Angular Momentum of Light

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Over the last few decades, angular momentum of light has attracted increasing interest from many research groups. This comes without surprise, considering the widespread range of applications related to the classical and quantum implications of this property of light in fields like optical forces and torque, quantum optics, microscopy, etc. Also, a large variety of devices and techniques continue to be developed to progress in the manipulation and structuring of angular momentum as versatile degree of freedom of light. This Special Topic aims at showcasing the latest progresses in theory and experiments related to the angular momentum of light.

I. INTRODUCTION

Over the last 30 years, the angular momentum of light has attracted growing interest from the scientific community, both at the theoretical and experimental level. Rapidly, this field evolved and cross fertilized many different areas of photonics and physics, such as particle manipulation, classical and quantum communication, microscopy, topology, metrology, and light-matter interaction, to name a few. A central theme emerging from this Special Topic Collection is the continued expansion of both the foundational understanding and the applied capabilities associated with orbital angular momentum (OAM) of light. The selected articles illustrate how OAM-enabled approaches are reshaping structured-light generation, wavefront analysis, light–matter interactions, coherence engineering, quantum-enhanced metrology, and particle manipulation, but also they are inspiring further theoretical investigation of the topological structure underlying light beams and the role OAM plays in it.

II. TOPOLOGIES OF LIGHT AND TOPOLOGICAL LIGHT-MATTER INTERACTION

Starting with advances in understanding of the geometrical and topological structure underlying structured light, the work of Marco *et al.*[1] discusses several ways, inspired by cartography, to construct Skyrmionic textures in optical fields that preserve their correspondent Skyrme density. They then predict theoretically, and verify experimentally using vector beams, that 2D polarisation patterns presenting such periodic textures necessarily exhibits zeros in the field, a feature that makes then susceptible to perturbations. Wu *et al.*[2], instead, consider the problem of creating accelerating Skyrmionic lattices using Airy beams. In their work, they encode Skyrmionic lattices into vortex-type Airy beams by means of a cubic phase and analyze, both theoretically and experimentally, the topological stability of such lattices, taking the Skyrme number N_{sk} as a reference quantity. In particular, they show how for finite-energy Airy beams the topological stability of Skyrmionic lattices will inevitably degrade during propagation, mainly due to the intensity distorsions introduced by the finite-energy cut of the Airy beam spectrum.

Coming to topological light matter interaction, instead, Mitra *et al.*[3] demonstrate how to map the Skyrmion topology of a vector beam onto a cloud of cold atoms with high-fidelity. In their work, using an adiabatic passage technique, the authors show how it is possible to efficiently transfer the topological texture of vector beams onto a cloud of 87-strontium gas at low temperature. Their results open up interesting possibilities for topological data encoding and storage, and provides an improved platform to detect complex topologies in structured light. Furthermore, Viedma *et al.*[4] show how OAM can be used as a synthetic dimension to implement nontrivial topologies in photonic flat band systems. In their work, in fact, they show how a zig-zag lattice of OAM-hosting waveguides mimics the dynamics of flat bands systems decorated with onsite impurities, resulting in the emergence of nontrivial topology. In particular, they show how the coupling of different OAM modes induces a phase in the coupling constant, between the waveguides of the lattice, that acts as an artificial gauge field. This, combined with the synthetic dimension provided by the OAM, allows direct access to the topologically nontrivial dynamics of the system.

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III. GENERATION OF NEW OAM STATES AND TAILORING OF OAM OF LIGHT

At the device and materials level, Zhang *et al.*[5] demonstrate that domain-engineered nonlinear photonic crystals can simultaneously tailor the OAM spectrum and radial intensity profile of second-harmonic beams. Their approach, based on angular and radial modulation of the nonlinear susceptibility, provides a versatile platform for generating OAM superposition states at new wavelengths. Complementing this, Chavilkkadan *et al.*[6] realize purely geometric spin–orbit Laguerre–Gauss (LG) waveplates fabricated by three-dimensional laser nanostructuring of silica glass. By eliminating dynamic-phase distortions, they achieve full spin-controlled generation of LG modes, revealing the potential of 3D anisotropic structuring for robust mode shaping. Savarese *et al.*[7] report the fabrication of a metasurface described with non-unitarian Jones matrix, where losses are polarization dependent. Their approach is based on incorporating a dye with dichroic properties within a liquid crystal. In this context, Vogliardi *et al.*[8] report high-efficiency generation of OAM-independent perfect vector vortices using phase-only silicon metalenses. Their multifocal metasurface design simultaneously controls geometric and dynamic phase, enabling perfect-vortex beams with invariant ring size regardless of topological charge.

In parallel, new frameworks for generating or analyzing OAM states continue to emerge. Scharwald *et al.*[9] develop a theoretical treatment of parametric down-conversion in cascaded nonlinear interferometers pumped with LG beams. Their analysis shows how pump and interferometer parameters control the distribution of OAM-carrying Schmidt modes, with implications for enhanced angular displacement measurements. Eriksson *et al.*[10], on the other hand, show how it is possible to use the high OAM carried by whispering gallery modes of an optical fiber to realise, exploiting the Talbot effect in the transverse angular domain, multiport beam splitters, with a splitting ration up to 1 : 30. Their findings suggest Talbot-based multiport devices as an interesting platform for classical and quantum photonic networks, as they could virtually provide crosstalk-free OAM sorting. In the THz regime, Liu *et al.*[11] generate higher-order Poincaré beams, which polarization states across the beam cover the full Poincaré sphere with angular momentum. This is performed by applying a radial polarization to an input pump beam before propagation through a 111-cut ZnTe crystal, with axial symmetry. The THz beam emerges as the superposition of positive and negative second-order vortices. Huang *et al.*[12] present a single-shot diffractive spectrometer capable of reconstructing arbitrary vortex wavefronts without beam-specific calibration, achieving accurate OAM decomposition even at high topological charges. Because the method relies only on a diffusing modulator, it is particularly suited to spectral regions where conventional optics are challenging to fabricate. Aguiar Maduro *et al.*[13] demonstrate a simple way to identify the topological charge of a beam : knife-edge diffraction produces a fork-like pattern which dislocation singularity provides sign and value of the vortex order. A complementary theoretical perspective is offered by Bekshaev[14], who reviews the principles and properties of spatiotemporal optical vortices (STOVs). By modeling STOVs as Hermite–Gaussian superpositions, the work clarifies their phase singularities, internal energy flow, and transverse OAM. On a similar trail, Diouf *et al.*[15] demonstrate experimentally how the OAM carried by spatiotemporal wavepackets (ST) can survive after propagation of the wavepacket through a line obstruction or, more generally, a scattering medium. Their findings show that, contrary to LG and Bessel beams, the innate spatiotemporal correlation of OAM-carrying ST, mainly appearing as a form of self-healing, increase the resilience of OAM to external perturbation.

New insight on spin and optical angular momentum also comes from the work of Forbes *et al.*[16]. They, in fact show that longitudinal spin and OAM can also arise from linearly polarized Gaussian beams under tight focussing conditions. The appearance of these quantities, predicted to be zero in the purely paraxial regime, are generated by the wavefront curvature and only appear because of the nonparaxial nature of tightly focussed light. Their understanding and control would then enable wavefront gradient engineering as a viable way to create spin- and OAM-light matter interaction at the subwavelength scale by simply using linearly polarized Gaussian beams.

The interaction between OAM and material excitations is examined experimentally by Pylypets *et al.*[17], who test predictions that vortex beams could alter Raman selection rules in $Bi_4Ge_3O_{12}$. Their measurements show no observable OAM-dependent effects, suggesting that phonon coherence lengths are too short for the helical phase structure to couple effectively.

IV. COHERENCE AND ANGULAR MOMENTUM OF LIGHT

Coherence-based structuring represents another emerging direction. Liu *et al.*[18] engineer partially coherent light fields that generate deterministic higher-order vortices at specific propagation distances. Their experiments illustrate controlled transitions between coherence vortices and deterministic vortices, identifying conditions where the OAM spectrum becomes pure. This provides tools for shaping vortex behavior in fluctuating or turbulent environments. Expanding toward guided-wave platforms, Skvarenina *et al.*[19] introduce a bend-resolved modal basis for deformed multimode fiber, constructed using a two-stage singular value decomposition of speckle statistics. Their framework enables tracking OAM-carrying mode evolution under bending, suggesting opportunities for robust mode-division multiplexing and distributed fiber sensing. Stefańska *et* *al.*[20] also investigated the propagation of OAM beams in multimode fibers, but from a different point of view. The authors explore the apparent birefringence behavior of this cylindrically-symmetric medium. They demonstrate numerically and experimentally the importance of quadrupolar effects and phase velocity difference between modes on the propagation of OAM-carrying light which yields circular and orbital birefringence.

V. SPIN-ORBIT COUPLING

Li *et al.*[21], on the other hand, provide an important new perspective on spin-orbit coupling (SOC) of twisted random light. Using the mode decomposition method, in fact, they analyze SOC of tightly focussed twisted random light, unraveling how, even when the coherence of the beam is low, its SOC might still be significant. These findings offer a new perspective on partially coherent light; harnessing its properties, in fact, could lead to novel ways to control and generate OAM, even in the absence of well-defined spatial or polarisation states.

OAM is highly relevant to different areas of optical metrology. Willner *et al.*[22] use the superposition of higher-order Bessel beams to generate intensity patterns that rotate along propagation distance. Since the structure of the intensity pattern is only weakly affected by scattering, the rotation angle of the pattern provides an efficient tool to retrieve the position of distant objects in turbid media. Another optical metrology tool is demonstrated by Tribaldo et al *et al.*[23]. The authors compare experimental and analytical spectral response of the scattering of LG beams by a spherical microparticle, in the framework of Mie theory to accurately retrieve its size.

VI. STRUCTURED ILLUMINATION

Illumination with structured light is also an emerging topic with attractive applications. Orlov *et al.*[24] demonstrate edge detection in the framework of single-pixel THz imaging. The authors show that at high numerical aperture, it is necessary to use structured illumination carrying a vortex charge to benefit of edge detection property of vortex beams. In the regime of high-harmonic generation, Schmidt *et al.*[25] investigate Hermite-Gauss beams to generate controllable high harmonic beamlets; the latter create a controllable interference pattern with future application to single-shot ptychography.

VII. PARTICLE MANIPUALTION, FREQUENCY CONVERSION AND QUANTUM METROLOGY

The manipulation of microparticles with OAM-carrying light is well known. In this context, Wu *et al.*[26] have integrated the generation of the OAM onto the tip of an optical fiber. This allows straightforward trapping and rotation of micro-beads. Another interesting application of beams with OAM is in the high-power regime of filamentation: Fu *et al.*[27] explored the characteristics of the hollow filaments produced by different orders of LG beams for applications to air waveguides and laser triggering of lightnings.

Vector fields also play a significant role in nonlinear frequency conversion, as the work of Fan *et al.*[28] suggests. In their work, placing two orthogonally-oriented nonlinear crystals in a nested ring cavity containing spatial light modulators, they in fact show how it is possible to generate a variety of different vector beams and obtain an enhancement of second-harmonic generation (SHG) form this special cavity that is up to 80 times that of conventional methods to generate SHG vector beams.

Finally, OAM is increasingly relevant in quantum metrology. Yesharim *et al.*[29] introduce "wavefront photonic gears" that combine spiral phase plates with N00N states to enhance mechanical rotation sensing. Their compact, low-loss system achieves multi-fold improvements in both angular resolution and sensitivity while maintaining high photon-pair flux, enabling real-time rotation and acceleration measurements.

VIII. A TUTORIAL ON OPTICAL FORCES

This Special Topic Collection also includes a tutorial, by Iker *et al.*[30], focused on optical forces on micron-sized particles illuminated by LG beams. This tutorial represents a good starting point for understanding optical forces, and the role of helicity and angular momentum in particle manipulation. This work, in fact, provides a comprehensive set of essential literature, detailed analytical calculations of optical forces and torques on micron-sized particles, and a Multipolar Optical Forces Toolbox, available on GitHub, to calculate optical trapping stability maps.

IX. CONCLUSIONS AND OUTLOOK

Together, these works demonstrate the breadth of ongoing innovation in OAM science, from nonlinear frequency conversion and geometric mode shaping to wavefront diagnostics, coherence engineering, phonon interactions, and quantum sensing; highlighting OAM as a powerful and versatile degree of freedom in modern photonics.

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