution of the effective topological charge, a phenomenon never observed nor achievable with standard q -plates. In the future, the same technology can be adapted to fabricate devices with arbitrary molecular patterns [5], positioning spatially twisted liquid-crystal metasurfaces as a versatile route toward on-demand optical functionalities.

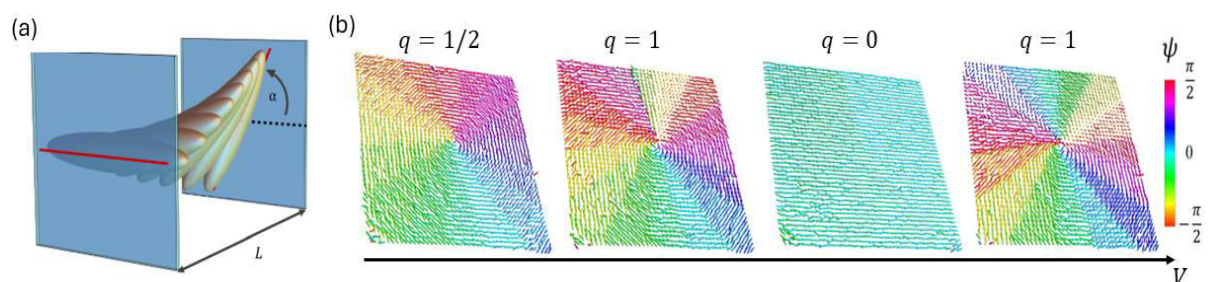


Figure. (a) When nematic liquid crystals are placed between parallel glass plates with differing alignment directions, the bulk twists to match the boundary conditions. (b) By applying an electric field across a dual- q -plate, we can tune the effective topology of the output polarization patterns, parametrized in terms of the ellipse angle ψ .

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Bloch oscillations of momentum anti-correlated particle pairs

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The evolution of an entangled photon pair through a series of spatially varying unitary operators reveals novel quantum interference effects.

We consider position-correlated particle pairs, e.g., biphotons emitted via Type-I SPDC, propagating on a lattice under the action of an external synthetic field. In addition to the state revival observed in single-particle Bloch oscillations [1,2], we show, both theoretically and experimentally, that an additional revival can occur at intermediate times, induced by two-photon quantum interference.

We introduce the concept of biphoton rays to explain this phenomenon: two-photon interference effects are found at focal points (in space-time) of the biphoton ray bundle.

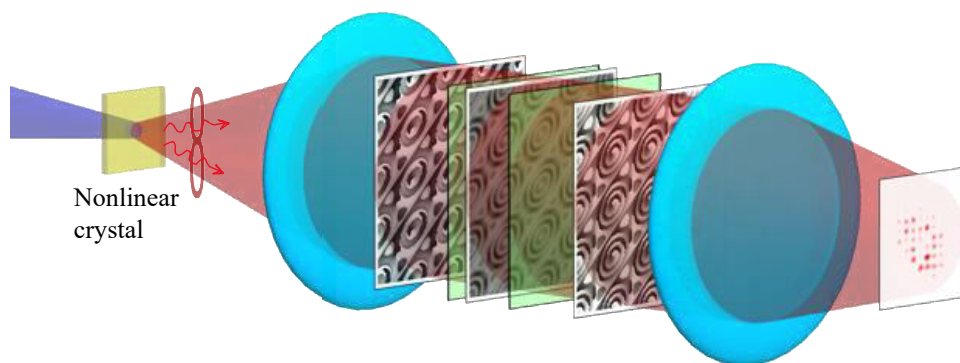


Figure 1. An entangled photon pair, generated by pumping a nonlinear crystal, is sent through a series of phase masks implemented by a spatial light modulator that simulates a quantum walk process. The entangled pair is then directed to a time-stamping camera for spatially resolved coincidence measurements.

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Imaging structured biphotons through complex media

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Quantum states of light consisting of exactly two photons, or biphoton states, are a fundamental tool for studies and applications in quantum optics, due to the manifestation of various non-classical correlations in all light's degrees of freedom: polarization, time-frequency, and spatial modes [1].

Several of these applications require accurate knowledge of the generated high-dimensional quantum state. We will show how modern single-photon-sensitive cameras, combined with phase measurement techniques inspired by classical optics, allow us to measure the spatial structure of the biphoton wavefunction in a fast and efficient way [2-4].

We will then explore how measuring the spatial properties of biphotons can help us investigate inhomogeneous media interacting with quantum states. Examples include non-interferometric quantum phase imaging [5], and scattering media.

We investigate how Orbital Angular Momentum (OAM) correlations of two-photon states are affected after propagation through a scattering medium, showcasing the creation of realization-specific distributions, deemed "OAM-correlation speckles."

Furthermore, we will demonstrate that post-selection on spatially correlated biphoton events allows us to isolate ballistic from scattered contributions, thereby providing a novel approach to improving quantum imaging of objects immersed in scattering media.

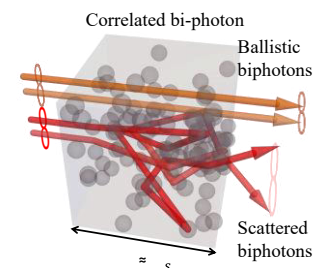


Figure 1. Spatial correlations are preserved by ballistic biphotons. Postselecting correlated events can thus improve imaging in turbid media.

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High-dimensional photonic circuits using liquid-crystal metasurfaces

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Encoding quantum information in high-dimensional photonic states enhances information capacity and resilience. A key requirement is to implement arbitrary unitary transformations. Multi-Plane Light Conversion (MPLC)[1,2], or equivalently diffractive neural networks[3], efficiently achieves these transformations through alternating free-space propagation and phase modulations. Traditional MPLC implements spatial light modulators (SLMs) or refractive optics, however, encounter scalability challenges due to optical losses and reflective designs. Here, we introduce a novel method using **liquid crystal metasurfaces** (LCMSs)[4] to implement MPLC in a **transmissive geometry**, featuring a thin liquid-crystal layer with an artificially-patterned optic-axis and tunable birefringence. This configuration allows for precise control of polarization transformations while minimizing optical losses and enhancing stability.

We treat the MPLC system as a series of phase-only diffractive layers separated by free-space propagation. We optimize these layers using two distinct approaches: **Wavefront Matching (WFM)**, which iteratively matches the forward and backward-propagating input and target fields at each interface, and **Diffractive Neural Network (D²NN)** which treats each phase pixel of each mask as a trainable parameter; optimized via backpropagation and the **Adam algorithm** to minimise the fidelity loss between obtained and target modes. To enhance optimisation speed and simplify fabrication of the LCMS plates, we arrange the four spatial transverse momentum modes along the x-axis, reducing the phase modulations to **one-dimensional profiles** as shown in **Fig. 1**. As an experimental demonstration, we implement unitary transformations to establish LCMS-based MPLC as a viable platform for scalable high-dimensional quantum photonic circuits.

(a)

(b)

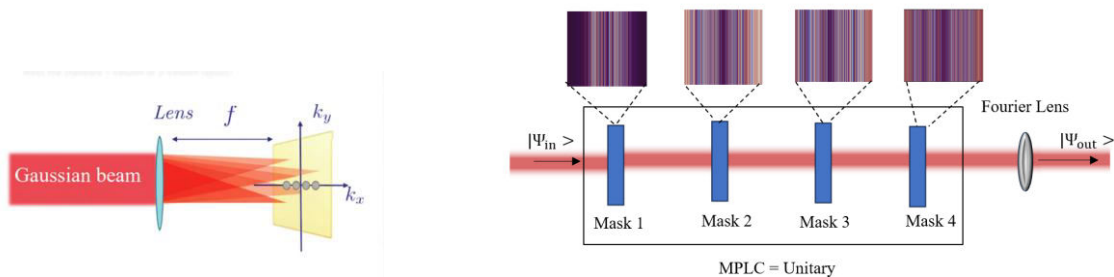


Fig. 1: LCMS-based MPLC (a)transverse momentum modes (b) optimized 1D phase masks for Hadamard transformation and the transmissive MPLC architecture

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Polarization based Weak measurement differential microscopy

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Detecting the edge or boundary of phase objects is challenging because they are generally invisible and transparent in bright-field microscopy due to their weak scattering and minimal absorption properties in the presence of light. To overcome this problem the idea of differential microscope has been proposed. A differential microscope gives the differentiation of the input electric field as output. As a result, it acts as an edge detector for a phase object. Even if there are many digital techniques available for differentiating a specific item or image, the analog or optical method is still practical because of its quick operation and low energy requirements [1]. In this work, we proposed a new kind of analog or optical differential microscope based on the method of weak measurement.

We consider a Gaussian beam of wavelength λ , incident on a birefringent plate tilted by an angle θ with respect to the beam's propagation direction. The analysis is carried out in a local Cartesian coordinate system, referred to as the beam frame, where the beam propagates along the positive z -axis. In this frame, the transverse profile of the beam lies in the $x - y$ plane and polarization along y axis as o -ray and polarization along x axis as e -ray. Under this configuration, the one-dimensional transverse distribution of the complex electric field along the x -direction can be expressed as $E_0(x, z) = E_{0x}(x, z)\hat{x} + E_{0y}(x, z)\hat{y}$. Where $E_{0x} = E_{0y}$ for $+45^\circ$ polarization state that is $(1 \ 1)^T$. A birefringent plate with optic axis oriented at an angle ϵ with respect to x direction will introduce an additional phase ϕ_0 in x component as the e -ray has different refractive indices depending on ϵ . Now, if we introduce a tilt in birefringent plate by an angle θ along the $x - z$ plane, the various transverse momentum components k_x of the Gaussian beam experience different phase anisotropies as there will be a constant gradient of phase throughout the plate. As a result a weak coupling between the transverse momentum k_x and polarization is introduced. The weak coupling Hamiltonian can be written as $H = \Delta_x \sigma_z k_x$. Here σ_z is polarization operator and Δ_x is coupling coefficient. In this weak measurement scenario we use polarization states as pointer that provides the weak value of the transverse momentum k_x . The weak value of transverse momentum has the form $\langle k_x \rangle_w = \frac{\langle x | k_x | E \rangle}{\langle x | E \rangle} = \frac{\partial \ln E(x)}{\partial x}$ this is nothing but the differentiation of the electric field with respect to x coordinate. Using some simple calculation it can be shown that the real and imaginary part of the weak value of the momentum can be found using the basic Stokes vector measurement.

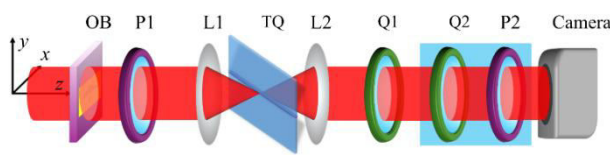


Figure 1. Schematic experimental setup for weak measurement differential microscopy experiment. The blue shadow region is indicating the Stokes parameters measurement part.

We perform the experiment using a He-Ne laser having wavelength 632 nm . We pre-select the input beam using a polarizer P1 in order to obtain the polarization dependent shift from the tilted quarter waveplate - TQ. A $4 - f$ system consisting of two spherical lenses L1 and L2, with both having focal lengths 400 mm is introduced to get the real image of the object (OB), kept at the back focal plane of

L1. TQ is placed between imaging lenses L1 and L2, aligning with the front Fourier(focal) plane of L1. An additional quarter waveplate Q1 is used to remove the extra phase coming from TQ. The polarizer P2 and quarter waveplate Q2 together serve as a platform for measuring the Stokes parameters that are the post selected state of our system. A CCD camera with pixel size $24 \mu\text{m}$ is placed at the front focal plane of L2 to collect the image of OB.

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Towards spatially coherent low-energy electron and ion beams

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In recent years, structured matter waves have attracted significant attention. Spatially coherent field-emission electron sources are already well understood and widely used, enabling coherent manipulation of the electron beam wavefront. The innovations within the field have enabled many applications of structured electrons in electron microscopy, and ongoing developments aim to further exploit structured electrons for use in quantum experiments and advanced microscopy schemes [1].

We are working towards an experimental setup with a low-energy field emission and gas field ion emission source for structuring electron-, and ion beams. A cryogenically cooled nanotip field emission / gas field ionization source together with a 1.5 m-long free propagation region enables the generation of a transverse-spatially coherent electron/ion beam, with coherence lengths exceeding multiple micrometers for ions, sufficient for beam structuring using nanofabricated electrostatic elements. Initially we will explore the physics of low-energy vortex electrons and ions generated using electrostatic chopsticks as a minimally intrusive and tunable shaping element [2]. A custom-built vacuum chamber is used for full access to a magnetically shielded beamline equipped with electrostatic deflectors and lenses.

The first implementation of a spatially coherent ion source will open a new field of coherent ion research, with many interesting possibilities ranging from exploring fundamental physics within the framework of composite charged wave systems, to developing new techniques for advances in e.g. ion microscopy, utilizing the low wavelengths and electric and magnetic properties of the structured ions.



Figure 1: A combined field emission and gas field ionization source

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High-Power Generation of Optical Vortices via Coherent Beam Combining

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Light beams with tailored spatial phase, particularly those carrying orbital angular momentum (OAM), are increasingly important for applications ranging from optical communications to high-intensity laser–matter interactions [1]. Optical vortices (OVs), characterized by a helical phase structure, enable advanced control of light–matter interaction, but scaling their power while preserving complex spatial properties remains challenging. Here, we employ coherent beam combining as a scalable approach for generating high-power structured light without compromising phase fidelity or modal purity [2,3]. As a representative demonstration, we combine optical vortex beams with topological charges $\ell = 1, 5$, and 8 , achieving an average power of 100 W and a peak power of 100 kW . Off-axis digital holography confirms that the phase and intensity profiles are well preserved, even at high topological charges with modal purity exceeding 91% [4]. Figure 1 presents the schematic of the experimental setup for generating and coherently combining optical vortices, together with measured beam profiles and reconstructed phase–intensity patterns. These results highlight coherent beam combining as an effective route toward high-power, high-purity structured light for advanced photonics applications.

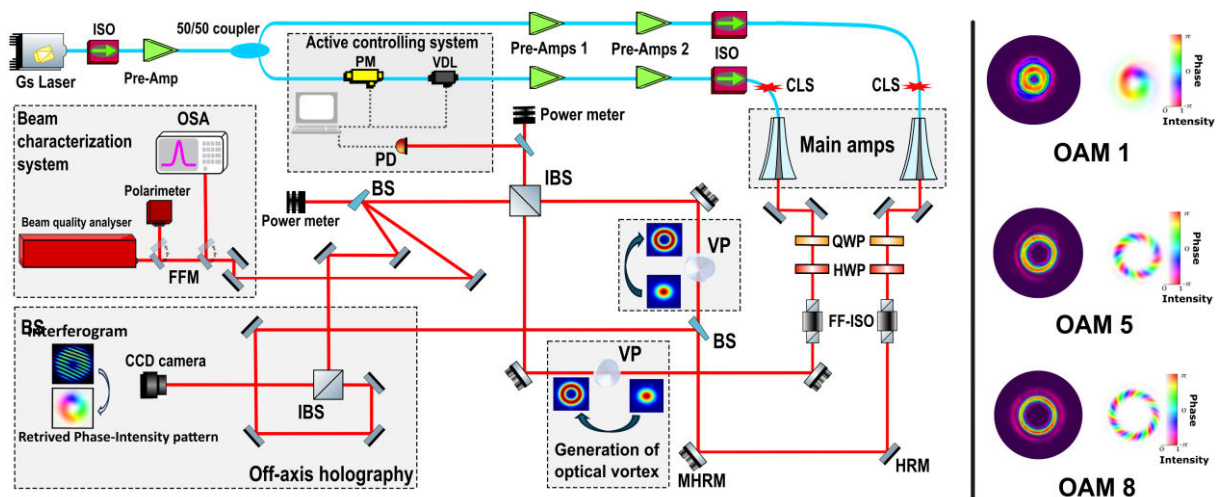


Fig. 1 The schematic of experimental setup for the generation and coherent combination of OV, along with the measured beam profile of the combined beams with reconstructed phase-intensity patterns.

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All-optical turbulence mitigation for free-space quantum key distribution using stimulated parametric down-conversion

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Recently, stimulated parametric down-conversion (StimPDC) has attracted increasing attention as an effective phase-conjugate process. Importantly, studies have demonstrated that StimPDC can generate phase-conjugation of partially coherent beams, making this technique particularly suitable for correcting beams that have been distorted by turbulent media [3]. A StimPDC process refers to a PDC process seeded with a signal beam with frequency ω_s , which stimulates the generation of idler photons at frequency $\omega_i = \omega_p - \omega_s$ (Fig. 1a). Crucially, the idler field is related to the phase-conjugate of the seed beam. In this work, we propose and demonstrate the first all-optical self-correction scheme for turbulence-resilient free-space high-dimensional QKD using StimPDC. Specifically, by exploiting the intrinsic phase conjugation property of the StimPDC (Fig. 1b-c) we combine the spatial structure of the quantum state intended for transmission with the conjugate phase information of the turbulent channel, thereby embedding the correction within the nonlinear interaction.

Unlike previous approaches that involve channel characterization in advance, our scheme does not require either party to have prior knowledge of the channel, as the nonlinear process inherently performs the compensation. We test our scheme's performance under varying turbulence conditions through numerical simulations and demonstrate its feasibility and effectiveness using a proof-of-principle experiment. These results offer a promising foundation for developing turbulence-resilient quantum FSO systems and could have implications for long-distance QKD and remote quantum networks.

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A curvilinear framework for vector light fields

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Vector light fields are typically described as non-separable superpositions of spatial and polarization degrees of freedom, which ties their polarization structure to specific spatial mode families. In this work, we present a geometry-driven framework for constructing vector beams whose structure is encoded entirely in the polarization degree of freedom. The method is based on the use of conformal mappings to generate orthonormal polarization bases associated with curvilinear coordinate systems.

Within this framework, the local polarization states arise naturally from the geometry of the coordinates, allowing spatially varying polarization distributions without imposing predefined spatial modal profiles. We demonstrate the approach using four representative coordinate systems—elliptical, parabolic, bipolar, and dipole—which correspond to both algebraic and transcendental families of conformal maps.

Experimentally, the polarization structures are implemented using phase-only spatial light modulators and characterized through Stokes polarimetry. The reconstructed polarization distributions show strong agreement with theoretical predictions, confirming the feasibility of encoding curvilinear polarization bases using phase modulation alone.

This framework enables systematic control of polarization structures independent of the spatial beam profile and provides a versatile platform for generating structured vector fields with potential applications in optical manipulation, structured light, and optical communications.

Second Harmonic Generation of astigmatic beams

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We investigate the nonlinear frequency conversion of structured light undergoing astigmatic mode transformation, with particular emphasis on orbital angular momentum (OAM), spatial anisotropy, and the interplay between with second-harmonic generation (SHG). Structured beams such as Laguerre–Gaussian (LG) and Hermite–Gaussian (HG) modes are widely used in optical communications, quantum information, and imaging; however, their behavior under combined astigmatic and nonlinear transformations remains an open problem.

In this work, we employ a tilted spherical lens as a controllable astigmatic mode converter to mediate transformations between HG and LG modes prior to nonlinear interaction. Unlike cylindrical-lens converters, the tilted lens introduces continuous and tunable astigmatism, resulting in distinct propagation dynamics in the tangential and sagittal planes. We model this system using an ABCD matrix formalism that explicitly accounts for the anisotropic optical power induced by the lens tilt.

The nonlinear interaction is studied in a second order ($\chi^{(2)}$) crystal by positioning the nonlinear crystal at the astigmatic conversion plane, we ensure that SHG acts directly on the converted—yet intrinsically astigmatic—beam. This configuration enables direct observation of how spatial mode structure and phase singularities evolve under nonlinear frequency doubling.

Our results reveal a clear asymmetry in the nonlinear response depending on the input modal basis. For LG input beams, the SHG process preserves modal purity while doubling the topological charge, resulting in well-defined higher-order vortex beams. In contrast, HG input beams lead to a nontrivial superposition of modes after SHG, reflecting the non-separability of squared Hermite polynomials and highlighting the role of modal anisotropy in nonlinear interactions.

These findings demonstrate that astigmatism is not merely a perturbation but a key degree of freedom in nonlinear structured light. The use of a tilted spherical lens provides a compact and versatile platform for controlling modal transformations in nonlinear regimes, with potential applications in beam shaping, optical communications, and quantum photonics.

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Beam shifts and eigenpolarizations for reflection of vortex beams from homogeneous magnetic surfaces

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The recent observation of magnetic helicoidal dichroism (MHD) using extreme ultraviolet vortex beams [1] has opened new avenues for probing magnetic structures through the orbital angular momentum (OAM) of light. We have found two main results through extending the vortex singularimetry approach [2] of tracking the spatial position of vortices of an OAM beam after reflection to a homogeneous magnetic surface: i) Analytical expressions for both Goos-Hänchen (GH) and Imbert-Fedorov (IF) shifts for homogeneous magnetic surfaces [3]. ii) Eigenpolarizations of a surface, which are polarizations which maintain polarization direction upon reflection. These eigenpolarizations can illuminate magnetic properties of the surface [4], notably through polarization mixing terms absent for dielectric reflection. The corresponding eigenvalues allow for a direct expression of total phase accumulated upon reflection [5]. We have found analytical expressions for the eigenpolarizations of both plane waves and unit-charge vortex beams, Fig.1. These results allow for reflection from homogeneous magnetic surfaces to be completely characterized for unit-order vortex beams and could allow for surface magnetization to be measured directly from vortex position [2].

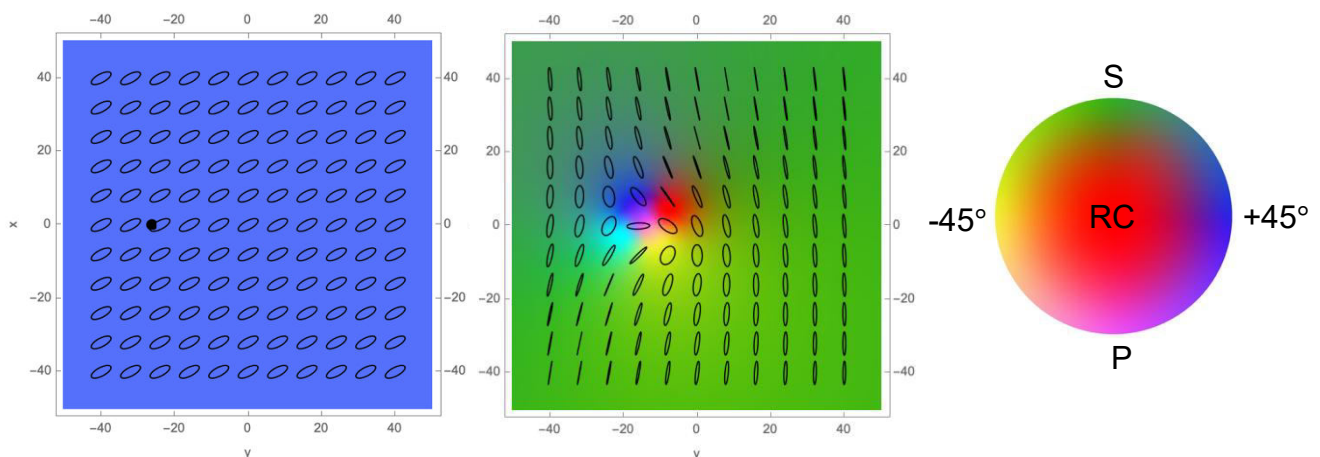


FIG1: Local polarization represented as black polarization ellipses, in units of k^{-1} . Left: Transverse eigenpolarization of a unit vortex beam for a homogeneous magnetic surface, with reflected centroid the black point. Middle: Reflected polarization structure of a s-polarized unit vortex beam, revealing non-homogeneous polarization structure after reflection. Right: Polarization legend as projection of full Poincare sphere, with RC (red) the top pole and LC (cyan) the bottom pole hidden.

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Entangled orbital angular momentum combs

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Orbital angular momentum (OAM) has been utilized extensively in recent years and has played a significant role in the advancement of classical and quantum optics. In particular, the high dimensional and discrete nature of OAM has been a key factor for the wide applicability of OAM in many fields. In recent work, these properties have been leveraged to create a spatially equivalent optical frequency comb, namely an OAM comb [1,2]. Here, we demonstrate the first quantum OAM combs which have been generated using a pair of entangled photons. We use binary phase gratings to modulate the bi-photon state such that the OAM correlations between the two photons are shaped into a myriad of OAM combs, as shown in Fig 1 (a). Further, we show that the comb creator itself can be non-local, not existing at all as a physical entity but rather acting non-locally on the bi-photon state, as shown in Fig 1 (b). These findings open potential developments in quantum sensing and high dimensional quantum encryption.

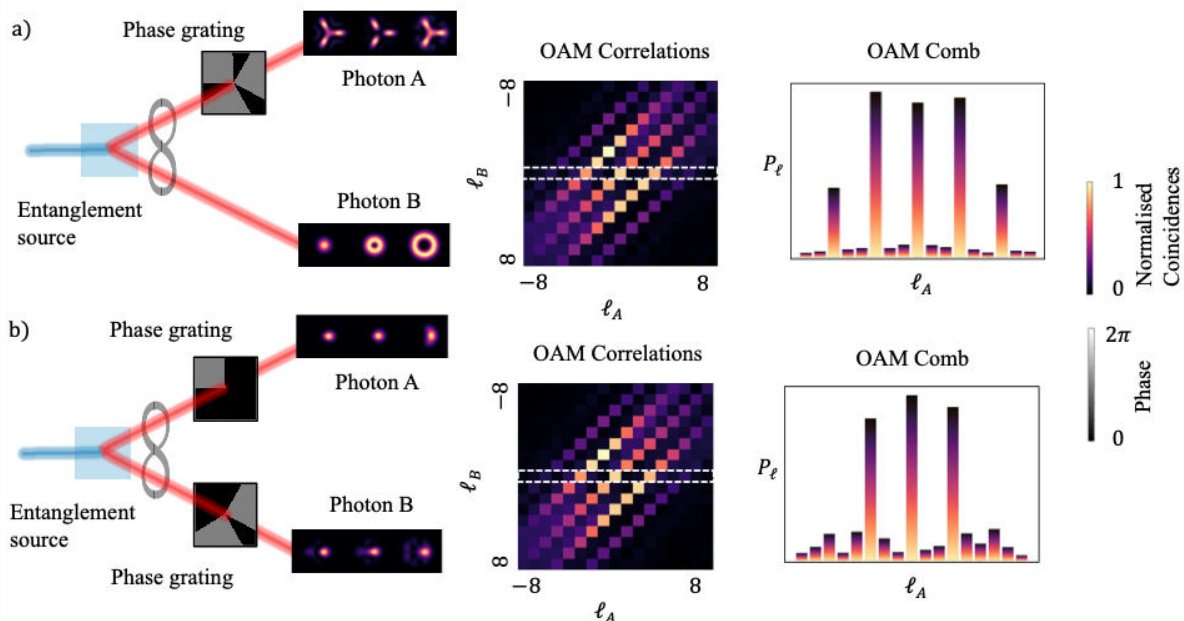


Figure 1. a) Experimental example of quantum OAM comb. b) Experimental example of the non-local comb creator.

References:

Spin-to-Orbital Angular Momentum Conversion in evanescent fields

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Spin (SAM) and orbital (OAM) angular momentum of light, characterized by $\sigma=\pm 1$ and ℓ , couple in non-paraxial regimes, leading to spin-to-orbital angular momentum conversion, as described in detail by Bliokh, K. Y. et al. [1]. In this work, we investigate this effect for a strongly focused, circularly polarized beam incident on a dielectric interface under total internal reflection (TIR) conditions. We used a high numerical aperture objective (NA=1.49, TIR Objective) to focus a ring of light (with radius r_0) that is generated by means of a Spatial Light Modulator. Under this configuration, the TIR objective gives rise to a cone of light with angle θ_1 that impinges the glass-water interface where the evanescent field is formed. The conversion efficiency increases with focusing and is maximized when θ_1 matches the critical angle θ_c (see Fig. 1 A). We show these results theoretically, using formal electromagnetic theory [2], and experimentally by means of the trajectories followed by nanoscopic particles trapped by the evanescent fields (see Fig. 1 (B)).

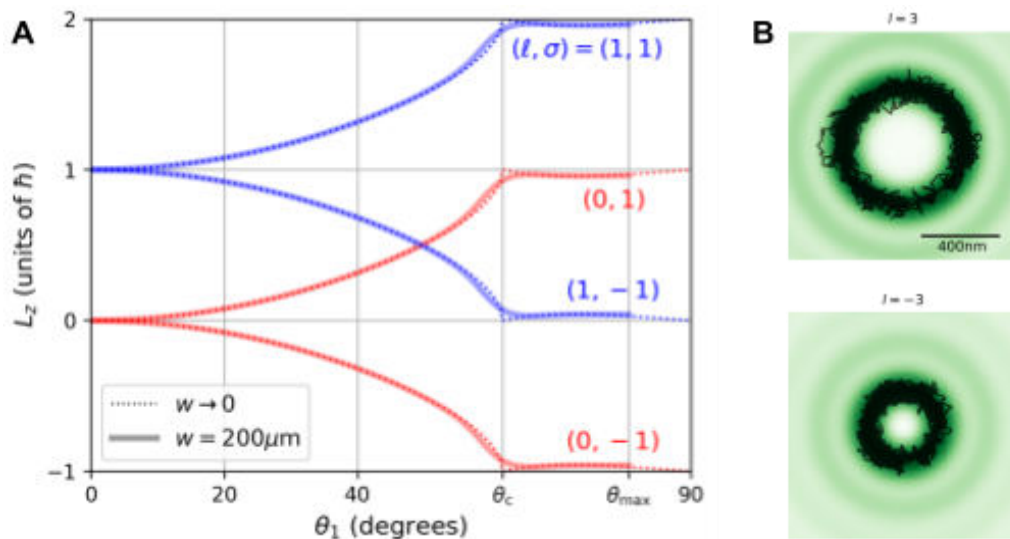


Fig. 1. (A) Orbital angular momentum for a ring-shaped beam focused by a high-NA objective onto a glass–water interface, shown for two ring radii and four (ℓ, σ) combinations as a function of the radius defined by $r_0 = f \sin(\theta)$. Above the critical angle, the transmitted (evanescent) field exhibits high spin-to-orbital angular momentum conversion efficiency. (B) Trajectories of a 293 nm silica particle in an evanescent field carrying spin ($\sigma=1$) and orbital angular momentum for two values of ℓ with equal magnitude and opposite sign.

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Orbitals in photonic waveguides enable non-dimerized SSH-chains

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Structured light enables precise control over optical fields, opening new possibilities for *photonic analog quantum simulation*, in which classical light emulates quantum dynamics. In arrays of coupled optical waveguides, evanescent coupling of neighboring waveguides reproduces electronic tunneling, allowing tunable band structures and condensed-matter phenomena, including topological effects, to be explored in a versatile platform.

Topological effects enable robust and loss-free transport. A key example is the Su–Schrieffer–Heeger (SSH) model [1], which can be realized in single-mode waveguide lattices by alternating strong and weak couplings through dimerized spacing (Fig. 1a). This configuration supports topological edge states whose existence depends sensitively on the lattice geometry and boundary conditions.

Here, we extend this concept to higher-order transverse electromagnetic (TEM) modes using structured light introduces additional degrees of freedom, enabling richer simulations of complex materials [2-4]. TEM-modes can be viewed as analogues of atomic orbitals, e.g. TEM_{00} corresponds to an s-orbital, while TEM_{01} is called p_y -mode, etc. By engineering waveguides with elliptical cross-sections, we tune the propagation constants of different modes and enable inter-modal coupling between neighboring sites. This allows realizing an effective SSH chain in a uniform lattice with one waveguide per unit cell, where the two modes within each waveguide provide the effective dimerization (Fig.1b). Using this platform, we observe the transition between trivial and topological phases controlled by the waveguide shape or spacing (Fig. 1c). This system also is largely independent of lattice geometry or chain length. Our results establish multimode photonic waveguides as a versatile platform for topological simulation with orbital degrees of freedom.

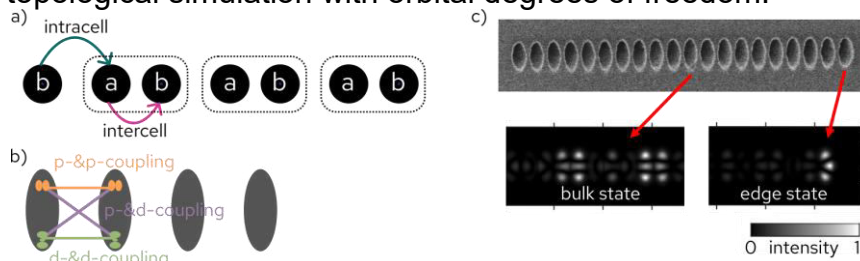


Fig. 1: The SSH model. a) Sketch of the dimerized SSH chain. b) Sketch of the SSH chain with higher orbital modes und uniform spacing. c) SEM image of elliptically shaped waveguides, with numerically calculated intensity profiles for guided hybridized p_x - d_y modes of a bulk and an edge state.

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Complex frequency poles of Kerr optical resonators

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Understanding nonlinear systems remains a central challenge in contemporary physics. Among nonlinear phenomena, third-order (Kerr-type) effects are particularly of interest, as the intracavity field modifies the refractive index and reshapes the resonance conditions governing the system's optical response. Despite extensive studies of steady-state input–output characteristics, the evolution of resonant states in the complex-frequency plane—where poles encode the full scattering dynamics—remains comparatively unexplored. In this work, we investigate the resonant behavior of a single Fabry–Perot resonator within the slowly varying envelope approximation [1] and assess its validity limits through comparison with exact finite element method results [2]. We extend the analysis to a distributed Bragg reflector with a Kerr-nonlinear core and study the trajectories of scattering poles in the complex plane as the driving intensity increases. We find that tracking these nonlinear pole trajectories provides an intuitive picture of how nonlinear feedback governs bistability in Kerr resonators. Our results offer new insight into nonlinear resonance dynamics and contribute toward a consistent nonlinear scattering framework.

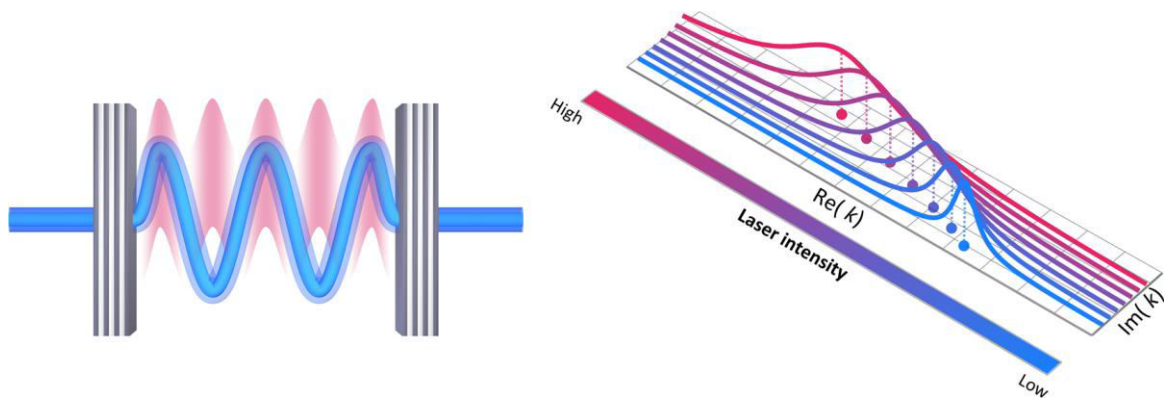


Fig. 1. Nonlinear self-action and complex resonance shift in a distributed Bragg reflector: (left) Kerr-induced refractive index modulation forms a self-consistent intracavity grating from the standing wave field. (right) Evolution of the resonance pole in the complex wavenumber plane with increasing intensity, showing shifts in both $\text{Re}(k)$ and $\text{Im}(k)$.

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Surface Contribution to the Angular Momentum of Light

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The decomposition of the angular momentum of a source-free electromagnetic field into orbital and spin parts, $\mathbf{J} = \mathbf{L} + \mathbf{S}$, remains conceptually challenging because the separate orbital and spin terms $\mathbf{L}$ and $\mathbf{S}$ do not, in general, possess an unambiguous gauge-invariant status. Previous optical studies identified a relevant surface contribution in the angular momentum of light beams [1]. A re-examination of the standard spin-orbital decomposition raises a natural question: can the decomposition remain consistent without a surface term? The present analysis establishes that the source-free angular momentum of the electromagnetic field takes the form $\mathbf{J} = \mathbf{L} + \mathbf{S} + \mathbf{H}$, where $\mathbf{H}$ denotes the surface contribution, and that several familiar difficulties of the orbital-spin decomposition arise from omitting this term. A gauge transformation makes this point explicit: removing $\mathbf{H}$ introduces gauge dependence into the orbital-spin decomposition, whereas the full combination $\mathbf{L} + \mathbf{S} + \mathbf{H}$ remains gauge-invariant. Circularly polarised light provides a simple and revealing example. In that case, the usual spin-orbital decomposition leads to the apparent paradox $\mathbf{J} = \mathbf{0}$, $\mathbf{L} = \mathbf{0}$, but $\mathbf{S} \neq \mathbf{0}$. Including the surface term resolves this paradox through $\mathbf{S} + \mathbf{H} = \mathbf{0}$. Retaining the surface contribution therefore becomes essential for a consistent interpretation of the standard decomposition of the angular momentum of light. A final remark connects this perspective with structured light.

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On Optimization Methods for MPLC-Based OAM Sorters

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OAM provides a scalable route to high-dimensional information transfer, but efficient mode sorting remains a central challenge [1–3]. Here, we investigate the design of multi-plane light converter (MPLC)-based OAM sorters for varying dimensionalities using two optimization approaches: wavefront matching [1,4] and gradient ascent [3]. We compare these methods in terms of sorting fidelity, crosstalk, insertion loss, convergence behaviour, and scalability as the number of sorted OAM modes increases. Each algorithm offers a different balance between design flexibility, computational complexity, and robustness during optimization. By studying these approaches within a common design framework, we aim to better understand how algorithm choice influences the achievable sorter performance. This provides a basis for evaluating which optimization strategies are best suited for MPLC-based OAM sorting as dimensionality increases. We examine how these methods behave as the design space becomes more demanding with increasing mode number. This comparison also helps distinguish algorithm-dependent limitations from constraints that arise more generally in MPLC-based OAM sorter design.

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Transverse spin angular momentum of optical non-Hermitian skin modes in MT-symmetric media

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Non-Hermitian skin modes (NHSE) are eigenmodes that accumulate at boundaries under open boundary conditions. While NHSE has been mainly discussed in discrete models, recent studies have shown that optical NHSE can emerge as surface localized eigenmodes even in uniform continuous media [1,2]. Here we consider TE skin modes in an MT-symmetric (mirror-time) anisotropic dielectric, where the in-plane permittivity tensor has complex-conjugate eigenvalues (Fig. 1(a)).

Using closed-form solutions, we evaluate the time-averaged Poynting vector and the Stokes parameter S_3 , which quantifies the local circular-polarization handedness. We find that the longitudinal energy flow $P_y(x)$ exhibits the expected exponential boundary localization, whereas the spatial profile of $S_3(x)$ does not follow the conventional relation to the transverse spatial derivative of the Poynting vector known for Hermitian surface waves such as SPPs [3,4]. In particular, $S_3(x)$ vanishes at locations where $P_y(x)$ has the steepest boundary gradient (Fig. 1(b)).

Overall, the finite $S_3(x)$ indicates an intrinsic helicity bias and a transverse-spin-like texture carried by the NHSE. At the same time, MT-symmetric non-Hermitian anisotropy modifies the familiar Hermitian relation between $S_3(x)$ and energy flow, highlighting that helicity textures in optical NHSE cannot be inferred from energy-flow gradients alone. This suggests polarization-selective excitation of skin modes with circularly polarized light, and offers a route to probe angular-momentum transport and optical torque exerted on the medium in optical NHSE systems.

This work was supported by JP20H05641, 24K01377, 24H02232, 24H00400, 23KJ0355, 25K17906.

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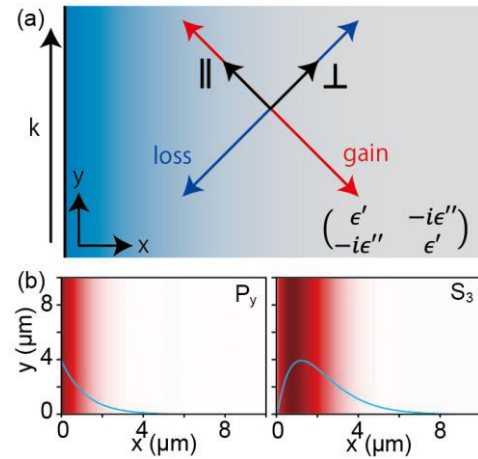


Fig.1 (a) Schematic of an MT-symmetric medium supporting TE non-Hermitian skin modes. (b) Spatial distributions of normalized axial energy flow P_y and third Stokes parameter S_3 . Blue curves show the cross-sections at $y = 0$.

Optimal beam displacement measurements using high order structured light modes

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Measurement of small beam displacements, both lateral and angular, is a fundamental task in high-precision optical metrology. In conventional approaches based on fundamental Gaussian beams, the sensitivity is limited by the standard quantum limit [1]. Although quantum resources such as squeezed light can enhance precision [2], they usually require more complex implementations and are more sensitive to losses. In this context, higher-order Hermite–Gaussian and Laguerre–Gaussian modes provide an attractive alternative, since their larger spatial footprint and more complex phase structure make them inherently more sensitive to small perturbations [3,4]. Here, we show that the intrinsic parity and symmetry properties of these high-order modes can be used for optimal beam displacement sensing using an interferometric method, rather than relying on quantum light or homodyne detection [5]. The method is based on the fact that small lateral or angular displacements induce crosstalk between modes of opposite parity, so that the displacement information is encoded in a parity flip of the field. The sensitivity increases with the mode order relative to that of a fundamental Gaussian beam. Signal-to-noise ratio improvements of up to 41 times for HG modes and 21 times for LG modes indicate that high-order structured light is a robust and efficient resource for high-precision metrology, with promising applications in alignment, tracking, nanotechnology, and fundamental physics.

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Observation of OAM non-conservation in entangled photon generation

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Orbital angular momentum (OAM)-entangled states produced by spontaneous parametric down-conversion (SPDC) are considered ideal for realizing high-dimensional entangled states, which have several advantages for quantum technologies. However, the limited sensitivity of current two-photon OAM detectors is a major roadblock not only for realizing such technologies but also for resolving foundational questions, such as OAM conservation in SPDC. The current theoretical understanding is that OAM is not conserved in Type-II SPDC but is conserved in Type-I [1]. Experimentally, although non-conservation in Type-II has not been demonstrated, conservation in Type-I has been reported frequently and has become an underlying assumption for techniques generating high-dimensional OAM entangled states. In this work, we experimentally demonstrate a high-sensitivity two-photon OAM detector, using which, contrary to the current understanding, we report non-conservation of OAM in Type-I SPDC. We attribute this to a spatial walk-off effect and prove it using a framework free of standard phase-matching approximations.

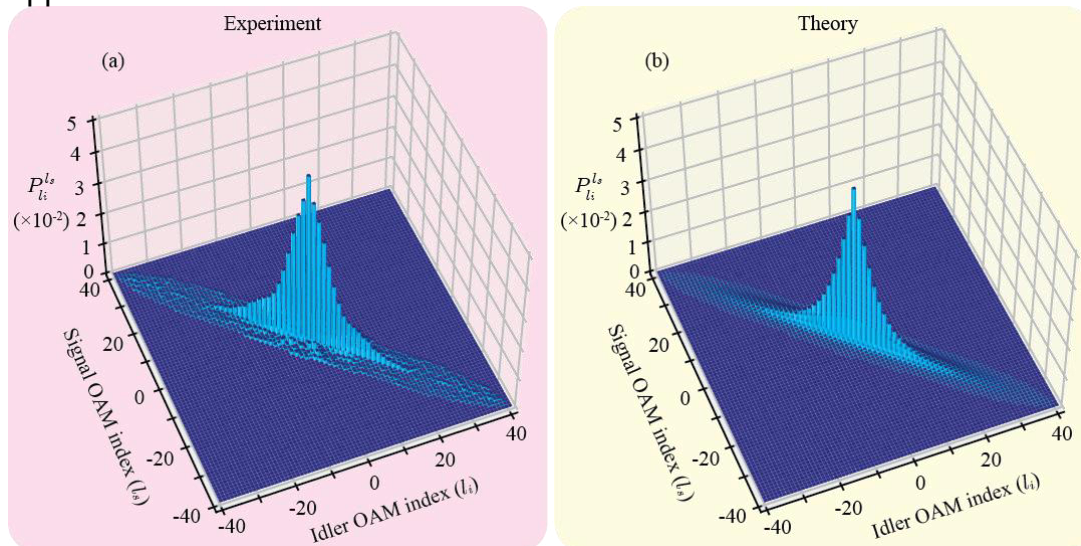


Figure 1. **Experimentally measured two-photon OAM spectrum for Type-I SPDC.** (a) Reconstructed two-photon OAM spectrum $P^{ls_{ii}}$ from experimental observations and (b) numerically evaluated $P^{ls_{ii}}$. This shows experimentally observed OAM non-conservation of 42.92%.

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Phase space description of Cherenkov radiation

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We develop a theory of photon emission in phase space using the Wigner function, highlighting the influence of the measurement procedure on the evolved electron-photon state. The two final particles are entangled; therefore, the distribution of the photon field is affected, whether or not the structured electron wave packet is measured. As a basic example, we consider Cherenkov radiation [1]. In particular, we study the near-field regime, where the Cherenkov cone has not yet formed and the Cherenkov condition is not fulfilled [2]. In this regime, the spatial distribution of the photon wave packet resembles the shape of the electron wave packet, effectively providing “snapshots” of the emitter’s wave function.

The predicted effects – such as finite photon spreading time, finite flash duration, and a quantum shift in the photon arrival time – are spatiotemporal phenomena that remain hidden in a momentum-space description. All these effects arise from quantum interference, as seen in the Wigner function, and are directly related to the constructive interference that forms the Cherenkov cone. The characteristic timescales lie in the *atto- and femtosecond ranges*, highlighting the atomic-scale nature underlying these macroscopic phenomena. In addition, we estimate experimental parameters required to observe a *negative temporal shift* in the photon arrival time.

We extend the approach to arbitrary dispersion [3], of particular relevance to slow-light regimes. In strongly dispersive media, in the vicinity of sharp refractive-index variations, temporal shifts on the picosecond scale can be obtained, providing suitable conditions for experimental verification.

The work was carried out with the support of the Russian Science Foundation Grant No. 23-62-10026.

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Topological invariance of entangled OAM states in high decoherence limits

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Orbital angular momentum (OAM) entanglement offers a high-dimensional Hilbert space for quantum encoding, yet its practical utility is historically limited by its extreme sensitivity to noisy channels [1]. Recently, an underlying topology has been identified within these entangled states [2]. Here, we experimentally investigate the resilience of this topological observable in the most complex channel possible. Using a one-sided turbulent channel, we show that the topological invariant is robust even in regimes where the constituent OAM modes are heavily distorted, and the state purity decayed significantly [3]. We show this stability persists in both static and dynamic scenarios, proving the topological invariant is fundamentally more resilient than the OAM correlations upon which it is built. This discovery advances the field of quantum optical topologies and opens new possibilities for long-distance quantum communication and sensing in fluctuating and chaotic media.

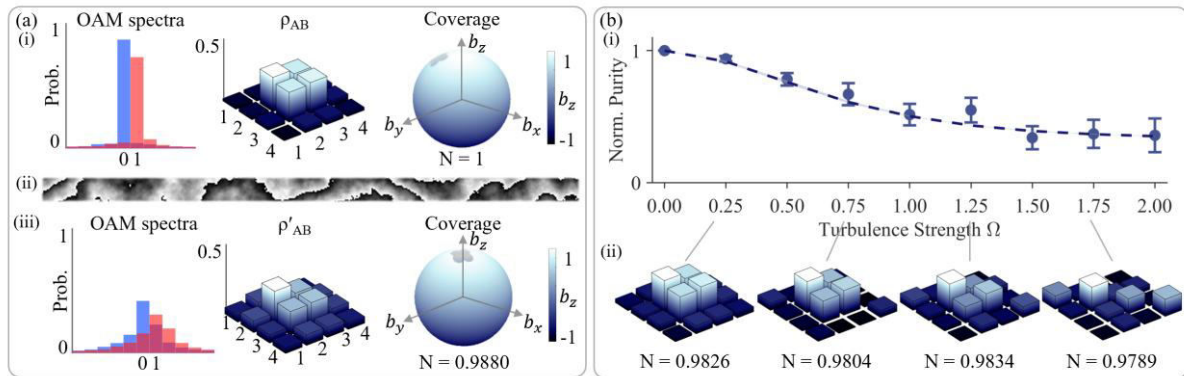


Figure 1: (a) (i) OAM spectra, density matrix and coverage plot before turbulence (ii), and after turbulence (iii) for static channel. (b) (i) Normalised state purity as a function of turbulence strength, showing a decay toward the mixed-state limit. (ii) Density matrices and corresponding Skyrme number recovered from the dynamic channel.

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Optimization of the Shack-Hartmann sensor using structured light

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The measurement of the wavefront using a Shack-Hartmann sensor is based on determining its derivative at a given point. The accuracy of determining the position of the light spot is crucial for precise measurements. In the classical Shack-Hartmann sensor, the Gaussian beam is used to determine the wavefront.

The accuracy of determination of the position of the light spot center at a high signal-to-noise ratio limits the measurement range of a classical Shack-Hartmann sensor. In our work, we propose using an optical vortex instead of a classical Gaussian beam. We show that determining the position of the optical vortex singularity, rather than the center of the light spot, improves measurement precision and extends the operating range of a conventional Shack-Hartmann sensor [1].

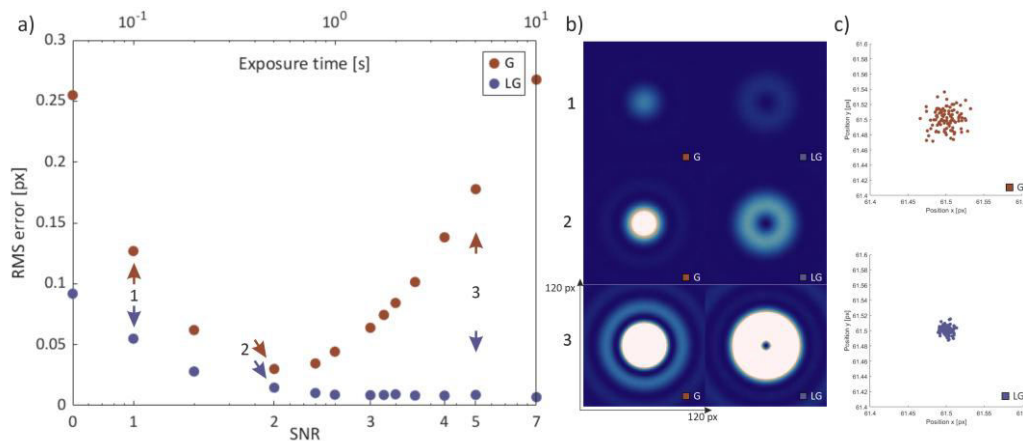


Fig. 1. a) Localization precision for various SNRs for both the weighted centroid applied to a Gaussian beam (orange) and the Laguerre-Gaussian transform applied to an optical vortex (blue). b) Single frames of the registered image under various exposure times, shown by arrows in a). 1) 0.05s, 2) 0.5s and 3) 5s. c) Scattered localization positions for all iterations registered for case 3) 5s of exposure time.

Funding: National Centre for Research and Development, 0230/L-13/2022.

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Orbital Angular Momentum Transfer in Ro-Vibrational Spectroscopy of Molecules

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Light carrying orbital angular momentum (OAM) provides a powerful route to tailoring light-matter interactions beyond the standard dipole-plane-wave approximation. In such structured fields, the helical phase profile and associated spatial gradients allow photons to exchange OAM with the rotational and center of mass molecular degrees of freedom, opening excitation channels that are inaccessible in conventional spectroscopy. In our recent work [1], we showed that this effect can strongly enhance rovibrational transitions that are forbidden for non-helical light, and that the underlying mechanism is governed by the coupling of molecular multipole moments to the spherical gradients of the electric field. This establishes a general framework for understanding how field topology and molecular symmetry determine OAM transfer in light-molecule interactions.

Building on these results, we develop a general framework for optimizing the coupling of structured light to molecular matter beyond the dipole approximation [2]. By deriving figures of merit for the interaction of different optical modes with quadrupole and higher-order transitions, we identify the field properties that govern efficient OAM transfer and the conditions under which OAM-dependent spectroscopic signatures, including chiral-sensitive effects [3], can be observed. This analysis also highlights experimentally relevant platforms, such as vortex lattices and other structured beams, whose tunable phase singularities and mode purity make them especially suitable for enhancing and controlling light-matter coupling. Our work thus bridges fundamental selection rules, beam metrology, and spectroscopic applications, paving the way toward tailored structured-light probes of molecules and mesoscopic objects.

Acknowledgments:

This research was funded in whole or in part by the Austrian Science Fund (FWF) [10.55776/F1004].

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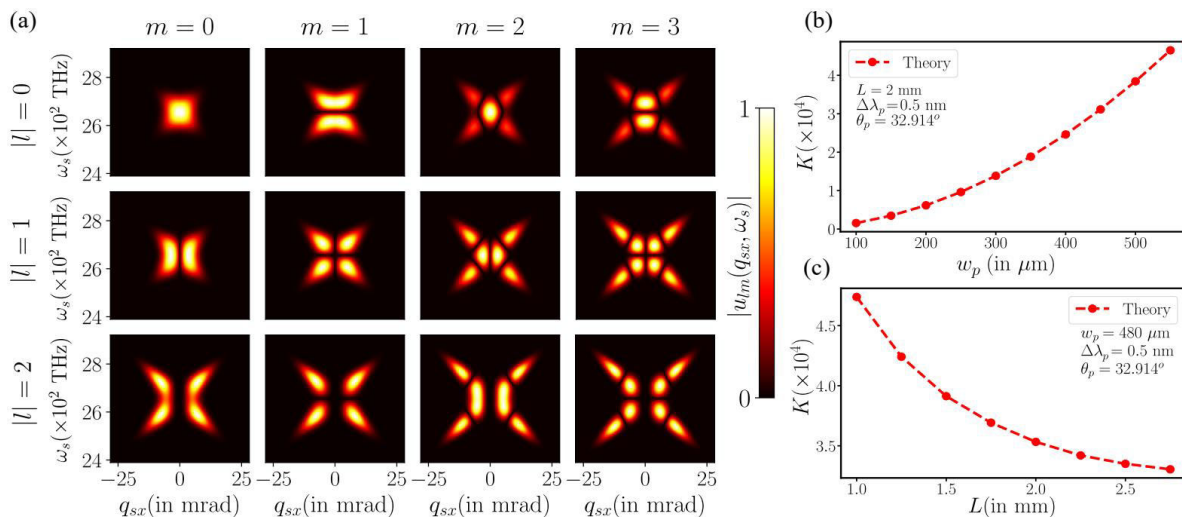
Full Schmidt characterization of spatiotemporally entangled states produced from spontaneous parametric down-conversion

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The full Schmidt decomposition of spatiotemporally entangled states generated from spontaneous parametric down-conversion (SPDC) has not been carried out until now due to the immense computational complexity arising from the large dimensionality of these states. In this work, we show that in common experimental scenarios involving a rotationally symmetric pump field, the computational complexity of the Schmidt decomposition can be reduced by a factor of $O(N^2/\log N)$, which for $N = 300$ yields a speedup factor greater than 10^4 . Consequently, we are able to perform the Schmidt decomposition for the first time and compute the precise form of the spatiotemporal Schmidt modes along with the Schmidt spectrum. We show that the Schmidt modes possess a phase profile with a transverse spatial vortex structure that imparts orbital angular momentum (OAM) to them at all frequencies. The corresponding Schmidt spectrum has a large dimensionality with a Schmidt number $K \sim 10^4$. Our efficient method also enables us to characterize the variation of K with respect to experimental parameters such as the pump beam waist and crystal length. We then consider the high-gain regime of SPDC and show that the Schmidt modes broaden while the Schmidt spectrum narrows with increasing pump amplitude. Our work can have important implications for quantum protocols based on entangled states produced via SPDC.



Low-gain SPDC: (a) Magnitude profiles of the Schmidt modes first 12 Schmidt modes. (b) and (c) depict the variation of the Schmidt number (K) with pump beam-waist (w_p) and crystal length (L), respectively.

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Machine Learning Classification of OAM Quantum Correlations in SPDC Photon Pairs using coincidence photons time-stamps

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High-dimensional photonic states encoded in orbital angular momentum (OAM) provide a powerful platform for quantum communication and information processing. However, experimental characterization of OAM quantum correlations generated through spontaneous parametric down-conversion (SPDC) typically requires complex optical projections and alignment-sensitive measurements [1]. Here, we report for the first time a machine learning framework for classifying OAM quantum correlations in SPDC photon pairs using coincidence photons time-stamps.

Recent studies have shown that the 2D spatial information of OAM beams can be mapped onto a 1D temporal speckle sequence by passing the beam through random scattering media, such as ground glass or multimode fibers [2–4]. Machine learning models, including support vector machines and 1D convolutional neural networks, can efficiently recognize OAM states from these temporal speckle signals. In this work, we extend this classical concept of spatial-to-temporal OAM mapping to the quantum regime to classify OAM quantum correlations in SPDC photon pairs.

Correlated photon pairs are generated by pumping a nonlinear ppKTP crystal with a 405nm Gaussian beam, producing signal and idler photons at 810 nm. The signal photon is projected onto a selected OAM mode using a spatial light modulator (SLM) and coupled into a single-mode fiber connected to a single-photon counting module (SPCM). To encode spatial information into measurable temporal signatures, the idler photon, after projection through an SLM, is transmitted through a multimode fiber, which acts as a random scattering medium, and detected by another SPCM. This process maps spatial OAM information onto photon time-stamps. A large labeled dataset of coincidence photons time-stamps is recorded by scanning the OAM holograms of both signal and idler photons. Preliminary results demonstrate successful identification of correlated states $|\ell, -\ell\rangle$ for $\ell \in [-4, +4]$ indicating that coincidence photons time-stamps encode signatures of OAM quantum correlations. This approach provides a novel data-driven strategy for high-dimensional quantum state characterization using coincidence photons time-stamps. More results will be presented at the conference.

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Efficacy of single-pixel imaging for imaging glioblastoma tumours: A simulated assessment

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Glioblastoma (GBM) is an aggressive brain tumour with poor treatment response. Recently, a microphysiological system (MPS) to maintain viable GBM samples, and thus, better recapitulate the native tumour's heterogeneity, has been developed [1], creating a need for an imaging solution that best takes advantage of it. This research proposes an application of single-pixel imaging (SPI) to explore GBM within the MPS. Imaging biological tissue is inherently challenging due to its scattering and absorption; however, SPI systems are well-suited to low-light environments. Single-pixel detectors can be used in (a) low-light conditions, (b) enable imaging at wavelengths that would otherwise be inaccessible [2], and (c) have demonstrated potential in diagnostics [3]. The first step of this work is to simulate the system. Photon propagation in the SPI system will be modelled using MCX, a Monte Carlo platform for light transport through heterogeneous scattering media [4], with optical properties set to match those of the brain. Structured illumination will be implemented using a Hadamard pattern basis, and the system's ability to retrieve information from within the scattering medium will be assessed. The outcomes of this simulation will inform the design and optimisation of a physical SPI imaging system, representing the first step toward depth-resolved imaging of ex vivo GBM within the MPS.

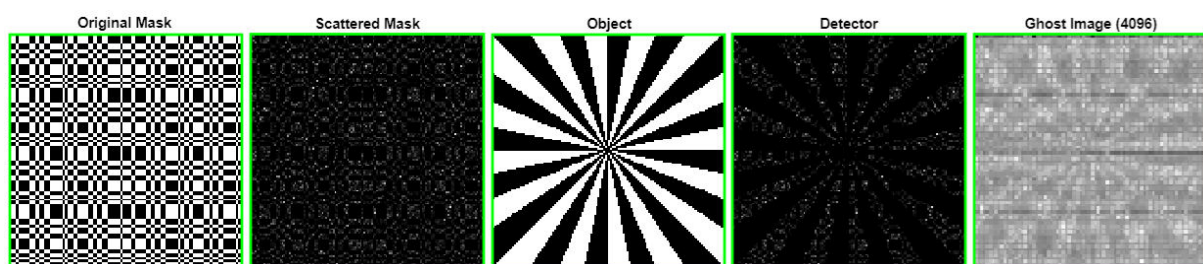


Figure 1: Stages in the simulation of the reconstruction of a binary mask using single-pixel imaging.

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Spatiotemporal Vortex Imprinting in High-Harmonic Generation

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We investigate high-harmonic generation (HHG) driven by the overlap of a Gaussian beam and a spatiotemporal optical vortex (STOV) [1] beam in an orthogonal two-beam geometry [2]. Our simulations show that the transverse orbital angular momentum (TOAM) carried by the incident STOV is clearly imprinted onto the high-harmonic emission along the Gaussian-beam propagation direction, indicating that spatiotemporally structured light can leave distinct vortex features onto the HHG field. To gain physical insight into this process, we further examine the emission within a quantum-orbit (QO) framework [3] and analyze how the structured driving field influences the underlying electron trajectories. These results establish a clear example of spatiotemporal vortex imprinting in high-harmonic generation and connect it to the corresponding quantum-orbit dynamics.

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Attosecond Extreme-Ultraviolet Skyrmion Pulses through High Harmonic Generation

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Paraxial optical skyrmions are polarization distributions in a beam's transverse region that span the full set of paraxial polarization states, thereby covering the Poincaré sphere. While widely explored under continuous-wave and long-pulse regimes, their realization at attosecond timescales has remained elusive. Here we demonstrate extreme-ultraviolet attosecond skyrmion pulse trains generated by high-harmonic generation in argon, driven by an engineered infrared linearly polarized vector beam whose circular components carry fractional orbital angular momenta (Fig. 1(a)) [1]. We show that a phase-locked sequence of consecutive harmonics around 70 eV exhibits nearly identical skyrmion polarization textures in the far field; this spectral window can be experimentally isolated using realistic Al and Zr foils. Their coherent superposition produces ~ 500 -attosecond pulses that retain a well-defined skyrmion topology throughout the pulse duration, with the instantaneous spatial polarization distribution effectively spanning the Poincaré sphere (Fig. 1(b)). This approach provides an experimentally feasible route to attosecond topological light textures and opens opportunities for controlling photoelectron angular and spin distributions, high-resolution EUV imaging, topological harmonic spectroscopy in solids, and ultrafast probing of chiral materials and magnetic helicoidal dichroism.

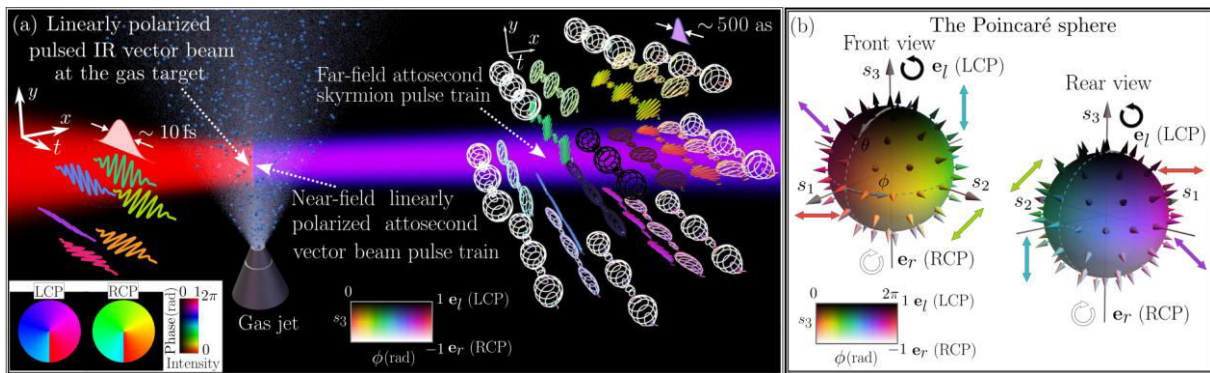


Figure 1: (a) Far-field generation of attosecond skyrmion pulses via HHG driven by a linearly polarized infrared vector beam. (b) Representation of the Poincaré sphere.

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Detecting Light's Parameters with Passive Waveguide Architectures: From On-Chip Polarimetry to Spatial Mode Decomposition

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Light is described by many parameters, each of which may convey significant information. Thus, accessing these parameters is essential in many applications ranging from biomedical sensing to communication, and beyond. However, conventional light detectors can only directly detect intensity information, while established methods for phase and polarization detection are typically bulky, computationally demanding, and often costly. Photonic Integrated Circuits (PICs) provide a compact and stable platform that can overcome these limitations by replacing bulky optical setups with small-footprint devices to detect light's parameters. In this work, we present a fully passive PIC architecture with multiple input pixels for measuring various parameters of the light field. After coupling free-space light into the PIC, an architecture of passive on-chip interferometers provides access to intensity and phase information of the light at the positions of the input pixels [1]. By replacing the freespace-to-chip interface by polarization splitting units, the same evaluation architecture can be used to measure polarization information [2]. This approach enables scalable, real-time detection of structured light without requiring active components or computationally expensive post-processing. As proof of concept, we demonstrate modal decomposition, for Laguerre-Gaussian modes (see fig. 1). Passive photonic circuits expand the toolbox available for detecting structured light, enabling unprecedented miniaturization. Furthermore, these architectures can be manufactured using standard CMOS processes.

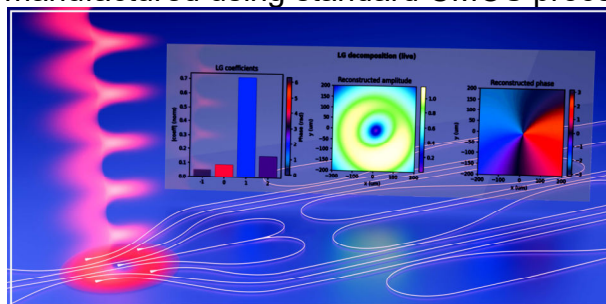


Figure 1: Artistic illustration of a passive waveguide architecture used for spatial mode decomposition. The presented chip architecture features five input pixels that are interconnected by passive on-chip interferometers. This chip design enables the simultaneous measurement of the relative phase and intensity of the light field at each pixel position, which ultimately enables reliable discrimination between different modes in the Laguerre-Gauss basis.

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Sensing and generating structured light through photonic integrated circuits

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Advances in optics and photonics have led to unprecedented control of the spatial and temporal properties of light fields, with applications ranging from optical imaging and sensing to communication and quantum technologies [1,2]. Central to these developments is the strong demand for precise and scalable tools to measure, manipulate, and generate structured light. Traditional approaches often rely on bulky free-space optics, which limit integration and scalability in real-world applications. Photonic integrated circuits (PICs) offer a promising solution, enabling compact, robust, and highly flexible platforms for structured light applications [4,5,6].

Here we present a PIC designed for the measurement and generation of structured modes of light, implemented on a silicon-on-insulator platform [3,4]. Our photonic chip consists of a mesh of Mach-Zehnder interferometers combined with carefully arranged grating couplers, acting as a free space interface. We analyze the sampled light using a theoretical framework based on transmission matrices to obtain information about intensity, phase, and polarization. We discuss the basic physical principles underlying our measurement scheme [5] and demonstrate its applicability as a photonic sensor by processing structured light modes. We demonstrate on the example of LG modes the distinction and sensing of orbital angular momentum (OAM) states of light as well as the handedness of their twisted phase fronts [3]. By operating the chip in reverse, this configuration also enables fast and precise generation of complex structured light fields in free space with well-defined amplitude and phase distributions [4]. Our results prove that the presented photonic chip provides a flexible workbench for numerous applications as well as developments towards future applications in imaging, sensing, or manipulation in nanooptics [6].

Financial support from the Austrian Federal Ministry of Labour and Economy, the National Foundation for Research, Technology and Development, and the Christian Doppler Research Association is gratefully acknowledged.

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Hybrid Intelligent Strategy enabling One-to-Many High-Dimensional Orbital Angular Momentum Multicasting

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Achieving higher degrees and dimensions of light is one of the primary interests for increasing data-transmission capacity of the optical communications community. Orbital angular momentum (OAM), with its infinite and mutually orthogonal nature, offers a promising carrier for high-capacity and high-dimensional optical data-transmission. However, most current OAM-based shift keying and multicasting schemes rely on multiple single-mode encodings or simple OAM-mode complexing, which fail to fully exploit the high-dimensional potential of OAM. This limitation primarily arises from the challenge of directly modulating complex multiplexed OAM states—such as OAM combs—which typically requires bulky optical setups and complicated iteration algorithms. In this presentation, we propose a hybrid intelligent strategy for OAM comb multicasting, enabling simultaneous multi-channel transmission with high-dimensional OAM encoding via a single hologram. By integrating deep learning with iterative algorithms to form the manipulation scheme, where data-driven OAM-comb generation and physics-guided wave vector manipulation are jointly exploited. We design a phase-only proposal capable of directly encoding multiple structured OAM combs for multicasting, significantly improving the photon efficiency of OAM shift keying. To demonstrate the scalability and fidelity of our method, we experimentally validate multicasting transmission across four, six, and eight channels, where each channel transmits 1024-ary symbols. Furthermore, benefiting from the high-dimensional transmission capability, we develop a mixed encoding protocol to enhance the security of high-dimensional OAM-comb transmission in one-to-many multicasting scenarios, where different images are delivered to different users in parallel. A 6-channel OAM combs data-transmission system is implemented, achieving a real-time transmission under 7×10^{-5} bit-error-rate (BER).

Generation of attosecond spatiotemporal vortices from non-scaling topological charge high-order harmonics

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Spatiotemporal optical vortices (STOVs) are structured light pulses that couple the spatial and temporal domains [1], carrying transverse orbital angular momentum (t-OAM) [2]. Although the generation has been limited to the visible and infrared regimes [3], extending STOVs unique topology to the extreme-ultraviolet (EUV) may open new opportunities in ultrafast and nanoscale science. We present theoretical and experimental demonstration of EUV-STOV generation via high-order harmonic generation (HHG) process driven by elliptical STOV beams [4] and by spatio-spectral optical vortices (SSOVs), the spectral counterparts of STOVs [5]. We propose that HHG driven by SSOV fields yields far field EUV-STOV harmonics with non-scaling topological charge [Fig. 1 a)], enabling the synthesis of attosecond EUV-STOV pulses [Fig. 1 b)]. Finally, we show that topological charge and t-OAM are not tied by analyzing the scaling laws of these quantities in the HHG process [Fig. 1 c)]. These results open new paths for controlling light topology and OAM in space and time in non-linear optical processes, with potential applications in ultrafast dynamics, nonlinear spectroscopy, and light–matter interactions with structured fields.

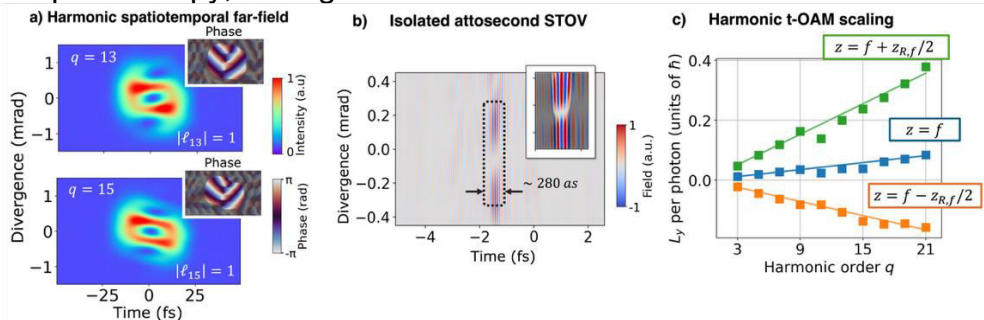


Fig. 1. High-order harmonic generation driven SSOVs. a) Simulated HHG far-field intensity and phase distribution of 13th and 15th order harmonics. At the far field all harmonics are emitted with unity topological charge. b) Isolated attosecond EUV-STOV resulting from overlapping several harmonic orders. c) Harmonic intrinsic t-OAM scaling for different target positions with respect to the driving SSOV focus, before focus (orange), at focus (blue) and after focus (green).

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Single, Double, Triple Slit Diffraction of Ellipse Field Singularities

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In the advancement of singular optics, ellipse field singularities, also known as C-points, have been a topic of interest. A C-point is a location of circular polarization embedded within an inhomogeneous field dominated by elliptical polarization states. The properties of generic C-points have gained significant attention due to various potential applications [1,2]. The basic understanding of these beam are key to unlock these potentials. The studies indicate that the fundamental interference and diffraction behaviour of phase vortices and higher-order cylindrical beams uncovers topological characteristics beneficial for detection applications [3]. In this work, we aim to extend these phenomena to C-points using single, double, and triple-slit configurations.

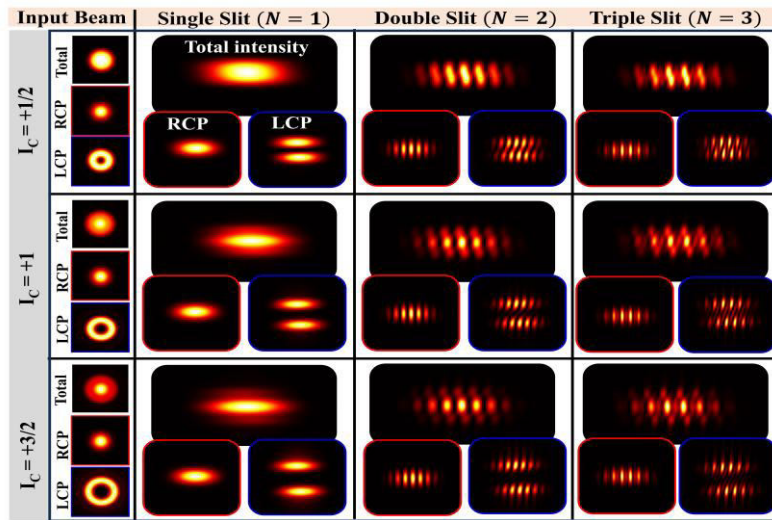


Figure 1: Theoretical multiple slit diffraction patterns of C-point singularities with singularity index $I_c = +1/2, +1, +3/2$. The right and left circular polarization (RCP and LCP) components and the total intensities of the (Fresnel) diffracted fields of C-points.

Single slit diffraction of C-point beams does not yield significant features in the total intensity, but decomposition into RCP and LCP components reveals underlying topological characteristics. The tilt and separation between the vertical lobes of the LCP component increase with increasing index, which becomes finer with increasing number of slits. Also, the direction of tilt reveals the handedness associated with the input beam.

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Vector-vortex structured chiral light for enhanced sensing of chiral molecules

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Chirality is an ubiquitous phenomena in nature, spanning many orders of magnitude in length, from the cosmic scale in spiraling galaxies to the microscopic one in chiral molecules. Chiral electronic states supported by both chiral molecules and achiral atoms can be accessed via ultrafast methodologies, from time-resolved photoelectron circular dichroism to high-harmonic generation spectroscopy. These techniques can unveil the ultrafast evolution of electronic currents supported by the chiral potential of a molecule, paving the way for the ultrafast control and sensing of molecular enantiomers.

The interaction of polychromatic synthetic chiral light fields (SCL) with chiral molecules has been theoretically predicted to lead to a large enhancement of chiral signals in observables such as HHG or photoelectron yield [1]. The combination of SCL with bicircular structured beams carrying orbital angular momentum has been shown to lead to a beam carrying a chiral topological charge [2], which can imprint robustness on the enantiosensitive observables detected in an optical ultrafast experiment.

Here, we show that by using vector-vortex beams with radial and azimuthal polarization the chirality of these beams can be increased by two orders of magnitude, leading to a huge enhancement in chiral signals. We prove theoretically such enhancement by using an ab-initio based strong-field approximation approach to describe HHG in fenchone and camphor, with state-of-art saddle point methods to describe and analyze polychromatic three-dimensional quantum orbits in the continuum [3,4]. Our results bring the goal of experimental proof of these techniques closer to reach, both in chiral molecules as well as in atoms.

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Optical Skyrmions irradiating an atomic medium

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Structured light-matter coupling enables the control, manipulation, and information encoding in quantum materials via fine-tuning of light degrees of freedom. Among those, orbital angular momentum (OAM) has recently gained traction both in the theory of OAM transfer processes and in advanced optical applications [1].

Motivated by optical vortex beams interacting with media [2], here we consider an optical skyrmion beam, a superposition of oppositely oriented circularly polarized components, irradiating an atomic medium showing a Lambda-transition model.

We investigate the possibility of transferring OAM from the incoming skyrmion beam to both the medium and the emitted beam. First, we consider the optical beam coupled to atoms using numerical simulations with GRANAD [3]. Then, we study the time evolution of the intensity profile and the spatially dependent polarization states of the optical skyrmion beam due to propagation by analytically solving the Maxwell–Bloch equations. Finally, we consider further implications of the topological light-matter paradigm for information storage.

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Propagation of Optical Vortex Constellations

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Optical vortex beams with higher topological charges are one of the foundations to structured light in terms of their applicability in different branches of physics [1]. However, such higher order vortices are intrinsically unstable and decompose into constellations of unit-charge vortices upon the smallest perturbations, i.e., in real world settings [2]. Despite their ubiquitous presence in all real experiments, a compact description of their longitudinal propagation – the most fundamental and experimentally relevant form of optical evolution – has so far been lacking. Here, we experimentally demonstrate that the propagation of an arbitrary vortex constellation in twisted light is fully described by a simple, universal, and deterministic law governed by its complex elementary symmetric polynomials (ESPs), a concept we recently introduced when exploring topological aberrations [2]. We find, that ESP e_j evolves with propagation of the constellation as $e_j(z) = e_j(0) \left(\frac{z_R}{z_R - iz} \right)^{-j}$ where z is the propagation distance and z_R is the Rayleigh range of the beam.

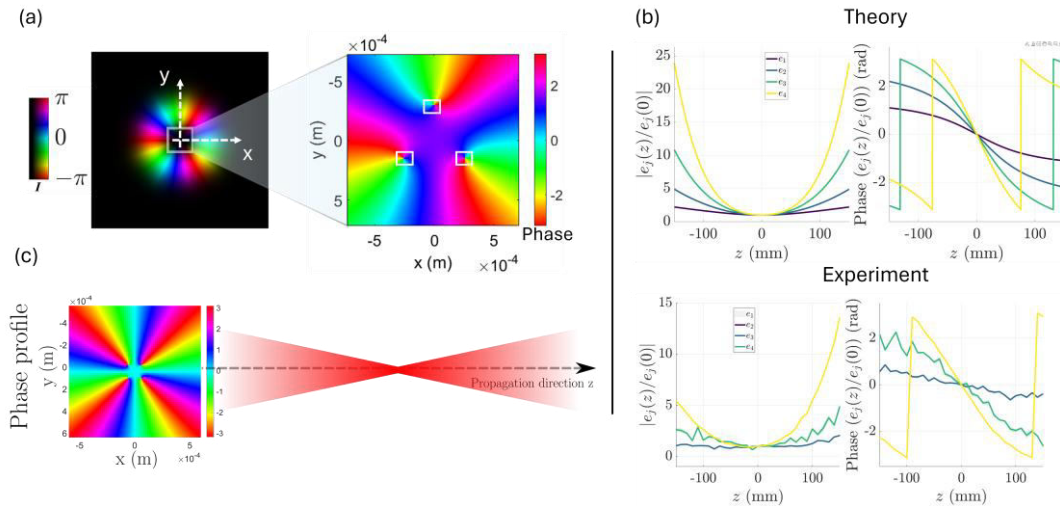


Fig. 1 Propagation of an optical vortex constellation in a Gaussian beam [1]. (a) Amplitude and phase profile of a constellation present in high-order vortex beam. (b) Theoretically and experimentally obtained propagation of the complex ESPs e_j/e_0 ($j = 1,2,3,4$) of constellation coordinates for a four-vortex constellation given in (c). The ESPs are, in experiment, calculated from the barycentre frame of the constellation, giving rise to $e_1 = 0$.

We further show using the Fisher information formalism that complex ESPs provide an powerful metric for longitudinal length estimation, while the ESP-amplitudes maximize sensitivity in the far-field (far from waist), their phases exhibit maximal sensitivity around the waist. Our results establish ESPs as a minimal yet universal representation of singularity dynamics and introduce a new route to longitudinal sensing using singularimetry.

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Spatiotemporal effects in parametric downconversion: controlling quantum correlations with structured light

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Spontaneous parametric down-conversion is the most used method to generate entangled pairs of photons, being adopted in several areas of quantum optics. By appropriate controlling the SPDC process, it is possible to generate photons entangled in any degree of freedom of light [1,2]. The temporal degree, specifically, is interesting due to its high-dimensional state space and compatibility with propagation in single-mode fibers, being paramount for high-dimensional quantum communications. Thus far, control over the temporal structure of SPDC photons has been achieved by shaping the temporal shape of the pump beam [3] and by engineering the phase matching in the nonlinear medium [1]. Although powerful, this method is resource intensive as each quantum state of interest requires a particular design of nonlinear crystal.

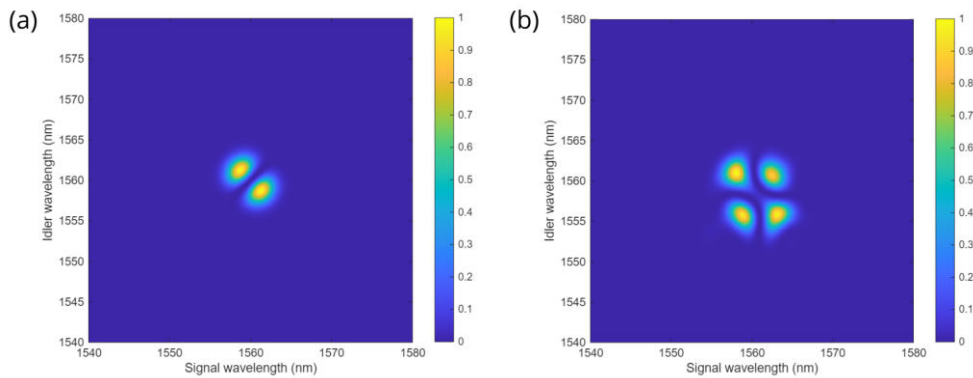


Fig. 1. Joint spectral intensities for two biphoton temporal states generated by SPDC. (a) An entangled state $|00\rangle+|11\rangle$, obtainable in both methods (see [1]; in our case, the fidelity $F > 0.97$). (b) A separable $|11\rangle$ state, only obtainable with our method, with $F > 0.90$.

In this work, we propose a novel method to control the temporal structure of SPDC without engineering the nonlinear crystal. Instead, we use the spatial structure [4] of the pump beam to control the phase matching, exploring the Gouy phase of light. Our method transfers the complexity of SPDC state design completely to the spatiotemporal structure of the pump, which can be changed on demand with standard wave shapers. Furthermore, we show that when the pump beam is shaped in a nonseparable spatiotemporal structure, we gain more general control over the temporal correlations of SPDC, accessing a class of quantum states that is not achievable with the crystal engineering technique.

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Partially coherent light field reconstruction based on phase space tomography

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The reconstruction of the spatial profile of light fields plays a major role in the use light for imaging, sensing and quantum information. Holography has been the preferred method due to its simplicity, but it requires a reference field, and it is limited to coherent fields. Non-interferometric methods such as quantum state (QST) and optical phase-space (PST) tomography allow for partially coherent field reconstruction, but they have their own limitations.

OPST is equivalent homodyne detection for photon numbers, but the limitation is the implementation of arbitrary rotations in 4D Wigner space to perform the inverse Radon transform. In our approach, we circumvent the necessity of Radon transform by directly measuring the Wigner function at every point. This approach relies on the equivalence between the paraxial wave equation and the quantum harmonic oscillators pointed out by L. Allen *et al.* [1]. The value of the Wigner function at any point is the expectation value of the displaced parity operator [2], for light fields, the displacement operator corresponds to shift and tilts of the light field, therefore the value of the Wigner function is retrieved by measuring the mode decomposition of a tilted and shifted light field.

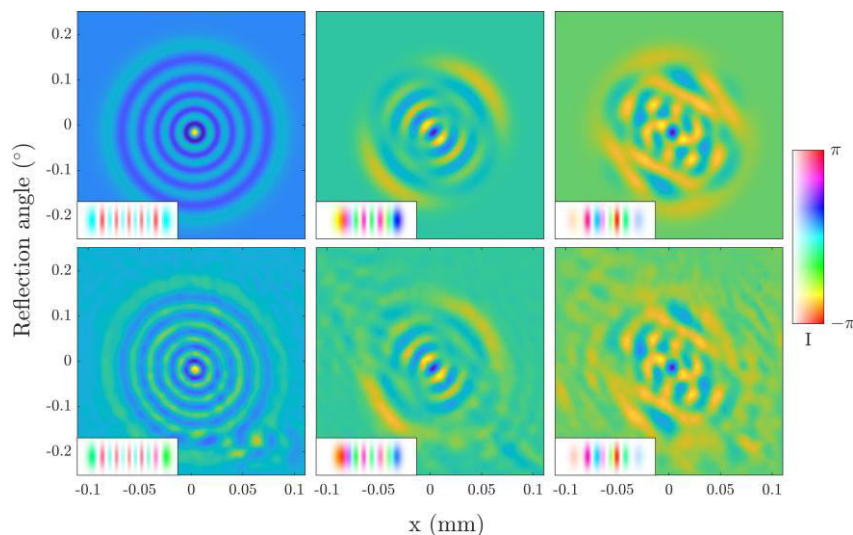


Figure 1. Theoretical (Top) and Experimental (Bottom) Wigner functions. Inset depict the corresponding fields.

The proposed technique can reconstruct arbitrary partially coherent 2D fields, but due to experimental challenges we focus on 1D fields. Fig.(1) shows the experimentally reconstructed Wigner functions and fields for different mode superpositions.

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Polarization-Resolved Interferometric Chiral Sensing with Geometric Phase Metasurfaces

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Structured light generated by metasurfaces provides powerful control over phase and polarization, yet its application in chiral sensing remains relatively unexplored, particularly in interferometric schemes. While vortex beams carrying orbital angular momentum have been used to probe chirality, polarization-resolved interferometric approaches offer additional sensitivity and insight. Here, we demonstrate a chiral sensing framework based on a geometric phase gradient metasurface with spatially varying anisotropic nanostructures. Under circularly polarized illumination (Fig. 1(a)), the metasurface generates a spin-dependent, spatially shifted vortex beam in the Fourier plane (Fig. 1(b)). Using a Mach–Zehnder interferometer, the metasurface-modulated beam interferes with a reference Gaussian beam. Although no interference is observed in total intensity due to orthogonal polarization states, polarization-resolved Stokes parameters (S_1, S_2), and the subsequent extracted rotation vector reveal fork-like fringe patterns (Fig. 1(c)) with a central polarization singularity (Fig. 1(d)). We show that opposite chiral enantiomers induce phase shifts that lead to measurable rotation and displacement of this singularity (Fig. 1(d)). This approach establishes a polarization-structured interferometric platform for sensitive chiral detection, combining metasurface-enabled structured light with Stokes polarimetry.

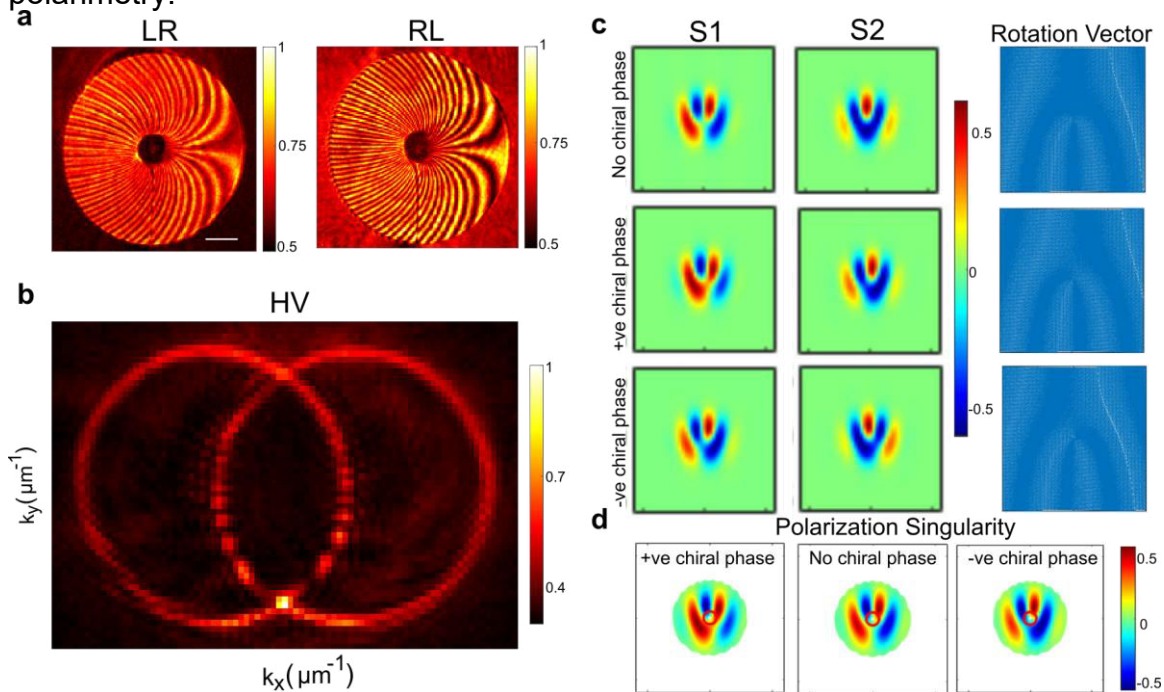


Fig. 1 (a) Cross polarized images of a phase gradient metasurface (scale bar $7\mu m$) shows the spatially varying anisotropic axis leading to the frequency shifted vortex generation in the Fourier plane (b) (C) Calculated polarization-resolved Stokes parameters S_1, S_2 , along with the corresponding rotation vector fields, shown for three cases: no chiral phase, positive chiral phase, and negative chiral phase. (d) Corresponding polarization singularity exhibits spatial shift for opposite chiral phases.

Linking momentum-space topology with position-space wave fields

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The success of topology in physics is based on its ability to describe complicated, intractable physical systems by simple quantities, the topological invariants. These topological invariants are integer-valued and will not change under continuous deformations, making them highly interesting candidates for robust technological applications.

Topology, however, relies on a compact base manifold. For infinitely extending wave fields that naturally occur in optics and hydrodynamics, a global real-space topological classification is generally well-defined only if the real-space can be compactified.

This can either be achieved by utilizing a spatial periodicity or by requiring the field to approach a uniform background at infinity.

Here, we show how one can use a momentum-space linking number to classify infinitely extending two-dimensional wave fields without requiring a compact base in real-space. Spin-momentum locked surface wave fields, such as capillary-gravity water waves (CGW) and surface plasmon polaritons (SPP), offer an ideal testbed, spanning multiple orders of magnitude in temporal and spatial scales. While time-resolved polarimetric photoemission electron microscopy (1) and near-field scanning optical microscopy (2) give direct access to the electric field vectors of SPPs, a 3D-printed water wave experiment allows for the reconstruction of CGWs by fast checkerboard decomposition (3). These experiments directly reveal the discrete transition between distinct topological sectors in modes carrying fractional orbital angular momentum, and their robustness against spatial deformations. An extension of the linking number to discrete momentum-spaces allows us to classify periodic and aperiodic fields in real-space, such as plasmonic quasicrystals (4). A connection between the momentum space linking number and the global vortex charge in position space is observed, showing the relation between topology in both spaces.

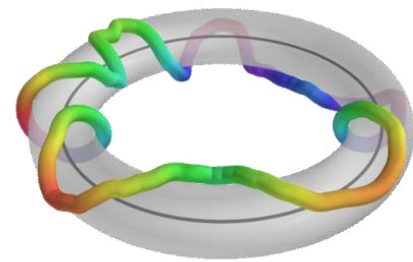


Figure 1: Momentum Space Linking Number. The phasor trajectory winds along the ring in momentum space linking with the ring.

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High-order Harmonic Generation driven by Vector Necklace Beams

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High-order harmonic generation (HHG) is a highly non-linear optical and parametric process which has been shown to possess the great advantage of conserving and up-converting various properties of light such as energy, linear momentum, orbital angular momentum (OAM), spin angular momentum (SAM), and even the linear combination of OAM and SAM, i.e., generalised angular momentum (GAM) [1]. By adjusting the SAM and OAM of the driving field, it has been both theoretically [2] and experimentally shown [3] that we can tune the SAM and OAM of high-order harmonics via their combined conservation.

According to Noether's theorem, a conserved quantity appears as a result of a continuous symmetry within a given system. The conservation and up-conversion of GAM during the process of HHG therefore requires the driving GAM field to be invariant under a particular kind of symmetric transformation defined in [4] as a coordinated rotation along the propagation axis. This involves a rotation of the spatial dependence by an angle ϕ , followed by a rotation of the polarization vector by a fraction $\gamma\phi$ of that angle.

In the context of a continuous symmetry, GAM light fields are invariant under coordinated rotations of any real-valued angle ϕ . However, in the case of a *discrete* symmetry, the specific values that the angle ϕ can take will be restricted. For instance, a necklace-shaped beam in both intensity (see Figure 1) and phase is only invariant under rotations that are multiples of $2\pi/N$ with N the number of necklace lobes. Generating high-order harmonics using beams with discrete symmetries was first attempted in [5] which demonstrated their ability to tune the line-spacing and divergence properties of the harmonics generated.

In this work, we explore the possibility of combining all of these degrees of freedom when designing the structure of harmonic fields and consequently XUV pulses, i.e., SAM, OAM, line-spacing and divergence, by driving HHG using vector necklace beams which possess both GAM and a discrete symmetry in their transverse intensity and phase profiles.

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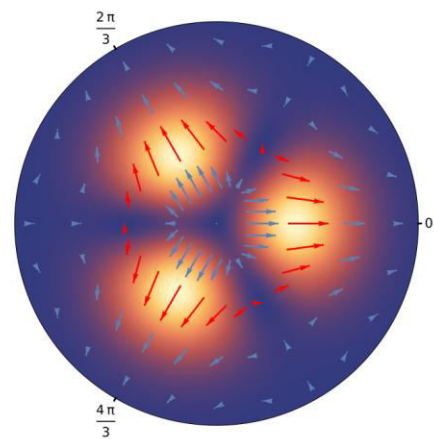


Figure 1: Example of the transverse intensity profile of a vector necklace beam with three lobes ($N=3$) with varying linear polarisation orientations across the transverse plane arising from its GAM content.

Unraveling the rich topological tapestry hidden within high-dimensional entanglement

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Optical skyrmionic topology has attracted strong interest as a robust resource for information encoding and processing, even in noisy environments [1]. In recent years, we showed that skyrmionic topology can arise as a joint property of entangled photons, as depicted in Fig. 1 a, revealing its potential as a nonlocal resource distributable over large distances even when entanglement is fragile [2, 3]. Here, we extend this framework beyond 2D spin-orbit systems to arbitrary degrees of freedom and high-dimensional states, as shown in Fig. 1 b, using OAM-OAM entangled states as an exemplary platform [4]. We identify multiple skyrmionic topologies within 2D subspaces, with corresponding skyrmion numbers shown in Fig. 1 c. Beyond 2D states, we uncover a rich landscape of topological structures within high-dimensional states derived from mappings between a reference two-sphere and submanifolds of the state space, revealing new mapping structures such as the disk-to-disk map depicted in Fig. 1 d. This enables a classification of high-dimensional quantum states through a spectrum of topological invariants that scales with dimension, with a topological spectrum for an example 3D state shown in Fig. 1 e. Notably, by separating trivial and nontrivial spectrum components, this framework offers both robustness to perturbations and sensitivity to them, providing a powerful tool for quantum diagnostics and encoding. Overall, it opens new avenues for topology-based quantum sensing and communication across diverse photonic systems.

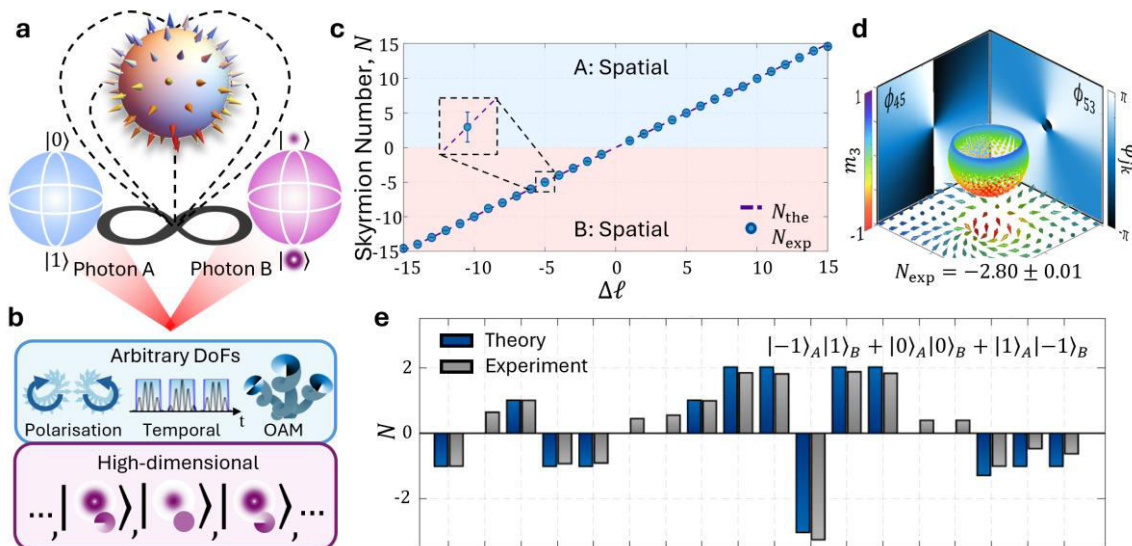


Figure 1: a, Non-local topology derived from entangled photonic states with tunable b, degrees of freedom and dimensionality. c, Skyrmion numbers for 2D OAM–OAM states. d, Mapping structure example and e, topological spectrum for 3D state.

Unveiling van Cittert-Zernike theorem in nonlinear optics

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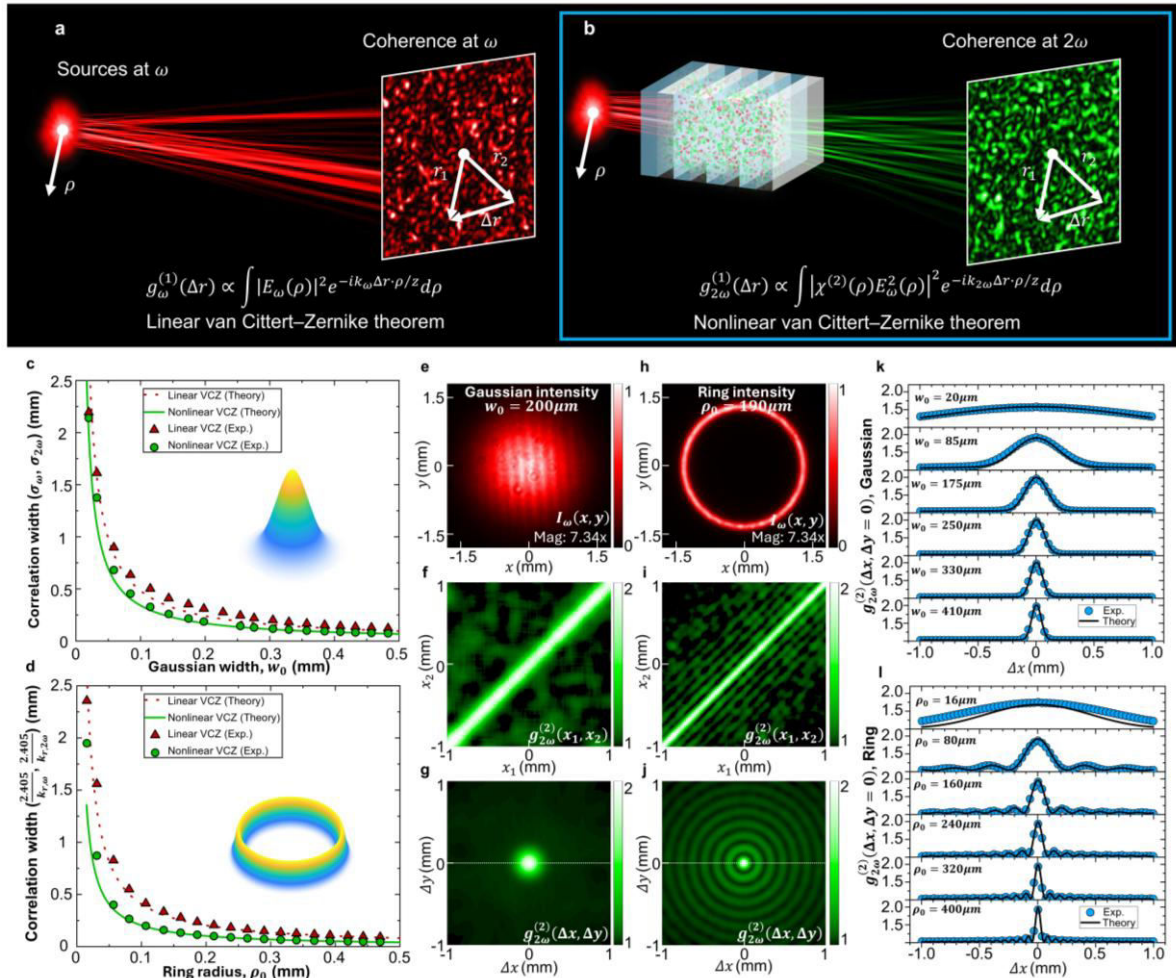


Fig. 1. Schematic of the van Cittert-Zernike theorem (VCZ) in (a) linear and (b) nonlinear optics. (c)-(l) Theoretical and experimental results for observing the VCZ theorem in nonlinear optics.

The VCZ theorem (Fig. 1(a)) underpins classical stellar interferometry and historically inspired the Hanbury Brown-Twiss interferometer in modern quantum optics [1]. In parallel, nonlinear optics has recently emerged as a powerful platform for engineering not only intensity and phase, but also the coherence of light [2]. Here, we experimentally establish a nonlinear extension of the VCZ theorem (Fig. 1(b)), unveiling a direct mapping between near-field source intensity at the fundamental and far-field coherence at the second harmonic (Figs. 1(c)-1(l)).

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Interaction of twisted light with free atoms

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We theoretically investigate the interaction between photons carrying orbital angular momentum (OAM) and atoms in free space. In contrast to conventional approaches based on plane waves, both the photon and the atom are treated as fully localized wave packets, and the motion of the atomic center of mass (CM) is included explicitly. The theory is formulated within second-order perturbation theory for nonrelativistic atomic velocities and yields the amplitudes of photon absorption and resonant scattering. Observable quantities are characterized through probabilities and generalized cross sections.

This framework reveals several effects that are absent when both particles are described by plane waves. The finite coherence length of the photonic packet leads to broadening of absorption and scattering lines, while the nonparaxial structure of vortex photons produces asymmetric spectral profiles. We also find a coherent recoil of the atomic packet, including the “superkick” effect [1], where the transferred momentum can exceed the photon momentum. In addition, the longitudinal structure of the photon wave packet can lead to a splitting of resonant peaks.

The main result is the transfer of OAM from the twisted photon to the atomic CM through the photon absorption [2]. This process arises from modified selection rules when the CM motion is included. For dipole transitions in a head-on collision geometry, the most probable OAM transferred to the atomic CM coincides with the photonic OAM. The resonant cross section of this process shows a weak dependence on the photonic OAM, suggesting a highly efficient mechanism for generating vortex atomic states. This provides a generation scheme complementary to the experimental production of vortex atomic beams using nanofabricated diffraction gratings [3]. We also examine the influence of a non-zero collision impact parameter on OAM transfer and establish the criteria for the stable generation of vortex atoms.

The work was carried out with the support of the Russian Science Foundation Grant No. 23-62-10026.

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Left-handed transverse spin vortices in plasmonic nanogaps

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The spin angular momentum of light has long been exclusively linked to the polarisation ellipticity of plane waves and paraxial beams. Due to the transverse nature of those electromagnetic waves, the spin angular momentum of light was thought to be only longitudinal, i.e., colinear to the wavevector. However, recent studies have highlighted the existence of transverse spin carried by structured light and evanescent waves [1]. From considerations on evanescent waves excited at material interfaces (surface plasmon polaritons, evanescent tail of guided modes, etc.), it was shown that a universal right-handed spin-momentum locking effect governs the direction of the transverse spin with regards to the direction of the wavevector [2,3]. The same rule was found to hold for focussed light beams [1,4], even in the case of unpolarized beams [5].

In this work [6], we study the emergence of transverse spin vortices around nanogaps formed by two plasmonic nanoresonators when two different unsynchronized modes interfere. We show that localised oscillating charges on both sides of the nanogap can create a much-localised momentum flow surrounded by a transverse spin vortex. Importantly, the rotation direction of this transverse spin vortex follows a left-handed spin-momentum locking. We show how this breakdown of the right-handed spin-momentum locking rule relates to the transport of saddle-point singularities in the nanogap.

Extending this concept to plasmonic multimer nanoantennas [7,8], we prove that transverse spin textures with toroidal vortex-like topologies can be created in the vicinity of plasmonic nanogaps formed by at least three coupled plasmonic nanoresonators. Nanoscale electric field spin skyrmions can therefore be created a few nanometres above or below the nanogap of plasmonic multimer nanoantennas. Our results provide new perspectives to study the interactions between nanostructured light and nanomaterials.

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Optical Singularities in Turbulent Media: Phase–Polarization Equivalence

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Optical topologies are often organized around localized singularities in phase or polarization that generate extended structures during three-dimensional propagation. Since the early studies of wave dislocations, the behavior of these defects in complex media has remained debated, particularly regarding whether phase and polarization vortices exhibit different resilience when the optical field is randomly distorted [1,2]. Here, we address this question in atmospheric turbulence, used as a controlled model of a complex propagation channel.

We describe turbulence as a one-sided complex operator acting on the transverse spatial degree of freedom while leaving the polarization basis unchanged [3]. For a vector field composed of Laguerre-Gaussian (LG) and Gaussian modes in orthogonal polarizations, singular properties extracted from the Stokes field are constrained to the zeros of the structured component. This implies that, under the same channel realization, polarization and phase vortices share equal wandering statistics. We further evaluate this theoretical prediction in matched simulations and experiments. Figure 1 (a,b) illustrate examples of the singularity distribution map and distorted complex fields for various turbulence strengths and topological charge $\ell = 1$. Figure 1 (c) presents a direct comparison across all conditions between the polarization- and phase-based positional spreads, yielding a linear relation with experimental (theoretical) slope of 0.8291 ± 0.0458 (0.9971 ± 0.0190). These results demonstrate that, in non-birefringent turbulent channels, phase and polarization vortices exhibit comparable behavior, supporting a unified description of their dynamics in complex media.

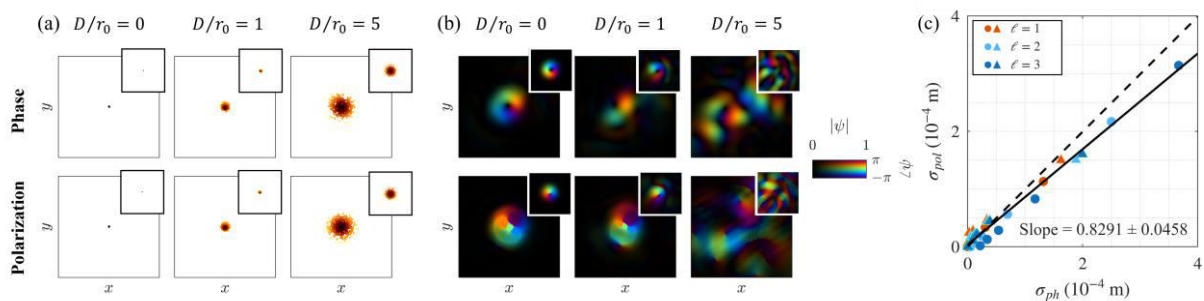


Figure 1. (a) Singularity distribution map and (b) complex fields of phase and polarization vortices for various turbulence strengths D/r_0 and $\ell = 1$, with experiments shown in the larger distribution and theory in the inset. (c) Experimentally measured positional deviation radius for both vortices (σ_{ph} , σ_{pol}) generated using LG modes with uncorrected (circles) and corrected (triangles) beam waist and $\ell = 1, 2, 3$.

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A nonlinear optical chirality for high-harmonic generation

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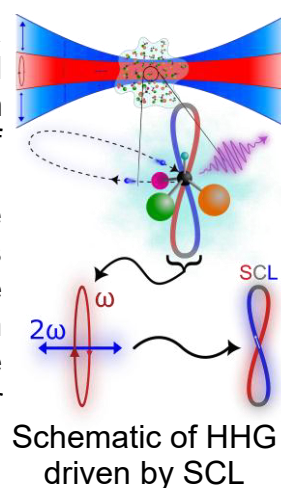
Chiral light-matter interactions hold enormous potential, as they allow us to access the full scope of chemistry – without restriction to the small set of symmetric achiral molecules – using photo-driven processes. In order for light-matter interactions to be chirally sensitive, the light itself needs to be chiral. Thus, the quantification of the chirality of an optical field has been a long-standing goal.

For linear optics, optical chirality [1] and optical helicity [2] capture all chiral interactions, and have been the subject of intensive study, including their conservation properties, optical singularities, and interactions with matter.

For nonlinear optics, the discovery of giant enantiosensitivity in high-harmonic generation (HHG) [3] has sparked an explosion in applications of synthetic chiral light (SCL) – multi-colour combinations whose electric-field Lissajous figures are chiral over time – to drive chiral processes. It has also prompted the creation of nonlinear chiral correlation functions [3], which encode the chirality of the light field in a way which captures the dynamics involved in few-photon nonlinear processes.

However, the existing nonlinear measures of field chirality are only directly applicable to few-photon nonlinear processes of perturbative nature, and, as such, they do not have any direct bearing on HHG or other nonperturbative processes. This raises the need, therefore, of a nonlinear optical chirality which does capture the nonperturbative dynamics involved in HHG and its sibling processes, and which can explain the mechanisms that underlie HHG driven by SCL as well as help design new experiments that fully harness its power.

Here we present such a nonlinear optical chirality, through a suitable orientation-averaging procedure applied to the universal expression for HHG provided by the strong-field approximation (SFA) [4]. This orientation averaging respects the usual form of the SFA, with a new prefactor, which fully captures the chiral (and achiral) geometric and structural responses of the molecule to the dynamical forcing provided by the driving field. This reveals the dynamical mechanisms that underlie enantiosensitive HHG, and allows clean and powerful ways to tailor chiral fields in order to maximize their chiral selectivity – and it also opens the door to experiments that can shape this novel extreme-nonlinear optical chirality in both time and space.



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Structured near-field spatial correlations of entangled photons

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Abstract: Structure in correlations are useful in applications like imaging. Classical structured light demonstrates enhanced resolution by beating the Rayleigh limit [1]. In the quantum regime, structured correlations offer noise robustness and improved signal-to-noise ratio in coincidence imaging [2]. Therefore, it is natural to expect that structured position-momentum entangled two-photon fields can push the boundaries of quantum imaging and microscopy even further beyond. The existing experimental schemes can produce either structured two-photon fields without position-momentum entanglement, or position-momentum entangled two-photon fields without structured correlations. Spontaneous parametric down-conversion is a process used to generate entangled photons having strong correlations simultaneously in position and momentum bases [3]. Our work structures these correlations in the near-field regime where entanglement is readily observed.

Results: The experimental scheme involves recording millions of intensity profiles and extracting the correlation structure from them, as described in [4]. Our results are presented in Fig. 1 below:

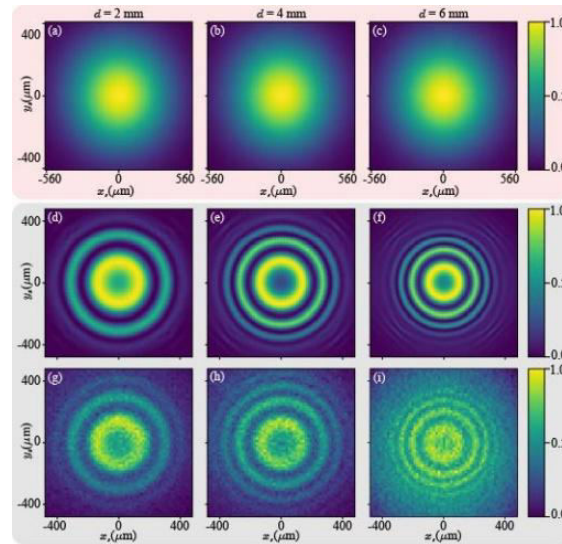


Fig. 1: (a)-(c): Theoretical single photon intensity recorded on the EMCCD camera remains a blob in the near field, irrespective of the phase-matching condition. (d)-(f): Theoretical conditional probability distribution for two-crystal setup for separation between crystals $d = 2, 4$ and 6 mm; (g)-(i): corresponding experimental results.

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Noise-resilient imaging through coherence filtering

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Noise is a fundamental barrier in imaging, often requiring prior noise characterization or complex quantum illumination. We present a coherence-based distillation approach that separates object from noise by leveraging differences in their temporal coherence. Our protocol reconstructs images by measuring the spatial coherence of optical field while simultaneously filtering noise through a controlled interferometric path-length delay set to be longer than the noise coherence length but shorter than the object coherence length. This effectively suppresses noise interference while preserving the object's signal.

Experimentally, we achieve extreme noise rejection by successfully recovering feature-rich objects, such as QR codes and grayscale wheels, even when obscured by noise 20 times more intense than the signal. Our method remains effective even when the frequency spectra of object and noise field overlap, a regime where traditional spectral filtering fails. Furthermore, unlike quantum techniques that often require hours of acquisition, our protocol achieves high-fidelity reconstruction within minutes using standard LED-based illumination.

This framework offers a robust, reference-free, scalable solution for biological imaging, fluorescence microscopy and optical communication in extreme environments.

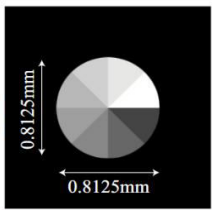
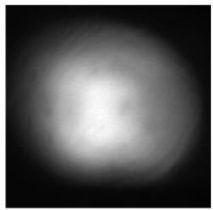
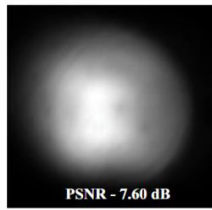
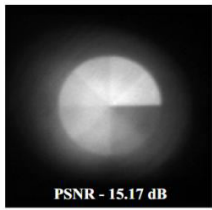
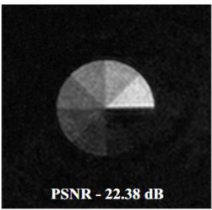
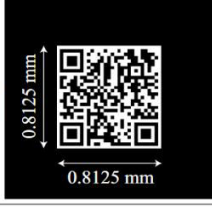
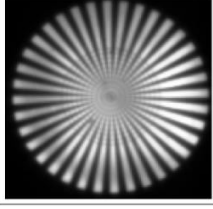
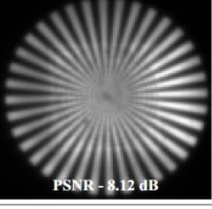
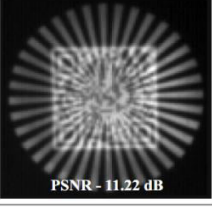
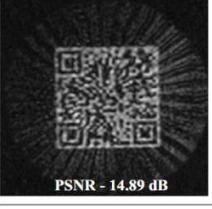
γ	Object	Noise	Intensity imaging	Spectral filtering	Temporal coherence filtering
1:15			 PSNR - 7.60 dB	 PSNR - 15.17 dB	 PSNR - 22.38 dB
1:20			 PSNR - 8.12 dB	 PSNR - 11.22 dB	 PSNR - 14.89 dB

Figure 1: Noise-resilient imaging with uniform and spatially structured noise. The parameter γ denotes the object-to-noise intensity ratio. Object illumination is centered at 633 nm with a 10-nm bandwidth, while noise is at 595 nm with a 90-nm bandwidth. Spectral filtering is performed using a 10-nm optical filter centered at 633 nm placed at the camera. While spectral filtering rejects only a portion of the noise, temporal coherence filtering significantly outperforms it, achieving superior contrast and higher peak signal-to-noise ratios (PSNR).

Polarization-based information encoding utilizing partially polarized vector beams

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The presented research demonstrates an information-encoding solution in which the engineered partially polarized vector beam maps transverse spatial coordinates to polarization states tracing a parametric curve within the equatorial disk of the Poincaré sphere. Hidden information is retrieved by applying a spatial mask that is derived from this parametric curve, and serving as a decoding key, followed by spatially resolved polarization analysis (Fig. 1). The scheme is validated through numerical simulations and experiments using multiple shapes as exemplary encoded information.

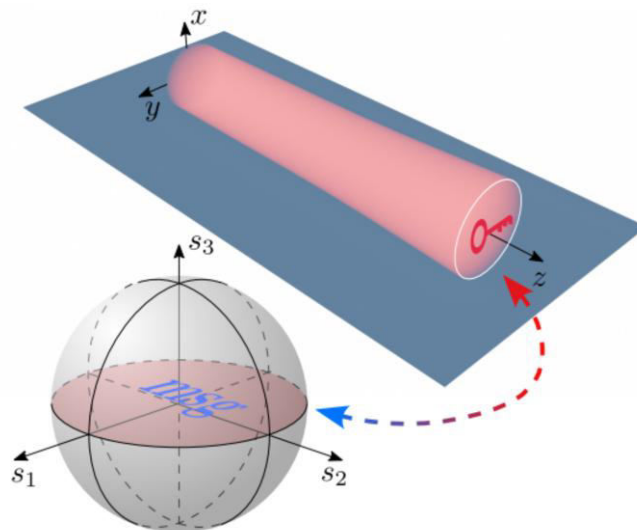


Fig. 1. Visualisation of the polarization-based information decoding with a spatial mask, which acts as a key applied in the transverse plane of the incoming field revealing the hidden information placed at the equatorial disk of the Poincaré sphere [1].

Funding:

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Nonlinear mixing of optical vortices to entangle photonic orbital angular moments

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The optical vortex carries an orbital angular momentum (OAM), which is a quantum variable of the photon; this is particularly interesting because, in principle, it can take on all relative integer values. Through nonlinear interaction, vortices can be combined to produce new, correlated vortices whose OAMs are entangled, or even multi-entangled. The specific nonlinear process employed and the class of vortices used determine the properties of the entangled OAMs, particularly those of OAM pairs in the case of a four-wave mixing.

We present a study which demonstrates the advantages of perfect vortices [1] over the usual Laguerre-Gauss modes in this context [2].

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Vector Talbot carpets: Polarization-structured self-imaging

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Nearly two centuries after Henry Fox Talbot's original observation of self-imaging, the effect that bears his name continues to attract significant interest due to the rich phenomena arising from different types of periodic structures across a wide range of wave systems, including angular [1], nonlinear [2], and plasmonic Talbot effects [3].

In parallel, full Poincaré beams (FPBs), introduced in 2010 [4], are structured vector beams whose transverse polarization distribution spans the entire Poincaré sphere. This polarization field can be mapped onto the surface of the sphere, and its topological properties are preserved upon propagation. Moreover, FPBs constitute optical skyrmions when the spatial distribution of their normalized Stokes vector defines a continuous mapping onto the Poincaré sphere with nonzero topological charge.

Here, we investigate theoretically and experimentally the formation of Talbot carpets generated by periodic vector fields. We consider different initial configurations, with particular emphasis on arrays of full Poincaré beams and skyrmion lattices [5,6]. Their near-field propagation is analyzed to characterize the Talbot self-imaging process, including the evolution of both intensity and polarization distributions at integer and fractional Talbot distances.

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Structured Light Fields and Atomic Magnetometers

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Absorption profile of the structured light upon interaction with atomic medium carries distinct signatures of external magnetic field vector. For example, symmetrical flower-like pattern appears with dark and bright petals for vector beam [1, 2] and in the case of Poincaré beam, we see asymmetrical absorption profile [3]. This absorption profile later can be utilized to determine strength, alignment, and also frequency of the (oscillating) magnetic field. However, for anti-parallel magnetic field vectors of equal magnitude, the absorption profile appears visually indistinguishable. In this contribution, we present theoretical analysis to overcome this limitation by obtaining absorption profile for vector light in the presence of reference and test magnetic fields. This analysis reveals a one-to-one correspondence between the magnetic field properties and the profile's contrast and rotational angle, see Fig.1 [4]. Our findings open an avenue to design an optical vector atomic magnetometer based on structured light fields.

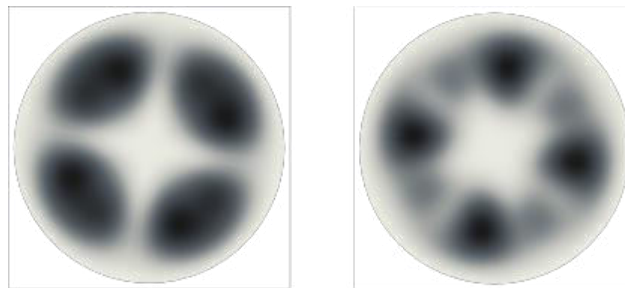


Fig 1. Absorption profile of vector light beam for (Left) positive and (Right) negative 3D magnetic field of equal magnitude in the presence of a reference magnetic field. The dark region corresponds to maximum absorption of vector light by atoms.

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Stochastic Spatial Light Modulator pixel partitioning as a programmable coherent beam splitter

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Measuring phase evolutions as a function of driving beam parameters in highly nonlinear processes remains a challenge. Ideally, one would generate two spatially separated coherent beams, perturb only one, and extract the phase from spatial interference fringes while keeping the reference source unchanged. We present a spatial light modulator (SLM) scheme that achieves this function within a common optical path, splitting a single laser beam into two phase-locked foci with continuously adjustable relative intensities. The method relies on a stochastic partitioning of the SLM pixels into two complementary subsets, each displaying a linear phase gradient that steers light toward a distinct position in the focal plane. Unlike periodic checkerboard approaches [1], which enforce a fixed 50/50 intensity distribution and produce localized parasitic diffraction orders, the random assignment allows the partition fraction to be tuned freely while redistributing scattered light into a diffuse speckle background, readily washed out by the nonlinear process under investigation, preserving clean focal spot profiles. To achieve independent intensity control of each focus, we label the two target beams A and B, with intensities I_A and I_B . Within each partition, a tunable sub-fraction of patches is redirected along a transverse direction orthogonal to the two-source axis, forming dump beams A' and B' respectively, thereby removing light from the corresponding main focus without affecting the other (Fig. 1a,b). We define the dump fraction α as the proportion of partition A redirected into A', so that $I_A/I_B = 1 - \alpha$ when no dump is applied to B. Scanning α from 0 to 1 thus varies the intensity ratio linearly from unity to near zero, as confirmed experimentally (Fig. 1c). This scheme provides a compact, vibration-insensitive and fully programmable multi-output beam splitter, applicable to settings requiring dynamic control over multiple coherent beams such as optical trapping, or nonlinear optics with structured beams.

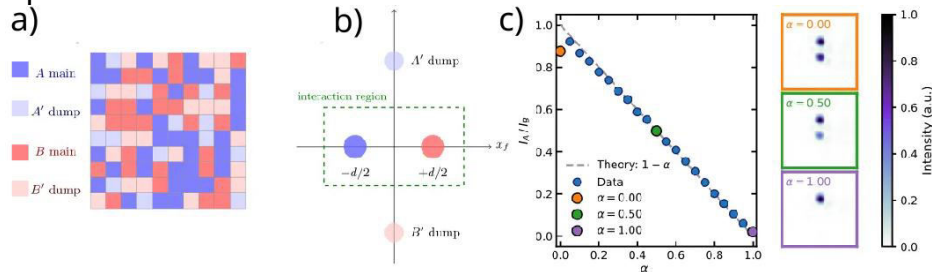


Fig. 1 — (a) Four-channel stochastic SLM mask. (b) Main foci A, B separated along the horizontal axis, dump beams A', B' deflected along the vertical axis. (c) Measured intensity ratio I_A/I_B vs. dump fraction α , with experimental focal-plane images for three values of α .

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Raman interaction with vortex beams in trapped ions

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Light beams carrying Orbital Angular Momentum excite electronic and motional transitions of trapped atoms, thus being interesting for quantum optics, sensing and information processing. Trapped ions feature a perfect preparation of quantum states including the electronic and motional degrees of freedom. Their wave packet can be positioned in the center of a focused vortex beam, and the transfer of optical orbital angular momentum to the bound electron has been demonstrated [1].

Presently, we investigate the effect of vortex light in a Raman transition, thus a genuine two-photon excitation scheme. We use two beams with different orbital angular momentum and employ near-resonant radiation to the dipole transition $S_{1/2}$ to $P_{1/2}$ at 397nm to excite trapped calcium ions. Now, the combination of orbital and spin angular momentum in combination with the direction of magnetic quantization axis and both k -vectors is conjectured to determine the electronic and motional excitation. We report on the Raman spectra for a single ion to present our recent progress on vortex topological algebra.

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OCAM or how to generate high-quality, super-stable vector beams

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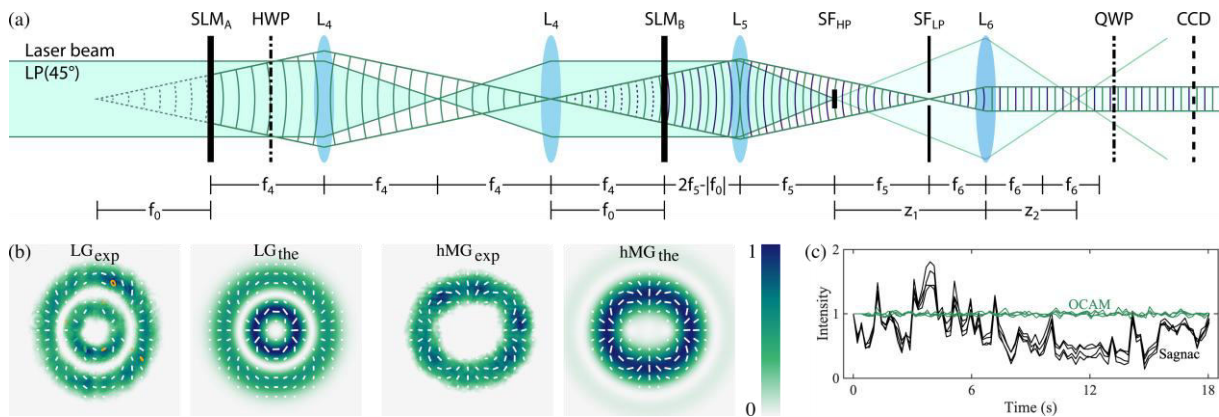
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We present OCAM [1], a method for generating complex vector beams that couples complex amplitude modulation (CAM) and on-axis modulation. Although for years these techniques were believed to be incompatible, we demonstrated that it is possible to incorporate their distinctive advantages into a single method. Our approach (Fig. 1a) is based on 3 key ideas: 1) using the grating in the hologram to redirect the unwanted unmodulated light to the first diffraction order, instead of the desired structured beam (which in our case we send co-axially with the zeroth order); 2) adding a digital lens to the hologram to spatially separate the focal planes of the desired beam and the zeroth order, and; 3) physically filtering out any remnants of the zeroth order. We visually evaluated the quality of our produced vector beams using Stokes Polarimetry (Fig. 1b) and found great similarities between experiment and theory, as well as demonstrated that our method produces more stable vector beams than a Sagnac-based interferometric approach [2] (Fig. 1c). As such, OCAM provides complex vector beams



with high accuracy and time stability.

Fig. 1. (a) OCAM concept sketch: (b) State of polarization distribution overlapping the intensity profile for two examples (Laguerre-Gauss and helical Mathieu-Gauss vector modes) of experimentally generated beams and their theoretical counterparts. (c) Comparison over time of the normalized intensity of the projection on linear polarization when using OCAM and a Sagnac-based interferometric method.

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Topology of Complex Vector Beams

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Structured light beams with space-variant polarization can be efficiently generated using voltage-tunable nematic liquid-crystal Q-plates [1]. By appropriately selecting the input polarization state and the Q-plate retardation one can generate the complex vector beams, such beams acquires a spatially structured polarization distribution capable of encoding non-trivial topological information across the beam profile. These hidden topological features can be revealed through interaction with plasmonic nanostructures, such as circular and spiral slits. Upon illumination, polarization-dependent excitation of surface plasmons converts the underlying polarization topology into observable field distributions, including plasmonic vortices and characteristic interference patterns (see Fig. 1).

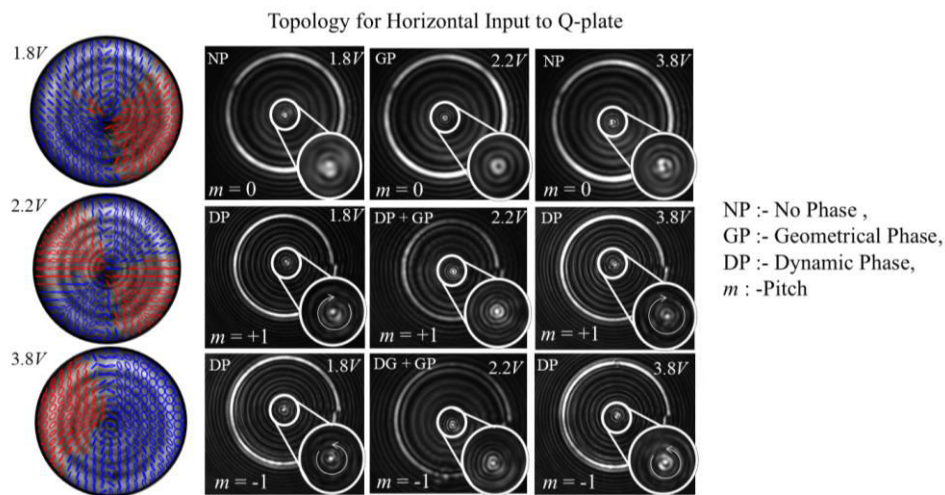


Figure 1: Hidden topological structure of the horizontal polarization incident beam on Q\$-plate revealed by a plasmonic circular slit.

The large freedom provided by the input polarization state, Q-plate retardation, and plasmonic geometry enables access to a wide variety of topological responses, ranging from bright central spots to higher-order plasmonic vortices and partial vortex formation. This flexibility allows systematic control over the generated plasmonic states without modifying the nanostructure itself, offering a compact and reconfigurable platform for topological light manipulation. Such controllable generation and detection of topologically structured beams is promising for applications in nanoscale photonics, optical information encoding, polarization-controlled plasmonic routing, and on-chip optical manipulation.

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Spatial Mode Encoding for Quantum Key Distribution: From Hundreds to Thousands of Modes

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OAM has been investigated for use in quantum cryptography for many years now. A critical issue for this technology is the fast generation of OAM modes for quantum key distribution (QKD), but other spatial degrees of freedom are more controllable. We present a proof-of-principle high-dimensional QKD protocol utilizing the position and momentum entanglement of photon pairs[1]. This structured protocol exploits the fact that position and momentum form mutually unbiased bases, linked via a Fourier transform. One photon of the entangled pair is measured by the sender in a randomly chosen basis-either position or momentum-selected passively via a beam splitter. In this implementation, we achieve a photon information efficiency of 5.07 bits per photon using 90 spatial modes, and a maximum bit rate of 0.9 Kb/s with 361 modes.

To assess the scalability of this spatial-mode encoding scheme, we theoretically show that using a brighter entangled photon source along with next-generation single-photon cameras - featuring improved quantum efficiency, timing and spatial resolution - this approach could achieve 9 bits per photon at 2000 spatial modes, and a bit rate of over 700 Mb/s at 4400 modes while accounting for finite-key effects. These results quantify the opportunities and performance bounds of spatially encoded, entanglement-based QKD and provide a benchmark for future high-dimensional quantum communication systems. We believe these results can be extended in the future to enable the fast use of OAM entanglement as a resource in high dimensional QKD.

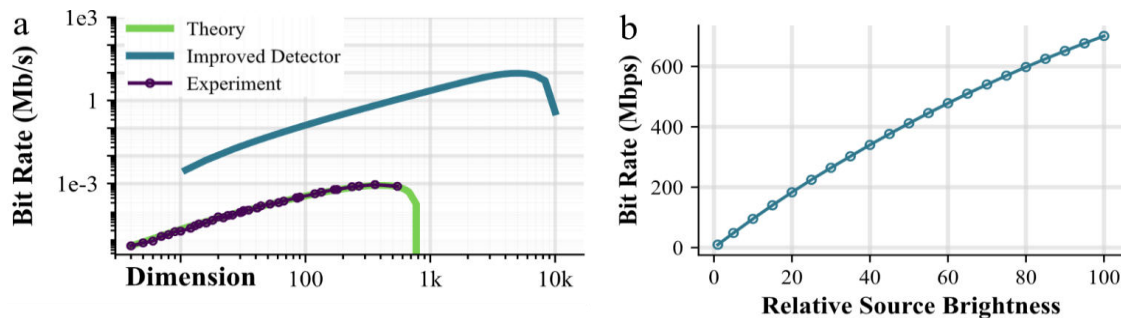


Figure 1: **Experimental and Theoretical Results.** **a)** Bit rate of QKD protocol using a position-entanglement spatial-mode QKD protocol. **b)** Theoretical results using an improved detector and source

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A Calibration of the Timepix3 Camera for Photon Correlations Imaging

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The ability to tailor photons in their degrees of freedom provides a powerful and versatile tool for both classical and quantum applications, including enhanced sensing, high-dimensional communication, and imaging [1].

In quantum experiments, structured photons are typically detected via time-correlated measurements [2-4], enabled by the recent development of time-tagging single-photon-sensitive cameras [5]. Among these, the Timepix3 (TPX3) camera stands out for its combined temporal and spatial resolution, making it a distinctive platform for photon-correlation measurements [6]. However, accurate reconstruction of photon coincidences critically depends on a homogeneous temporal response across the detector array.

Here, we demonstrate a pixel-resolved temporal calibration of an intensified TPX3 camera based on time-tagged coincidence measurements with an external single-photon reference detector which improves the overall timing performance of the system, thereby enhancing coincidence contrast.

The proposed calibration can be used for coincidence measurements with external detectors as well as for self-referenced analyses between different regions of the sensor, making it broadly applicable to quantum-optics experiments with structured light, including photon-correlation imaging, quantum interference, and multi-photon detection schemes.

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Tuning of topological properties enabled by surface phonon polaritonics: phonon polariton skyrmions, merons, and skyrmion bags

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Vector field textures, such as skyrmions, are extensively studied in optics and, in particular, plasmonics. However, their practical application has been limited by the lack of tunability between different topological properties.

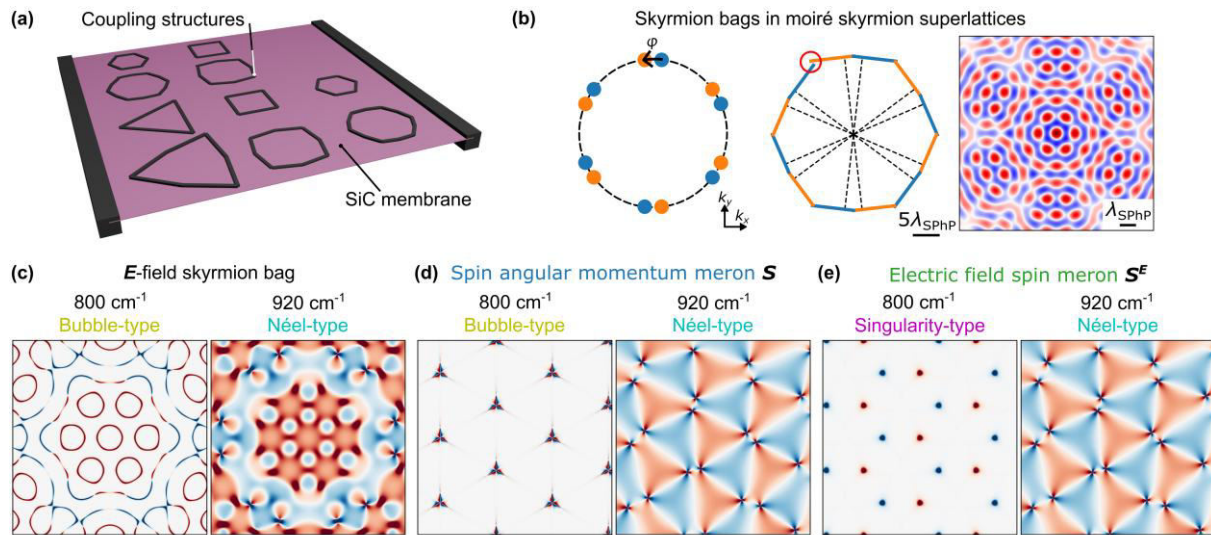


Fig. 1. a, Illustration of SiC membrane with coupling structures, which launch the SPhP waves. b, Fourier decomposition (left), coupling structure (center), and calculated out-of-plane electric field vector component of a skyrmion bag in a moiré skyrmion superlattice. (c-d), Skyrmion number density of three different topological vector textures at excitation wavenumbers of 800 cm⁻¹ and 900 cm⁻¹: (c) skyrmion bag in the electric field, (d) triangular meron lattice in the spin angular momentum, (e) triangular spin meron in the electric field spin.

Here, we present surface phonon polariton (SPhP) skyrmions, merons, and skyrmion bag vector textures on SiC membranes (Fig. 1a,b) and study the influence on their topology when tuning the excitation wavelength. We present simulation results on the bubble-to-Néel-type transition of topological vector textures appearing in the electric field and the spin angular momentum (Fig. 1c,d), and study singularity-type electric field spin merons (Fig. 1e) and the conservation of their topological charges in moiré lattices.

Our results broaden the tunability of topological textures in evanescent waves, which could be harnessed for next-generation photonic devices with applications in spin-optics, imaging, and topological and quantum technologies.

Controlling Solitons with Novel Vector Petal Beams

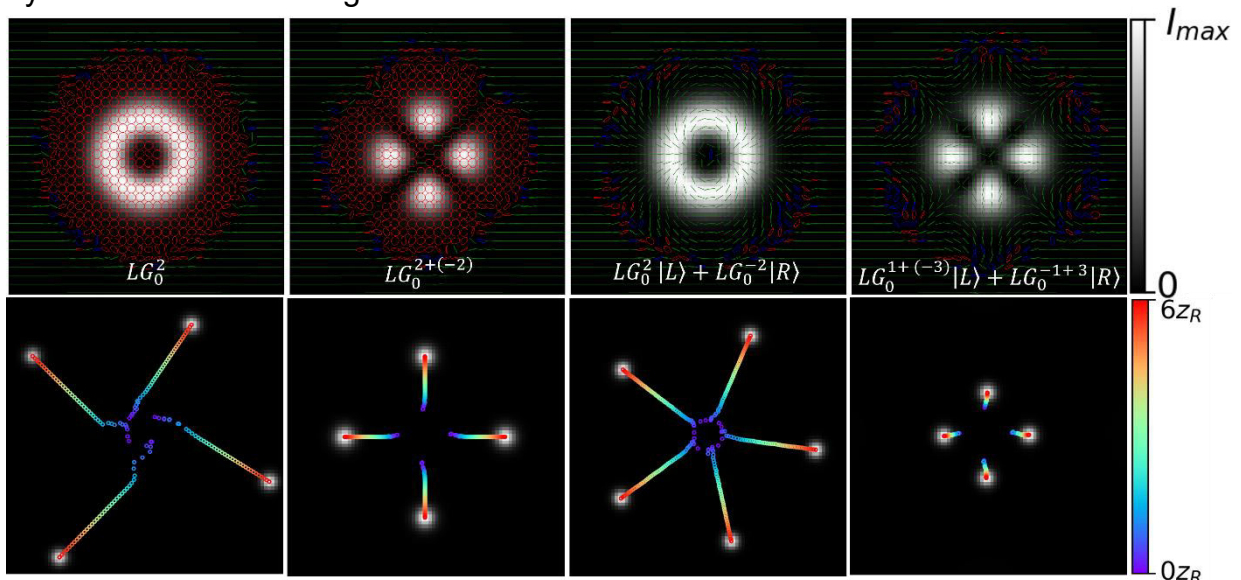
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Spatial solitons, (solitary wave packets formed from the balance of diffraction and self-focusing non-linearity) have long been of interest in communication and information systems. In recent years, however, there has been a renewed interest in the solitons that form when light carrying orbital angular momentum (OAM) propagates through a Kerr-like medium. Bouchard et al. [1] demonstrated the effect of polarization structure on soliton formation and, more recently, Henderson et al. demonstrated the formation of coupled light-ultracold atom solitons as a potential method to control atomic transport [2].

Here we investigate the use of novel petal beams resulting from the scalar superposition of two OAM beams to better control the number and velocity of the solitons formed. Unlike single scalar OAM beams which fragment into $2|\ell|$ solitons, where ℓ is the OAM of the beam [3], we have recently shown that our petal beams can produce any number of solitons. Moreover, we can design petal beams with different net OAM that each result in a fixed number of solitons but with very different trajectories. We now extend this to *vector* petal beams where, akin to cylindrical vector beams [1, 4], the orthogonal modes consist of OAM superpositions with equal but opposite *net* OAM. We will investigate how this affects both the stability and dynamics of the resulting solitons.



Top: Initial intensity and polarization distributions (red/blue corresponds to left/right-handed polarisation). Bottom: Propagation over 6 Rayleigh ranges (purple to red).

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Angular Super-resolution Imaging with light carrying OAM

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Super-resolution imaging refers to imaging techniques that surpass the Rayleigh resolution limit. One standard way to achieve super-resolution is by structuring the phase of the field illuminating the object. Although super-resolution techniques are already employed in commercial imaging devices, intense research efforts continue to enhance the resolution even further. In this work, we show theoretically and experimentally that if the field illuminating the object is structured in the azimuthal coordinate—such as a field carrying orbital angular momentum (OAM)—the azimuthal features of the object can be imaged with enhanced imaging resolution. We demonstrate it with two objects, namely, an azimuthal double-slit and a Siemens star. We find that for a given azimuthal feature, there is an optimum OAM mode index of the illumination that gives the best imaging resolution. Super-resolution imaging of azimuthal feature can have important implications, especially for some biological objects that are known to have predominantly azimuthal features, such as centrosomes.

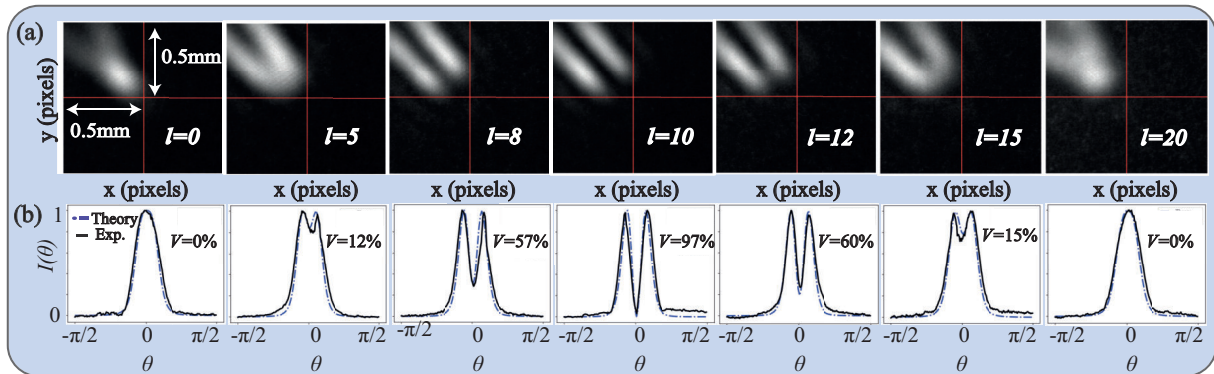


Fig. 1 Experimental results of angular super-resolution imaging with angular double slits

Here an angular double-slit object is illuminated with a phase-structured OAM beam, imaged through a 2f-2f system, and detected at the output. As shown in Fig. 1, increasing the OAM mode enhances resolution, reaching near-perfect visibility at $l=10$ for a slit separation of 0.1π . The resolution then decreases, approaching zero at $l=20$, revealing a periodic visibility behavior that depends on the object's structure.

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Spin Angular Momentum and Chirality in Optical Nanofibres: A Versatile Platform

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Optical nanofibres (ONFs) have become a powerful tool for studying light-matter interactions due to their strong evanescent fields extending from the fibre surface [1,2]. The vectorial and inhomogeneous nature of this evanescent field supports multiple components of spin angular momentum (SAM), including helicity-independent transverse SAM under the linear polarisation of the evanescent wave [3]. Hence, such structured fields can exert both radiation pressure and spin-dependent optical torques on nearby material objects [4], making ONFs an ideal system for exploring such optomechanical effects.

In this work, we experimentally demonstrate the mechanical effect of SAM generated by the evanescent field of an ONF on a single birefringent microparticle. A ~1 micrometer-sized birefringent particle was optically trapped using polarised optical tweezers and probed in close proximity to the nanofiber surface. Upon introducing a linearly polarised guided optical mode into the nanofibre and positioning the particle very near the fibre surface, we observed a significant enhancement (~40%) in the rotation of the trapped particle, indicating a strong contribution from the evanescent-field-induced SAM. Furthermore, we investigated the dependence of the rotation dynamics on key experimental parameters, including different input polarisation states of the guided beam, the particle-fiber separation, and various locations across the nanofiber. Additionally, by systematically varying the guided beam power and propagation direction, we explored the influence of power-dependent spin density and the role of spin-momentum locking. This study provides insight into the role of local transverse spin density, the gradient of the evanescent field, and light-induced chirality in determining the optical torque acting on the particle.

These results demonstrate a robust experimental approach for probing spin-dependent and spin-independent optical forces and torques at the nanoscale, offering new insight into angular momentum transfer in nanophotonic waveguides. The findings establish the versatility of optical nanofibres as a platform for optomechanics and studies of spin-orbit interaction of light in confined geometries. We further aim to extend our studies to interferometric sensing with potential applications in nanoscale force measurement, chiral light-matter interactions, and precision biosensing [5].

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Topological singularities of optical helicity in structured electromagnetic fields

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The spatial complexity of structured electromagnetic fields is encoded in topological singularities and textures: phase singularities scaffold the intensity distribution through optical vortices, while polarization singularities anchor skyrmionics textures [1,2]. We identify a new, hitherto unrecognised class of topological singularity native to generic chiroptical fields: simultaneous zeros of the two fundamental covariant invariants of Maxwell theory, the reactive energy density and the optical helicity density. These helicity singularities are generically isolated in any transverse cross-section of the field, carry a well-defined integer winding number, and provide a chiroptical scaffold that complements the established intensity and polarization skeletons.

The Beltrami decomposition of the electromagnetic field into helicity eigenstates [3] provides the natural framework for understanding the structure of generic chiroptical fields. Within this decomposition a precise complementarity emerges: the helicity density measures intensity imbalance between right- and left-circularly polarised sectors, while the imaginary Poynting vector captures cross-sector interference between them. A central analytical identity connects the curl of the imaginary Poynting vector to the gradient of the helicity density, with a correction term that is non-trivial in any structured superposition [4].

The helicity singularities obey topological conservation laws directly analogous to those governing optical vortices and polarization singularities. An index theorem constrains the total winding number to vanish on periodic domains, so singularities exist only in charge-neutral pairs that are created or annihilated together under smooth field deformations; in three dimensions they form oriented curves whose linking numbers are additional topological invariants.

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Generation and dynamics in external fields of twisted ions

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Twisted light and matter beams that carry well-defined orbital angular momentum (OAM) along their propagation direction have recently attracted significant attention because of their unique properties and wide range of applications. These beams are characterized by an annular intensity profile and a helical phase front. So far, most studies have focused on twisted photons and electrons. More recently, the concept has been extended to composite particles, and the first twisted atoms and even molecules have been demonstrated [1]. However, the generation of twisted ions has not yet been realized and remains an open challenge [2].

In this contribution, we discuss possible approaches to generate twisted ion beams and present the theoretical framework used to describe them. We pay special attention to the internal structure of the ions and its role during the generation process and during subsequent propagation. In addition, we study the dynamics of twisted ions in external electromagnetic fields.

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Beyond the Non-Diffraction Limit: Long-Range Hollow Beams with Tunable Longitudinal Fields

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The generation of longitudinal polarization in almost paraxial optical fields remains a central challenge in structured-light research [1]. We introduce a class of long-distance structured hollow beams that overcome fundamental limitations of conventional non-diffracting beams with hollow central core. Unlike Bessel-type or needle-type beams, whose non-diffracting range is constrained by aperture size and cone angle, our SLBs employ a tailored combination of optical aberrations that causes the intersection angle of wavefronts to decrease with propagation distance. This behavior arises from the self-intersection of the wave, in which axially symmetric regions carry oscillations of opposite phase shifted by π . As a result, the transverse beam profile remains preserved over arbitrarily long distances, effectively removing the classical bound on non-diffracting propagation. The divergence of the central hollow section is below $10\text{ }\mu\text{rad}$, which, for an initial core diameter of only $4\text{ }\mu\text{m}$, is nearly a thousand times smaller than the diffraction limit.

A distinctive property of these beams is the presence of non-zero electromagnetic fields inside the nominally dark hollow region. Although the Poynting vector vanishes, this region contains stored electromagnetic waves in the form of longitudinal electric and magnetic oscillations [2]. This counter-intuitive state—field without energy flow—creates an accessible domain absent in standard donut-type beams and enables independent control of the longitudinal electric and magnetic components [3,4]. The relative amplitudes and phases of these components can be tuned independently, providing a new degree of freedom for shaping the internal structure of non-paraxial fields.

To describe these configurations, we introduce a generalized 3D Jones formalism based on a vectorial phase triplet (ϕ_x, ϕ_y, ϕ_z) , which captures the full topological structure of non-paraxial polarization states. This framework extends the traditional 2D polarization description and offers a natural tool for analyzing complex 3D polarization distributions [5]. Finally, we present a practical generation method using a variable-thickness phase plate that imposes the required wavefront profile over depths of approximately fifteen wavelengths, providing an efficient and robust alternative to metasurfaces or digital modulation devices.

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Driving an atomic transition with longitudinally polarized light

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Vector light is usually studied in the paraxial regime, where all polarization can be considered to be a superposition of two orthogonal transverse polarization basis states. When light with a radial polarization component is focused, a portion of the electric field can become aligned with the propagation axis. This means it is possible to create light with a longitudinal polarization component [2]. So far, research on these three-dimensional polarization structures has largely occurred in the realm of theoretical physics, as conventional detectors do not pick up the longitudinal component [1].

We demonstrate that it is possible to drive an atomic transition with longitudinal light. Atomic transitions depend on the angular momentum transfer in the context of the magnetic field. The π transition with no angular momentum transfer is usually considered unavailable if the magnetic field is aligned with the propagation axis, as it is driven by light that is polarized along the propagation axis [3].

Using this principle, it is possible to spatially measure three-dimensional polarization structures. It can be shown that beams can have a spatially dependent longitudinal polarization component. This new degree of freedom in generating polarization structures and in atomic manipulation opens many avenues in the field of light-matter interaction. Applications relating to partial absorption and quantum sensing are being explored.

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Dark ray spot diagrams for aberration characterization

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The presented work studies the behavior of the singular point under manually introduced aberrations, utilizing the concept of off-axis optical vortex scanning, originally developed for microscopy [1], where the singularity served as an object scanner. It was further proposed as a marker of beam quality [2], indicating the presence or absence of aberrations. However, a reliable aberrometer requires not only quality assessment but also quantitative measures linking trajectories to specific aberrations. In [3], we showed that two perpendicular trajectories from x- and y-axis shifts exhibit unique responses to individual aberrations, enabling quantities sensitive to single Zernike polynomials and supporting an autofocus algorithm.

In this work, we extend this concept from two trajectories to a regular grid, mapping each singularity position from the vortex-generating element plane to the Fourier plane. This creates dark ray spot diagrams, where each "ray" is a phase singularity. This provides a new way to examine how aberrations affect optical systems. A key contribution is a machine-learning-based algorithm that directly locates phase singularities in intensity images with subpixel accuracy, eliminating the need for interferometric reference beams. Furthermore, an analytical framework was developed that exploits the geometric symmetry of the singularity point cloud for aberration classification and derives a quantitative polynomial mapping between the SPP and CCD planes.

We believe this work offers a new perspective on wavefront sensing and represents a significant step towards an aberrometer based on phase singularities.

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Ultra-sensitive tilt displacement measurements with structured light

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Precise measurement of angular tilt is critical in a wide range of applications, from advanced metrology to precision alignment and surface profile measurements. Optical techniques are particularly advantageous for angle measurements due to their non-contact nature, which is well suited for delicate or deformable components. In recent years, structured light—where properties such as amplitude, phase, or polarization are tailored in the transverse plane—has emerged as a powerful tool in optical metrology [1]. In this work, we propose a compact and ultra-sensitive method for measuring tilt displacements with structured light by harnessing the optical encoding concept of photonic gears [2]. The technique encodes angular tilt into the polarisation rotation of a collimated laser beam undergoing double passage through a polarisation grating. Using a low power laser source, we measured tilt displacements with a sensitivity of $290 \pm 18 \mu\text{W/mrad}$. The proposed approach provides excellent stability, compactness and ease of implementation, while relying on cost-effective optical elements. Our results may have a significant impact on research and industry, particularly in the development of advanced metrological systems.

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512-Fold Rotational Super-Resolution via Four-Photon High-Dimensional Structured Light

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Structured light enhances quantum information processing by combining quantum states of light and shaped wavefronts. However, until now, the advantages of high photon-number states and of high-dimensional structured light have only been demonstrated separately[1]. In this work, we report a rotation sensor that combines ℓ dimensional spatial modulation with four-photon quantum states, yielding a significantly improved angular resolution that scales as their product, $4 \times \ell$.

Our setup utilizes a spontaneous parametric down-conversion (SPDC) source to generate photon pairs and higher-order four-photon events. The photons pass through a pair of spiral phase plates (SPPs) with topological charges up to $\ell = 128$. By detecting the four-photon coincidence events using a very short coincidence window to minimize accidental coincidences, we isolated the super-resolved harmonic fringes. We implemented a PID feedback loop using high-rate two-photon N00N state detection for real-time phase stabilization, which allowed us to measure the rare four-photon events over extended periods.

By combining four-photon entanglement with very high-dimensional structured light, we demonstrated a 512-fold resolution enhancement. The minimum angular uncertainty achieved in our measurements was $\Delta\theta_{\{min\}} = 0.041^\circ$ for $\ell = 128$. This value is slightly below the corresponding classical shot-noise limit of 0.047° under Poissonian counting statistics, indicating sub-shot-noise sensitivity. Our work demonstrates the feasibility of combining high photon numbers ($N > 3$) and high-order spatial modes ($\ell \gg 1$) in a single system, opening new avenues in quantum sensing, communications, and quantum computing

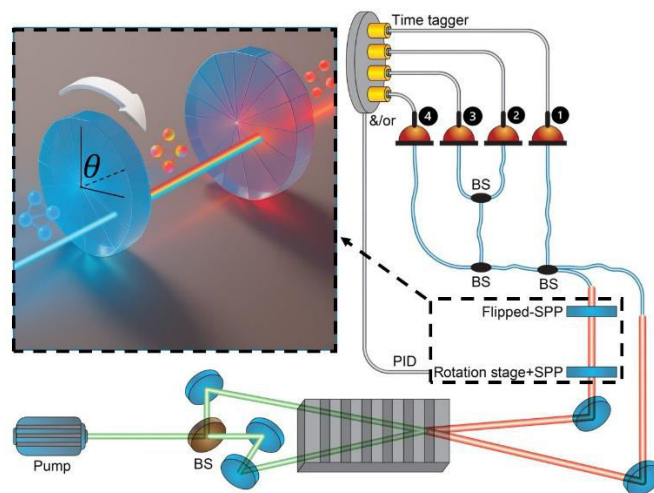


Figure 1: Experimental setup for 512-fold rotational super-resolution. A 532 nm laser pumps a PPKTP crystal to generate multi-photon states. The photons pass through a wavefront photonic gear consisting of opposite-charge spiral phase plates, converting mechanical rotation into a global phase shift.

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Multi-photon photoelectron helicoidal dichroism

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While the influence of the spin angular momentum (SAM) of light on photoelectron angular distributions has been extensively studied [1], the role of orbital angular momentum (OAM) in strong-field ionization remains largely unexplored. In a seminal publication, De Ninno et al. [2] reported that when helium atoms are ionized by a circularly polarized XUV pulse, in the presence of an IR field carrying OAM, the angular distribution of the emitted photoelectrons becomes sensitive to the sign of the OAM, showing photoelectron helicoidal dichroism (PEHD). So far, it was only observed in this direct photoionization regime.

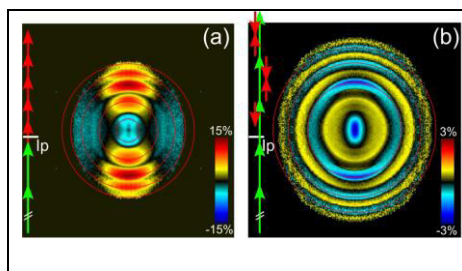


Figure 1. Normalised two-color PEHDs of ethanol acquired using femtosecond circularly polarized laser pulses. The signal corresponds to the normalized difference of photoelectron yields using identical circular polarization, SAM for both beams, and opposite OAMs ($m_{1030} = \pm 1$) for the $\lambda=1030$ nm beam. (a) Rydberg regime (b) ATI regime.

Using two-color multiphoton ionization and by varying the OAM and SAM of both beams, we observed that PEHD also appears in other ionization regimes. First, we used $\lambda=515$ nm pulses to excite Rydberg states of ethanol by absorption of 4 photons carrying SAM; and $\lambda=1030$ nm pulses carrying both SAM and OAM to ionize the excited molecules by absorption of 1 to 5 circularly polarized photons. We observed asymmetries of the order $\sim 10\%$ on this $4+n$ resonantly enhanced multiphoton ionization (Fig. 1), reflecting the non-dipolar character of the ionization from Rydberg states. Second, we increased the intensity of the $\lambda=515$ nm pulses to produce above-threshold ionization (ATI), and used weak $\lambda=1030$ nm pulses with OAM to induce continuum-continuum transitions, creating sidebands. We observed a $\sim 3\%$ HD at the sideband location, with opposite sign compared to the Rydberg ionization case.

These observations demonstrate the generality of PEHD, offering new insight into elementary light-matter processes beyond electric-dipole approximation, currently under modeling.

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Miniaturized OAM Modulated Transmission Method Based on Rydberg Atoms

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Over the past decade, orbital angular momentum (OAM) has emerged as a central theme across numerous research disciplines. However, the reliable identification of OAM at the microwave quantum scale remains challenges. This paper presents a miniaturized keying receiving system for vortex microwave quantum based on Rydberg atoms, aiming to achieve efficient identification and demodulation of OAM modes embedded in vortex electromagnetic waves. Leveraging the quantum electrodynamics framework [1], the proposed method exploits the electric quadrupole interaction between vortex microwave photons and Rydberg atoms to map OAM mode information onto characteristic splitting peaks in the electromagnetically induced transparency (EIT) spectrum [2]. This enables direct discrimination of OAM states and their conversion into binary bit sequences.

The proposed receiving architecture adopts a dual-path configuration: a conventional antenna path for signal power detection to assist in determining signal presence, and a Rydberg-atom-based path for high-precision OAM mode recognition. Signals from both paths are synchronously acquired by a data acquisition card and processed by a signal processing module, where cooperative decision-making significantly reduces misjudgment probability. In terms of mathematical modeling, based on the Lindblad–von Neumann equation and steady-state approximation, a quantitative relationship between EIT splitting interval and OAM mode is derived. Probabilistic models for mode misjudgment and signal existence misjudgment are established. Furthermore, using Bayes' theorem, an expression for the system misjudgment probability corrected by the antenna path is formulated.

Simulation results validate the superiority of the proposed dual-path architecture over single-path detection across the entire signal-to-noise ratio (SNR) range, with misjudgment probability reduced by more than 50%. Under high SNR conditions, the dual-path misjudgment probability reaches as low as 1.5×10^{-6} , an order of magnitude lower than that of the single-path scheme. The system also exhibits strong robustness against variations in EIT linewidth, transmission duty cycle, and antenna detection probability, demonstrating enhanced anti-interference capability especially in low-duty-cycle scenarios.

This study provides both theoretical foundations and practical implementation pathways for miniaturized reception of vortex microwave quantum signals, showing potential applications in quantum communications and radar detection. Future work will focus on system integration and experimental validation to facilitate engineering deployment.

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Measurement of the OAM of rotating vortex-lattices produced by an exciton-polariton condensate

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Exciton-polariton condensates can lead to a variety of pattern-forming behaviors, with the spontaneous formation of rotating vortex lattices among them (Fig 1). They are driven by the instability of high-angular-momentum modes in harmonically confined systems. Such non-stationary vortex lattices carry complex orbital angular momentum that is difficult to measure due to their rotation [1].

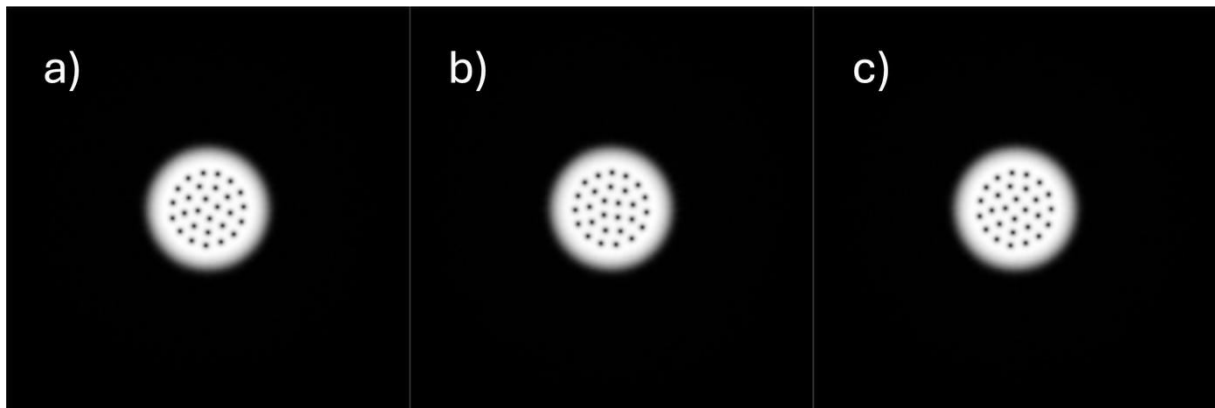


Fig. 1. Example of the vortex lattice with OAM = 28 at three different stages of rotation, corresponding to the recorded frames: (a), (b), and (c).

In this work, we present a testing platform that utilizes a spatial light modulator (SLM) to simulate the rotating vortex lattice. Further, we introduce a second SLM that analyzes the generated fields and provides an experimental tool to characterize its OAM content. The proposed method uses a Dammann vortex grating [2] and provides simultaneous multi-order OAM decomposition in a single measurement, taking advantage of the time-integrated nature of this technique.

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Excitation and Transmission of Electromagnetic Waves Carrying Orbital Angular Momentum in a Circular Waveguide

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Electromagnetic waves can carry both orbital angular momentum (OAM) and spin angular momentum (SAM). These two forms of angular momentum have significant potential in wireless communications and detection [1-3]. Meanwhile, waveguides constitute an important medium for electromagnetic wave transmission. Therefore, investigating the transmission characteristics of electromagnetic angular momentum in waveguides is of considerable importance. Reference [4] showed that the electromagnetic fields propagating in waveguides can carry both OAM and SAM, and that these quantities are related to the eigenmodes of the waveguide. That work also provided the average total angular momentum, average spin angular momentum, and average orbital angular momentum of the photons in the waveguides. Furthermore, reference [5] clarified the detailed composition of the angular momentum carried by the electromagnetic field corresponding to eigenmodes, including the specific modes of OAM and SAM and their respective proportions.

Furthermore, this paper proposes a method for generating electromagnetic waves carrying designated OAM modes in a circular waveguide by using monopole antenna arrays. Specifically, uniformly distributed monopole arrays are arranged inside the circular waveguide and excited accordingly. As a result, a corresponding superposition of eigenmodes is generated in the circular waveguide, and these eigenmodes correspond to the desired orbital angular momentum states. By employing multiple monopole antenna arrays, several different modes can be excited and transmitted simultaneously.

The validity of the proposed method is demonstrated by HFSS simulation results.

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Watt-level amplification of OAM modes in an active spun ring-core tapered fiber with preserved modal purity

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Beams carrying orbital angular momentum (OAM), characterized by a helical phase front of the type $\exp(i\ell\phi)$, have attracted growing interest for applications in optical communications, material processing, super-resolution imaging, and quantum technologies [1]. While OAM beams are commonly generated in free space using spatial light modulators or vortex phase plates, their amplification directly within optical fibers remains challenging due to mode coupling, differential gain, and modal dispersion that degrade purity and efficiency. Recent advances in fiber design, including ring-core and twisted architecture, have shown promise for lifting mode degeneracy and enabling stable OAM propagation [2,3]. In this work, we demonstrate an Yb-doped ring-shaped core spun tapered double-clad fiber (sT-RCF) as a gain medium for efficient amplification of OAM modes while preserving their complex phase and polarization profiles. The sT-RCF features a ring-shaped active core combined with a spun and tapered longitudinal architecture. The twisting geometry induces circular intrinsic birefringence supporting circularly polarized eigenstates, while the ring-core design enables efficient amplification of doughnut-shaped beams suppressing undesired gaussian-like mode gain. The theoretical framework based on coupled mode equations in the twisted reference frame [3] was developed to model OAM-mode propagation incorporating both twisting and tapering effects together with the active nature of the fiber.

OAM beams with topological charges $\ell = 1$ and $\ell = 2$, carrying 60 ps pulses at 15 MHz repetition rate at 1030 nm, were free-space coupled into the sT-RCF and amplified to over 1.2 W average power with gain exceeding 11.5 dB. Comprehensive characterization using off-axis digital holography, cylindrical-lens analysis, and spatially resolved Stokes polarimetry confirmed the excellent preservation of both phase and polarization topology. The modal purity was measured at 95% for OAM1 and 97% for OAM2 modes, with the circularly polarized topology remaining largely intact with only a slight increase in ellipticity. The experimental results showed good agreement with the theoretical predictions, validating the developed framework.

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Spontaneous vortex rings and catastrophes in ring reconnections

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Spontaneous vortex rings are fundamental to many physical systems, from BECs to turbulent water currents and, unsurprisingly, optics. Studying optical vortex rings may help uncover the underlying mechanisms of physical phenomena not yet fully understood, such as quantum turbulence and spontaneous knotting.

We present theoretical investigations of experimentally accessible optical vortex rings in free space and in a focusing nonlinear medium. The rings result from destructive interference between a Gaussian laser beam and a plane wave, and various topological transformations are observed when the initial parameters are varied. We demonstrate that the vortex rings in such a system are robust under symmetry breaking and nonlinear propagation.

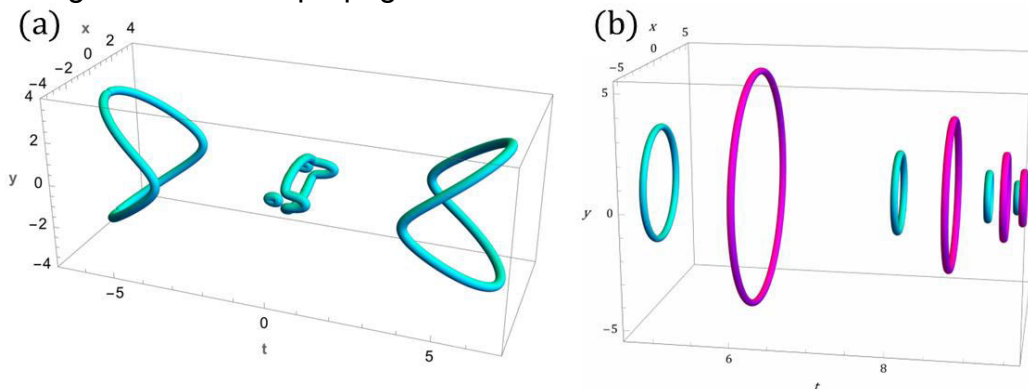


Figure 1. Spontaneous vortex rings in (a) free-space and (b) focusing Kerr medium.

Despite the perceived simplicity of this system, a variety of complex phenomena leading to the spontaneous nucleation of vortex rings are observed. We highlight two cases. In free space, highly elliptic Gaussian beams result in the spontaneous emergence of a pair of tiny vortex rings near the focal plane. These rings can be predicted by the manifestation of the butterfly catastrophe in the topological phase map. In a focusing nonlinear medium, for specific initial parameters, an array of multiple counter-rotating pairs of vortex rings appears spontaneously, partially suppressing collapse.

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Structured Light Nanoparticle-Enhanced Raman Spectroscopy: Selective Excitation of Raman Modes at the Nanoscale

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Raman spectroscopy is widely used for material identification and characterization, but conventional excitation schemes provide limited control over the polarization of the optical field interacting with the sample. Existing methods provide plasmonic field enhancement, while control over the spatial distribution of the incident polarization remains challenging. Here, we introduce Structured Light Nanoparticle-Enhanced Raman Spectroscopy (SL-NERS), combining tailored vector beams with single plasmonic gold nanoparticles to achieve controlled excitation of Raman-active modes with subwavelength spatial resolution. The method employs cylindrical vector beams to generate three-dimensional focal fields that enable selective interaction with different components of the Raman tensor.

Scanning the nanoparticle within this structured focal field provides spatial control over Raman excitation and enables polarization-dependent probing of anisotropic materials.

SL-NERS establishes a polarization-focused approach to nanoscale Raman spectroscopy, using structured light as an active tool for probing material properties. This enables characterization of crystal orientation, anisotropy, and tensorial optical responses beyond conventional Raman methods.

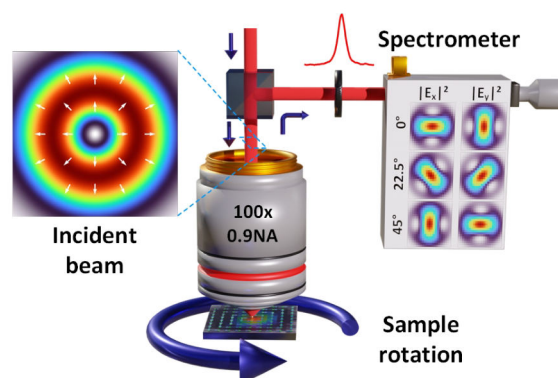


Figure 1: Artistic illustration of the SL-NERS method. A radially polarized beam is focused through a high-NA objective to generate a structured focal field that excites a gold nanoparticle on a silicon substrate. Scanning across the nanoparticle enables 2D mapping of the Raman response via the 520 cm⁻¹ silicon phonon mode. Signal variations upon substrate rotation indicate sensitivity to crystal orientation via polarization-dependent excitation.

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Gratings and metasurfaces for on-chip ion traps

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Quantum computing promises to revolutionize fields such as cryptography, optimization, and quantum simulation by providing exponential speedup over classical computers. Among the current hardware candidates, trapped ions stand out as a particularly promising platform, offering long coherence times and high-fidelity qubit operations [1]. However, as trapped-ion quantum computers scale to larger numbers of qubits, single-ion addressing via free-space optics becomes increasingly challenging. Phase stability is compromised by mechanical vibrations and precise individual addressing is becoming ever more difficult as ion chains grow longer. Photonic integrated circuits (PICs) offer a compelling solution to both challenges, enabling stable, scalable, and precise multi-ion addressing within a compact and robust platform.

In this paper, we present a PIC designed for ion trapping, implemented on a silicon nitride platform. Our photonic chip consists of an array of multiplexers combined with carefully arranged and optimized grating couplers, acting as a free-space interface. We guide light across the photonic circuit to generate high-quality beams targeting individual ions at focusing heights of tens of microns above the chip surface.

We optimize grating couplers based on finite-difference time-domain simulations for the precise addressing of single ions using Gaussian beams [2]. We present the basic physical principles underlying our optimization scheme and discuss its applicability to PIC-based ion trapping platforms for scalable quantum information processing.

Our results prove that the presented photonic chip provides a robust and versatile platform for numerous applications in ion trapping as well as future developments, including compatibility with multiple wavelengths, inverse design, and combinations with metasurfaces.

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