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EDITORIAL

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Editorial

A perspective on 25 years of advances as reported in the *Journal of Optics*

Andrew Forbes[1,*], Mohamed Swillam[2], Kayn A Forbes[3], Yijie Shen[4,5], Chao He[6], Shuyuan Xiao[7,8], Jörg B Götte[9], Goutam K Samanta[10], Tatsuki Tahara[11], Boris Malomed[12], Vasily N Astratov[13], Carmelo Rosales-Guzmán[14], Parinda Vasa[15], Peter Bermel[16], Martijn Wubs[17], Rocio Borrego-Varillas[18], Caterina Vozzi[18], Yunquan Liu[19], Celia Rowland[20], Elisa Pappalardo[20], Lynn Paterson[21], P H Souto Ribeiro[22], Min Qiu[23], Jinghua Teng[24] and Hongsheng Chen[25]

[1] School of Physics, University of the Witwatersrand, Johannesburg 2050, South Africa
[2] Department of Physics, American University in Cairo, Cairo 11835, Egypt
[3] School of Chemistry, University of East Anglia, Norwich, Norfolk NR4 7TJ, United Kingdom
[4] Centre for Disruptive Photonic Technologies, School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore 637371, Singapore
[5] School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, Singapore
[6] Department of Engineering Science, University of Oxford, Oxford, United Kingdom
[7] School of Information Engineering, Nanchang University, Nanchang 330031, People's Republic of China
[8] Institute for Advanced Study, Nanchang University, Nanchang 330031, People's Republic of China
[9] School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, United Kingdom
[10] Photonic Sciences Lab., Physical Research Laboratory, Ahmedabad 380009, Gujarat, India
[11] Applied Electromagnetic Research Center, Radio Research Institute, National Institute of Information and Communications Technology (NICT), 4-2-1 Nukuikitamachi, Koganei, Tokyo 184–8795, Japan
[12] Tel Aviv University, PO Box 39040, Ramat Aviv, Tel Aviv, Israel
[13] Department of Physics and Optical Science, University of North Carolina at Charlotte, Charlotte, NC 28223-0001, United States of America
[14] Centro de Investigaciones en Óptica, A.C., Loma del Bosque 115, Colonia Lomas del campestre, 37150 León, Gto., Mexico
[15] Department of Physics, Indian Institute of Technology Bombay, Mumbai 400076, India
[16] Birck Nanotechnology Center, Purdue University, West Lafayette, IN 47906, United States of America
[17] Department of Electrical and Photonics Engineering, Technical University of Denmark, Kgs. Lyngby DK-2800, Denmark
[18] Consiglio Nazionale delle Ricerche, Istituto di Fotonica e Nanotechnologie, Milano, Italy
[19] State Key Laboratory for Mesoscopic Physics and Frontiers Science Center for Nano-optoelectronics, School of Physics, Peking University, Beijing 100871, People's Republic of China
[20] IOP Publishing, Bristol, United Kingdom
[21] School of Engineering and Physical Sciences, Heriot Watt University, Edinburgh EH14 4AS, United Kingdom
[22] Department of Physics, Federal University of Santa Catarina, Florianopolis, SC 88040-900, Brazil
[23] Department of Electronic and Information Engineering, School of Engineering, Westlake University, Hangzhou, Zhejiang 310030, People's Republic of China
[24] Institute of Materials Research and Engineering, Agency for Science, Technology and Research (A*STAR), Singapore 138634, Singapore
[25] Interdisciplinary Center for Quantum Information, State Key Laboratory of Extreme Photonics and Instrumentation, Zhejiang University, Hangzhou 310027, People's Republic of China

[*] Author to whom any correspondence should be addressed.

E-mail: andrew.forbes@wits.ac.za

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Abstract

In this perspective, the Editorial Board of the *J. Opt.* reflects on the past 25 years of the journal. The advances reported in journal have shaped the progress of diverse fields, from fundamental advances in optics to applications with optics as a key ingredient. The journal's scope has seen it capture progress in several emergent fields, for instance, structured light covering orbital angular momentum, spatio-temporal solitons, topologies in light, singular optics and nonparaxial light. Reports include advances in optical devices, such as digital micromirror devices, metasurfaces and integrated photonics, as well as novel photonic materials based on nanophotonics. Application-based research includes super-resolution imaging, digital holography and nonlinear optics. We select key papers from across diverse disciplines to showcase the scope of the journal and the impact it has had on the wider community.

Keywords: 25 years, Journal of Optics, perspective

1. Brief history

Founded in 1912 as Revue Générale d'Optique et de Méchanique de Précision, the first issue of *J. Opt.* in its current form was produced in 1999, when the journal was merged with Pure and Applied Optics: Journal of the European Optical Society Part A to form J. Opt. A: Pure and Applied Optics, then shortening its name in 2010. Since its launch in 1999, the *J. Opt.* has grown into a highly respected, community-led resource for researchers working on all aspects of modern and classical optics, with over 6900 articles from authors across 97 countries published to date (see figure 1). Many articles defining important progress and impactful research have been published in the last 25 years, with several roadmaps becoming the reference work for specific topics. It would be unfair to highlight those only based on their citation or download numbers, as every author who has contributed to the journal has played a crucial role in shaping and advancing the field.

To celebrate its 25th anniversary, we are reflecting on the journal key achievements and publishing a series of invited articles solicited from leading authors, as well as Board Members and editors old and new. The celebratory anniversary collection provides oversight of notable progress which has been made in certain topics since 1999.

The current publishing team, together with the Editor in Chief also recognizes the support of the Editorial Board in ensuring the longevity of the journal, and without whom we would not be where we are today. We are thrilled that so many of them have contributed to this landmark perspective, where Board Members offer an overview of the last 25 years in their respective areas of expertise, both from the *J. Opt.* and beyond. With additional thanks to all of our authors, readers and referees, we invite you to join us as we commemorate this special occasion, and look forward to continuing to serve the optics community.

In what follows we have selected some advances to highlight as examples of topical research areas within the scope of the journal.

2. Orbital angular momentum (OAM) and structured light

When OAM was associated directly with the spatial structure of light, as shown in figure 2, a new research field was born [1], later expanded to include degrees of freedom beyond OAM for general structured light [2]. The *J. Opt.* has been central to this explosion in activity, capturing the advances in several reviews [3–5] and tutorials [6–9]. This field has given rise to a modern optical toolkit and a deeper understanding of light, allowing for enhanced applications with light tailored for purpose. Topical examples include optical trapping and tweezing, where OAM light can be used to exert a torque on matter to make it rotate [10], enhanced optical sensing, for instance, measuring spinning objects by a rotational Doppler effect with OAM light [11], and harnessing OAM entanglement [12], which has given rise to a multitude of applications, including quantum computing, quantum sensing and quantum communication.

The *J. Opt.* has captured many of the advances in this field over the past 25 years, including special issues on the topic [13]. Significant reports have included the role of light's structure in spin–orbit coupling (SOC) [14], energy flows in spin and OAM textured fields [15, 16] and the concomitant properties such as self-healing of light [17]. The journal has reported novel tools to push the limits of how large an OAM alphabet could be controlled [18, 19], a state-of-the-art at the time. Considerable focus has been on the use of these fields in many applications, from tailoring atomic landscapes [20] to optical communication [21–24]. The *J. Opt.* has likewise captured

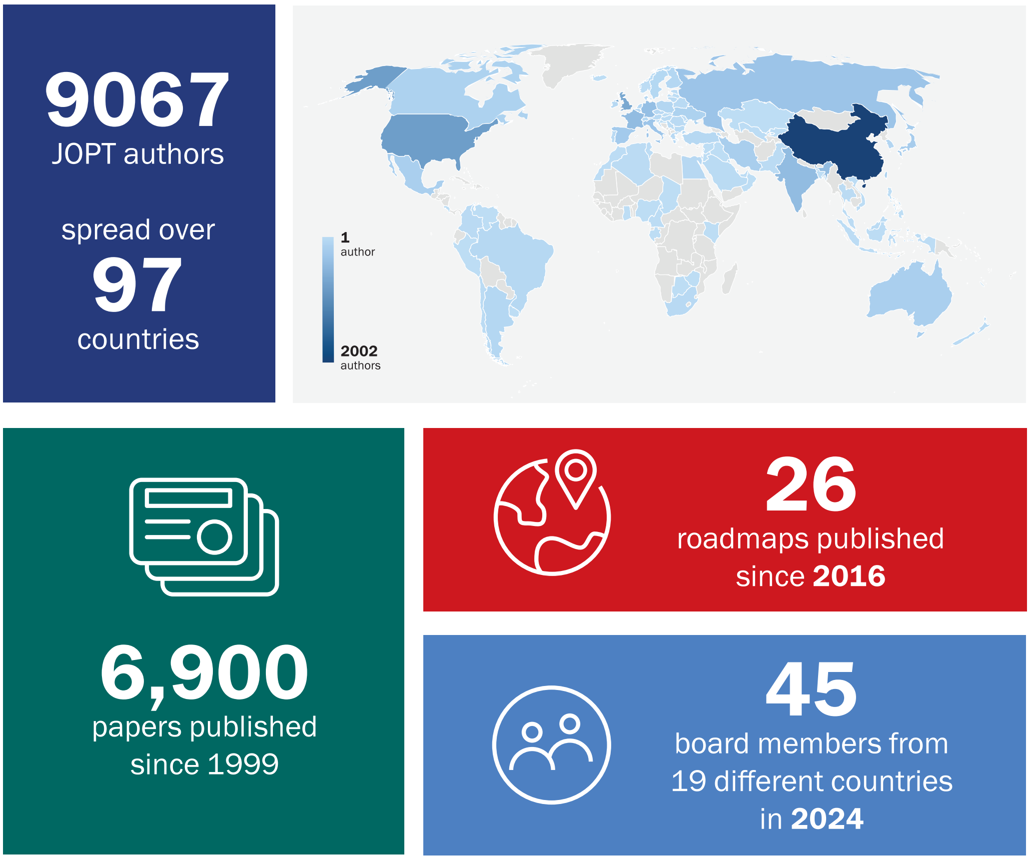

Figure 1. JOPT at 25. The reach of the *J. Opt.* is worldwide, covering over 9000 authors across nearly 100 countries.

many of the important advances in structured light beyond just OAM, including the use of spatial light modulators (SLMs) for fully multiplexed light [25, 26] and high quality structured light modes [27, 28] across any mode type. These foundational reports have opened the route to many advances with a modern digital toolbox, with recent roadmaps pointing to an exciting future in this highly topical research area [29–32].

3. The role of digital micromirror devices (DMDs) in structured light

Structured light fields, engineered in their various degrees of freedom, phase amplitude, polarization, amongst other, represent a powerful tool with applications in a wide variety of research fields [2, 33, 34]. As such, for more than three decades, devising novel techniques for their generation or characterization has gained increasing track, either to make them more flexible, compact or simply to make them cost-effective. Pioneering techniques, proposed as early as 1950, relied on the use of axicons [35, 36], and more recently, photographic-printed holograms [37] or spiral phase plates [38]. These early works focused on manipulating the spatial degree of freedom of light, while in the past decades it has become topical to manipulate other degrees of freedom. Of particular relevance are vector beams [3], also known as classically-entangled, which are generated as a non-separable superposition of the spatial and polarization degree of freedom. Such modes, characterized by a nonhomogeneous transverse polarization distributions, have become a topic of late, in part also due to their mathematical similarity with entangled photons [33, 39]. Vector modes have been realized experimentally through birefringent waveplates, such as q-plates [40] and metasurfaces [41] but are evolving towards more elaborated flat optical elements based on metasurfaces [42] or liquid crystals [43], in the search of real-world applications.

Along this line, liquid crystal SLMs and DMDs have been instrumental in advancing the field of structured light. Their reconfigurable screen, which is addressed with computer controlled holograms, allows for an almost unlimited flexibility and versatility in the generation of arbitrary structured light beams [3, 7, 44–49]. Such devices have been key in demonstrating proof-of-principle applications across a wide variety of research fields. Of particular interest are DMDs, since they are more affordable that SLMs, typically an order of magnitude in price difference. In addition, DMDs posses higher refresh rates, in the order of kHz, are polarization insensitive and can operate over a broader wavelength range.

Interestingly, DMDs were not developed as light beam shaping devices but rather for display technology in the 1980s, but it is nowadays essential in the generation and characterization of structured light beams. Figure 3(a) shows a typical DMD screen visible to users, were computer-controlled

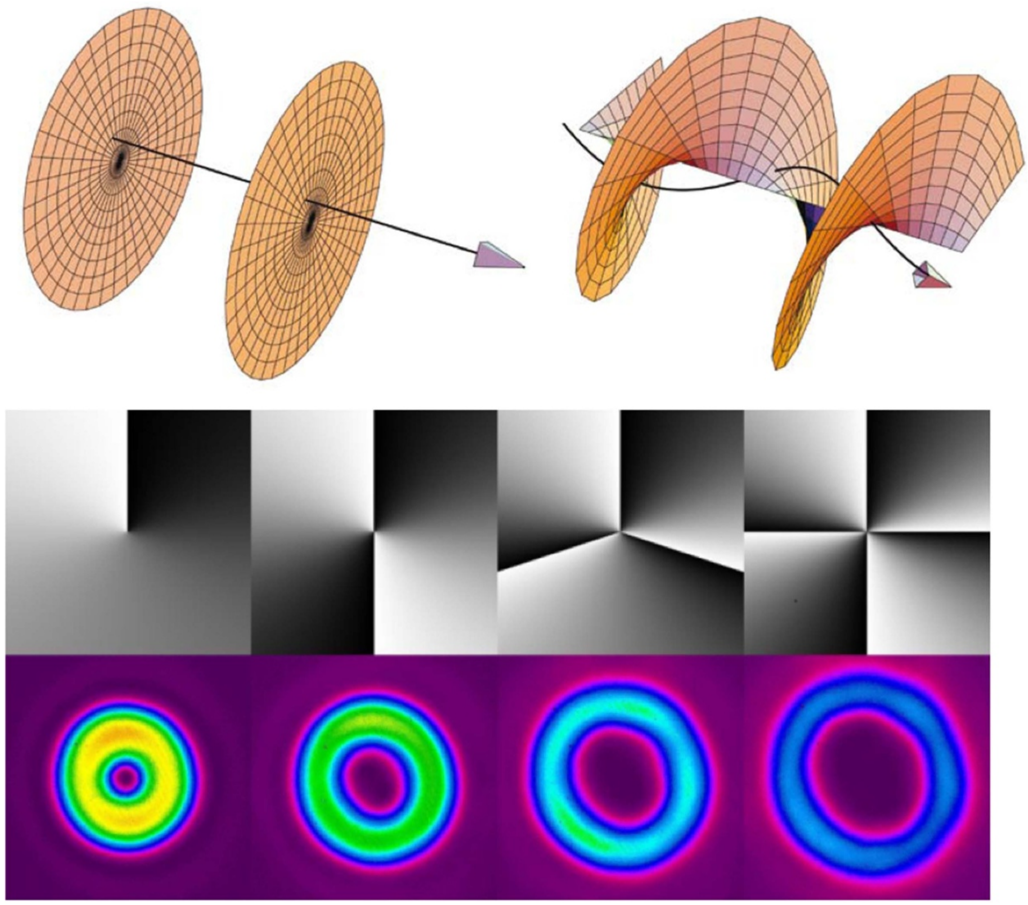

Figure 2. OAM: light in a twist. Examples of OAM light formed by twisting the planar wavefronts into helical forms. This is done by imbuing the phase with an azimuthal structure (shown as gray-levels) of the form $\exp(\mathrm{i}\ell\phi)$, for $\ell \times 2\pi$ phase twists about the azimuth (ϕ), resulting in $\ell\hbar$ of OAM per photon. In the transverse plane, the intensity is a ring of light, shown here as experimental images for $\ell = 1$ through 4, although in principle the alphabet spans from $-\infty$ to ∞. Caption and image reproduced from [4].

holograms are displayed and were light beam shaping occurs. This screen contains an array of millions of micro-sized mirrors, typically $8\,\mu$m in size, for clarity, figure 3(b) shows a section of a DMD screen seen to the microscope. Each of these mirrors has the possibility to rotate at any of two positions, $+12^\circ$ or -12°, corresponding to an 'ON' or 'OFF' state, respectively, as schematically illustrated in figure 3(c). Crucially, the state of each micromirror is controlled by computer-generated binary images.

In this context, the *J. Opt.* is playing a significant role by publishing articles which highlight the potential of DMDs, not only in the manipulation of structured light beams but also in other fields of relevance for optics. For example, in the tutorial-style article [6], the authors studied the capability of DMDs to generate structured light beams from broadband light sources. In the context of light beam shaping, in [51] the authors reported on the generation of higher-order Hermite–Gauss and vortex Hermite–Gauss modes. Here, the authors took advantage of the high refresh rates of DMDs to perform a controlled rotation of the generated modes, which might be useful in applications involving optical tweezers. In a similar way, in the manuscript [52], the authors reported on the generation of vortex beams embedded with non-uniform azimuthal phase jumps located at arbitrary positions, with potential applications in optical communications.

J. Opt. has also played a key role in publishing novel types of vector beams, as well as novel techniques for their generation and characterization. In relation to novel types of vector beams, in 2021 the first experimental realization of Mathieu–Gauss vector beams was reported [53]. Here the authors took full advantage of the polarization-insensitive property of DMDs to generate and study the propagation behavior of such beams. Crucially, a few years later, in 2024, it was demonstrated that such beams violate a Bell-like inequality, in particular the Clauser–Horn–Shimony–Holt–Bell type [54].

In regards to their generation, in [48] the authors demonstrated a powerful technique based on random spatial multiplexing capable of generating light beams at refresh rates limited only by the specific DMD model. In this technique two incoming beams with orthogonal polarization impinges on the DMD at slightly different angles but exactly at the centre of the binary hologram displayed on the DMD, as illustrated in figure 4(a). In the binary hologram some micromirrors are randomly selected to generate a scalar beam and the rest to

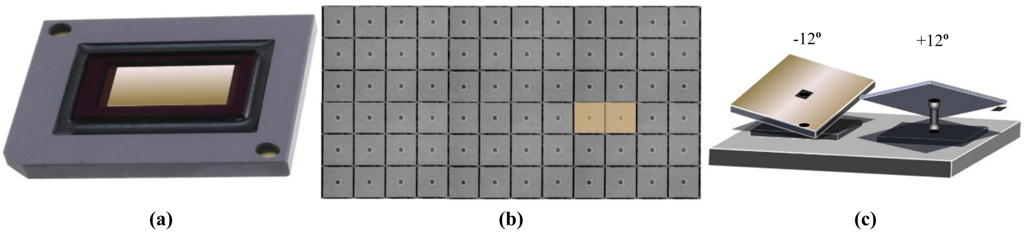

Figure 3. Digital micromirror devices. (a) Digital micromirror device (screen) where the computer-controlled holograms are displayed as binary images. (b) Micromirrors array observed through a microscope. (c) Schematic illustrations of the two positions each micromirror can rotate to. Reproduced from [50].

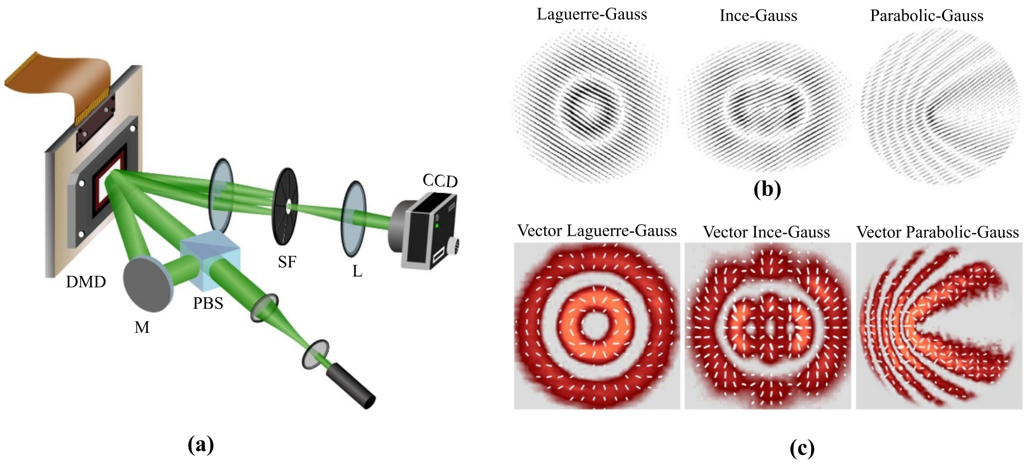

Figure 4. Vectorial beams from DMDs. (a) Schematic representation of a polarization-insensitive experimental setup for the generation of vector beams based on a DMD. (b) Typical computer-controlled binary holograms for the generation of the indicated scalar beams. (c) Polarization distribution overlapped with the intensity profile of the experimentally generated vector beams indicated in the top labels. (b), (c) Adapted from [55].

generate another scalar mode, orthogonal to the first. Each hologram is encoded with a unique linear grating to achieve a coaxial superposition of the first diffraction order of each impinging beam. In this way, vector modes are directly generated from the DMD. An alternative approach, also published in *J. Opt.*, proposes a highly stable generation of vector beams, based on the combination of a DMD and a common path interferometer of the Sagnac type [55]. Typical examples of the computer-controlled binary holograms displayed on the screen of the DMD are shown on figure 4(b). In a similar way, examples of vectorial light beams generated with the experimental setups described above are illustrated in figure 4(c). Here we show the nonhomogeneous polarization distribution (white line segments) overlapped with the transverse intensity distribution. The proper characterization of structured beams is also of great relevance, along this line in [56], the authors proposed a DMD-based technique to determine the topological charge of a vortex beams, using a triangular aperture. More precisely, the author used the diffraction pattern of a vortex beam after traversing a triangular aperture encoded on a DMD. In a different context, the authors in [57], also used a DMD to study the eigenmodes of aberrated systems. To this end, the authors encoded a superposition of modes into a hologram displayed on a DMD and used a tilted lens as an example of an aberrated system. The DMDs have also been used in the experimental implementation of Fresnel and Fourier digital holography (DH), replacing the traditional use of SLMs [58]. A combination of the DMD and multiplexing techniques allowed the authors for the optical processing of holograms that correspond to 2D static and dynamic scenes. In a different context, DMDs have been also employed for the generation of binary amplitude holograms for applications in holographic projections [59]. Here the authors implemented binary versions of phase-only holograms generated using an optimized Fresnel random phase and demonstrated that the generated binary holograms produced present significant advantages in computation speed without reducing the reconstruction quality.

Undoubtedly, the importance of DMDs for generating, characterizing or unliving novel aspects of vector beams is of paramount importance for *J. Opt.*. A last example of this is the recently published tutorial about the generation and characterization techniques of structured light beams [7]. In this tutorial, the authors provide the readers with a detailed explanation about the operating principle of DMDs and their use as SLMs for generating arbitrary structured light beams. Here they explain one of the most common methods for computing binary amplitude holograms for traditional structured light beams. Further, they also detail some of the common experimental setups for generating vector light fields. In the last part of the tutorial, the authors delve into the various DMD-based techniques for the characterization of vector beams, which allows for a real-time reconstruction of their transverse polarization distribution, as well as their vectorness, a measure that quantifies the coupling between the spatial and polarization degrees of freedom.

4. Multidimensional and spatiotemporal solitons

While there is a huge body of publications on experimental and theoretical properties of solitons in a great variety of physical settings, including many optical and photonic ones, an absolute majority of these studies address one-dimensional (1D) solitons. Extending the concept of solitons to two- and three-dimensional (2D and 3D) geometry (in particular, for spatio-temporal solitons, alias light bullets, in optics) is a natural direction for the experimental and theoretical works. In particular, an exciting possibility is to embed various topological structures into multidimensional solitons, thus producing various vortical modes and sophisticated ones in the form of hopfions and skyrmions. Equations (typically, these are self-focusing nonlinear Schrodinger (NLS) equations and coupled systems of NLS equations), However, the work in this direction is hampered by a fundamental problem: while 1D solitons naturally emerge as stable modes, their 2D and 3D counterparts are subject to instability, viz., spontaneous onset of the critical and supercritical collapse in the 2D and 3D cases, respectively, and a still stronger splitting instability of vortex solitons. Therefore, much interest was drawn to the theoretical prediction and experimental realization of physically relevant models that may support stable multidimensional solitons, an especially challenging issue being the stabilization of vortex solitons and more complex topological modes. In the course of the last 25 years, an essential progress in this work has been reported [60]. The most essential fundamental stabilization mechanisms are provided by competing (focusing–defocusing) nonlinearities, SOC in optical systems and quantum matter Bose–Einstein condensates, (BECs), and corrections produced by quantum fluctuations to the mean-field dynamics of waves in quantum matter. As relevant examples, figure 5 displays 3D solitons in a two-component BEC of the semi-vortex and mixed-mode (nonvortex–vortex) types, stabilized by SOC [61].

Essential contributions to these results were made in papers published in *J. Opt.*, for instance, an early review article on the topic [62] now garnered >1000 citations. Spatiotemporal evolution in nonlocal inhomogeneous media was studied in [63]. Filamentation of light beams and formation of light bullets in solid-state materials was addressed in [64]. Some aspects of this topic were considered in a roadmap paper [65]. Self-compression of soliton-like pulses in a self-focusing medium was studied in [66]. Spatio-temporal propagation of optical solitons in air was considered in [67]. A related topic is multimode shaping of light, which was the subject of roadmap paper [32]. In particular, the multimode evolution can be controlled by means of dispersion management [68]. Spatio-temporal evolution of vortex modes was recently studied in [69].

5. Nonparaxial light

The textbook description of light as a transverse electromagnetic wave, polarized transverse to the direction it propagates, is employed ubiquitously across optics [70, 71]. However, such a description is approximately true only in the paraxial regime. In reality light is nonparaxial, shown in figure 6, being polarized in all 3Ds [72], with the 3D polarization structure becoming more pronounced as the electromagnetic field is spatially confined. For laser beams this means tight focusing, a fact readily appreciated with recourse to Heisenberg's uncertainty principle $\Delta k_i \geqslant 1/2\Delta r_i$ for a photon's location r_i and momentum $\hbar k_i$ $(i = x, y, z)$, combined with the transversality condition $\mathbf{E}\cdot\mathbf{k} = 0$. This added degree of polarization complexity leads to remarkable optical properties [16, 73] of focused laser beams at the nanoscale, such as the transverse spin [74], spin-to-orbit [75] and orbit-to-spin conversions [76], and the optical chirality properties of vortex beams [77]. Moreover, the polarization properties reveal highly intricate subwavelength (fine) structures and patterns [78], including optical knots [79], Möbius strips [80], and skyrmions [81]. Additional motivation to continually develop the theoretical models of tightly focused beams is to enable quantitative interpretation of nonparaxial propagation, as well as microscopies and spectroscopies based on nonlinear optics.

The *J. Opt.* has a diverse portfolio of important studies on tightly focused beams. There have been a number looking at the extraordinary optical properties (energy, momentum, angular momentum, optical chirality) of tightly focused 'scalar' structured light beams [82–92]. Beyond these studies on scalar beams with their homogeneous polarization distribution [3], the journal has also been the home to many studies on tightly focused Poincaré vector vortex beams [90, 93–101]. A recent set of works looked at the topology and fine structure of focused light, including skyrmions and merons in nonparaxial fields [102–104]. Herrera and Quinto-Su [105] showed for the first time how classical interferometry can be used to study the 3D polarization structure of focused beams, which to date had relied upon near-field measurements. The *J. Opt.* has been home a wide array of both analytical and numerical theories to describe tightly focused beams [106–112], some of the more exotic modes including elegant Laguerre–Gaussian [113], hypergeometric [114], Mathieu–Gaussian [115], spatio-temporal optical vortices [116], and Hermite–Gaussian, Bessel, and Bessel–Gaussian light-sheets [117, 118]. Finally, some other select highlights published by the journal include 3D optical needles [119] and chains [119, 120], how optical angular momenta influence minimum beam spot size [121], higher-order radial Laguerre–Gaussian beams produce less spherical aberration in tight focusing [122], sub-wavelength magnetic energy density spots [123], and super-resolution and super-oscillations in nonparaxial beams [124–127]. The drive towards miniaturization and nanophotonics means the description and properties

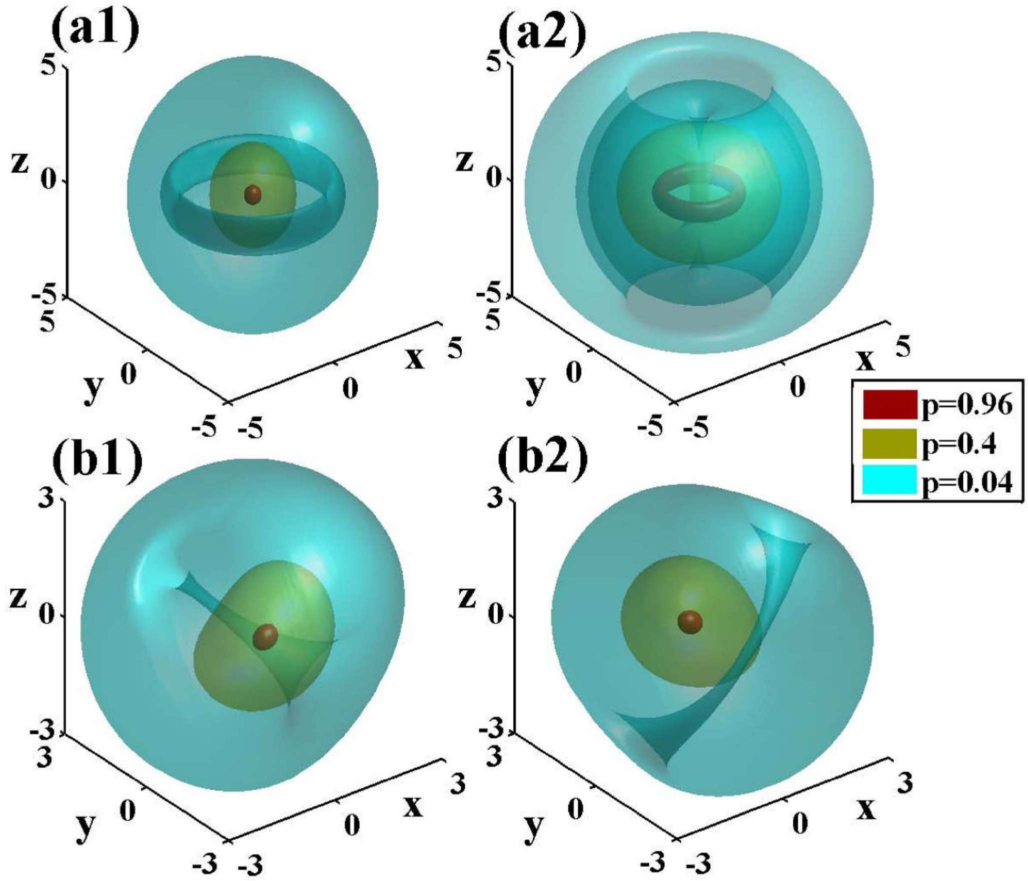

Figure 5. Solitons. Stable 3D solitons in the two-component BEC of the semi-vortex and mixed-mode (nonvortex–vortex) types, stabilized by SOC, see details in book [61]. Reprinted (figure) with permission from [61], Copyright (2025) by the American Physical Society.

of laser beams shrunk into tiny volumes of space continues to be an important and exciting area of optics research. The *J. Opt.* has been, and will continue to be, an important outlet to discover the cutting-edge in this exciting field.

6. Topologies of light

Topological phenomena and structures in materials have the potential to transform high-density data processing and storage, as evidenced by the Nobel Prize in Physics awarded in 2016 for groundbreaking discoveries in this field [128, 129]. In recent years, the intricate topological structures formed by electromagnetic waves have emerged as a cutting-edge topic, with a significant milestone being the advent of optical skyrmions—optical analogs of topological quasiparticles previously observed in condensed matter and particle physics [130], as illustrated in figure 7. The *J. Opt.* has been at the forefront of tracking these pioneering research directions, particularly focusing on the following challenges:

Higher-dimensional complex topologies: following the initial reports of electric field and spin skyrmions in surface evanescent waves [131–134], the *J. Opt.* published the world's first theoretical work on optical spin skyrmions in free space [103], sparking numerous subsequent studies on the generation and control of skyrmions in free space with increased degrees of freedom. Beyond 2D skyrmions, the manipulation of diverse topological structures from two to 3Ds and even higher-dimensional spaces has been explored. In line with the works on the generation and tuning of 3D optical hopfions [135, 136], the *J. Opt.* has published a roadmap on multimode light shaping, offering a rich perspective on extending topologically structured light into multiple degrees of freedom and higher dimensions [32].

Compact generators of topological light: current research on topological light remains in the realm of fundamental physics, with many promised applications yet to be developed. A primary reason for this is the absence of compact generators. Recently, the *J. Opt.* has published pioneering articles in this area, including a roadmap on metasurfaces which includes the perspective of meta-generator of topological light [137], and a recent study on a metasurface-based generator of optical skyrmions [138]. These contributions are in step with the recent mainstream publications in other high-impact journals, such as optical skyrmions from metafibers [139], GRIN lenses [140], and unitary wave-plates [141].

Topologies in space-time: topological structures of light can be created not only in continuous-wave states but also propagated as spatiotemporal pulses at the speed of light, as demonstrated by recent breakthroughs in toroidal and skyrmionic light pulses [142–144]. The *J. Opt.* has recently published a

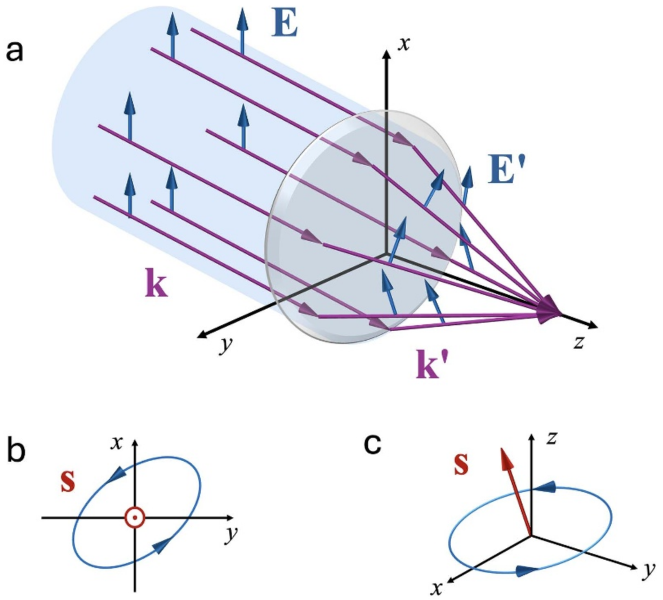

Figure 6. Nonparaxal beams (a) an incident z-propagating paraxial field is (2D) polarized in the transverse plane. Tight focusing generates a conical distribution of wavevectors with electric (and magnetic not shown) field components in 3D; (b) the familiar polarization ellipse of a 2D polarized z-propagating monochromatic paraxial beam with its spin vector $\mathbf{s} \propto \mathrm{Im}(\mathbf{E}^* \times \mathbf{E})$ aligned with the direction of propagation; (c) general nonparaxial polarization ellipse with spin vector $\mathbf{s}$ showing its non-zero components transverse x, y to the direction of propagation.

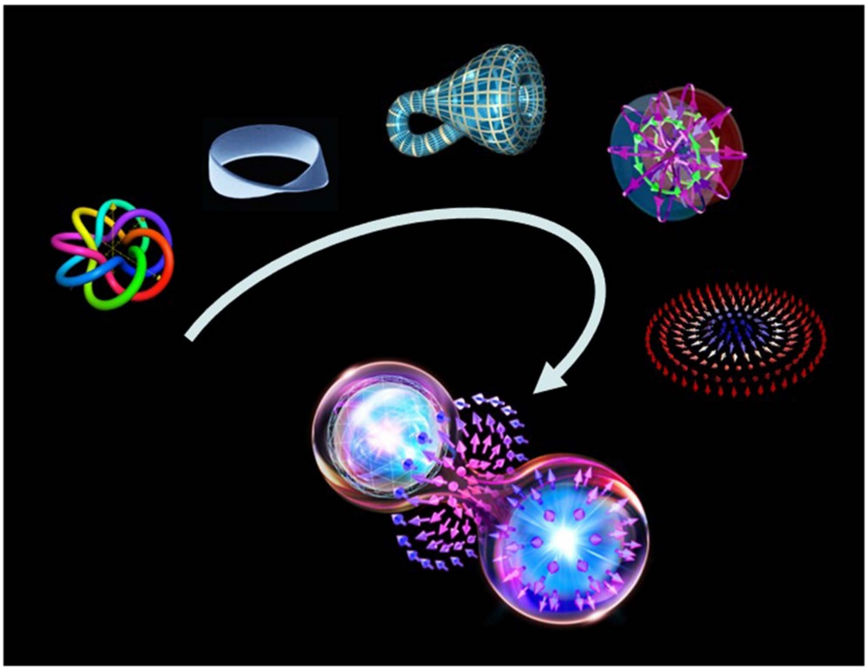

Figure 7. Topologies of light. Extended multi-dimensional topologies are going to be created and controlled in classical and quantum structured light.

roadmap on spatiotemporal light fields, which includes comprehensive technical reviews and perspectives on this innovative research direction [31], as well as recent research of sagittal skyrmionic pulses [101].

Topological resilience of light: the topological properties of light can provide unconditional resilience to information transfer, as the topological number remains invariant despite geometric distortions. This area of study is still emerging, yet the *J. Opt.* has already published a review summarizing the resilience to obstacles along the propagation path for certain special cases of topological light [5], which is highly significant for the development of more robust communication systems and practical applications of information transfer that can overcome atmospheric turbulence [145–148]. Most recently, resilience to complex media, such as spatially varying retarders, diattenuators, and depolarizers, has been investigated [149], along with the propagation invariance of light topology [150].

Topological light–matter interaction: inspired by topologies in materials, we can create analogous topologies using light. Studying the interaction between these two types of topologies may reveal new mechanisms for exciting complex topological structures in general wave systems and materials, which were highlighted by a recent *J. Opt.* roadmap [30]. While, a recent initial work on topological waves interacting with matter has been theoretically and experimentally studied in water wave systems [151], the implementation in light waves remains elusive. The *J. Opt.* stands at the forefront with recent publications on topological light–matter interaction, such as the interaction between optical skyrmions and graphene multilayers with multidimensional dynamic chiral control [152].

Singular optics: this year marks not only 25 years of the *J. Opt.*, but also the 50th year anniversary of the seminal paper by John Nye and Michael Berry on dislocations in wave trains [153], which founded the field of singular optics. Throughout the 25 years of its existence the *J. Opt.* has been instrumental to the development of fields of Singular Optics and OAM, perhaps never more so than in Les Allen's introduction to the special issue on atoms and OAM of light [154], in which he suggested coalesence of terminology and literature of these two fields, which has proven to be highly fruitful in shaping the current community working on structured light. This merging of the fields and communities continues with the NATO Advanced Research Workshop on Singular Optics, held ind Kiev, Ukraine in 2003 for which the *J. Opt.* published a special issue [155].

Addressing each of these challenges, with extended multidimensional topologies and across classical and quantum [130, 156], is anticipated to be a significant branch of the future development of topological light waves.

7. Nonlinear optics

The field of nonlinear optics, particularly optical parametric processes, has profoundly shaped modern photonics, influencing both applied and fundamental research since the first experimental observation of second-harmonic generation [157] in 1961 and optical parametric oscillations [158] in 1965. These developments have spurred new fields, such as attosecond science [159, 160], quantum technologies [161–163], ultrafast optics [65], frequency combs [164], supercontinuum sources [165, 166], and advanced imaging techniques. The *J. Opt.* has played a pivotal role in disseminating these advances through research articles, specialized issues, tutorials, and review articles.

Parametric processes such as second harmonic generation [167–170], optical parametric generation [171, 172], optical parametric amplification [173–175], and optical parametric oscillators [164, 176–178] have been explored across various materials and experimental schemes to produce new radiation across the electromagnetic spectrum. Additionally, nonlinear optics has branched into areas such as plasmonic nanostructures [179, 180], whispering gallery resonators [181, 182] and nonlinear silicon photonics [183]. Parametric amplification [173, 174, 184] has advanced to ultrafast optics, enabling the development of high repetition rate [185] few-cycle pulses [186, 187] tunable from the visible to the mid-infrared spectral range with milli-joule energy. These pulses have applications in high-flux soft x-ray generation and attosecond light [159, 188, 189], allowing the conversion of intense laser light into coherent extreme ultraviolet (XUV) and soft x-ray radiation through light–matter interactions [187]. Furthermore, intense terahertz (THz) radiation and next-generation mid-infrared sources, enabled by nonlinear optical processes, are opening new frontiers in biomedical imaging, environmental monitoring, and molecular fingerprinting [190]. Parametric down-conversion (PDC) [191–194] has evolved as an essential nonlinear optical process [162] in quantum technology, offering a reliable method for generating quantum-entangled photon pairs [195–197]. Continuous advancements in engineering PDC sources with higher brightness, tailored spectral-temporal properties, and integration into compact on-chip platforms are advancing scalable quantum technologies. Moreover, the nonlinear interaction [198] of structured optical beams [29] with unique spatial, temporal, and polarization profiles has made significant progress. Beams such as optical vortices, vector beams, and Bessel beams enable enhanced control over nonlinear processes, facilitating vortex harmonic generation, polarization-sensitive nonlinear effects, and spatial shaping of nonlinear outputs [199–202]. These advances expand the scope of nonlinear optics in areas such as high-resolution imaging, quantum information, and advanced spectroscopy.

8. Integrated photonics

Silicon photonics has seen remarkable progress, driving advancements in optical communication, data centers, lab-on-chip sensing, and quantum computing. Silicon's compatibility with existing CMOS fabrication processes has enabled the large-scale production of photonic devices with high precision and cost-effectiveness [203, 204]. Key components, such as resonators, interferometers, and couplers, have become foundational elements in silicon photonic circuits. Microring and disk resonators, for instance, enhance light–matter interactions and are commonly used in wavelength-division multiplexing systems to increase data transmission capacity [205, 206]. Mach–Zehnder interferometers play a crucial role in modulating light for signal processing in communication networks, while also being integral to quantum photonic circuits [207–211]. Couplers, including directional and multimode interference couplers, are essential for splitting and combining optical signals, providing the backbone for creating switches, beam splitters, and other components required for efficient high-speed data processing and sensing [212–215].

Hybrid integration, combining silicon photonics with plasmonics, organic materials, or microfluidic channels has further expanded the capabilities of photonic devices. Plasmonic elements allow light to be confined to subwavelength scales, enhancing light–matter interactions, improving integration, modulation speeds and energy efficiency, which is critical for next-generation communication systems [216–219].

Similarly, the integration of organic materials with silicon photonics has led to highly tunable, low-cost solutions for data centers and sensing applications [220–222]. These hybrid systems enhance device functionality while reducing power consumption, making them ideal for lab-on-chip sensors and quantum computing [161, 183, 223–228]. The combination of optics and fluids by integrating miniaturized optical components and microscale channels allow a new host of experimental possibilities in biosensing, molecular biology and fluid control of optical elements [229].

The *J. Opt.* has been instrumental in disseminating research on these breakthroughs, particularly in hybrid integration, positioning itself as a leading platform for cutting-edge studies in integrated photonics.

9. Optics for extreme environments

Given the ubiquity and versatility of optical technologies, there is a natural desire to employ them in a wide range of scenarios, including in particular, extreme environments: these can be characterized by the presence of extreme temperatures, vacuum pressures, radiation, and/or corrosive chemicals. While one may suspect that environment can impact performance and reliability, measurements and theory are both needed to provide relevant, quantitative insights into the significance and magnitude of such effects.

Over a decade ago, the magnitude of the sensitivity of advanced optical systems to such environments was demonstrated experimentally in this journal [230, 231]. To address some of these challenges, authors herein have sought both to create systems with greatly reduced sensitivity to such environments [232], and to devise methodologies like thermal laser processing [233] and hot-carrier thermophotovoltaics [234] that make use of such extreme environments.

Additionally, to enhance fundamental scientific understanding of this area, authors have also sought to characterize the optical properties in these environments [235], as well as the fundamental corrosion mechanisms [236].

The *J. Opt.* has played an important role in discovering and reporting significant environmental risk factors for optical systems, developing and demonstrating new technologies to make use of extreme environments, and enhancing fundamental scientific understanding of this area in the context of optics.

10. Super-resolution imaging

Super-resolution imaging is defined as imaging with a resolution exceeding the classical diffraction limit determined by half the wavelength of the light being used. Many methods of super-resolution microscopy have been developed due to the ability to stain specific sub-cellular structures with bright fluorescent (FL) markers, such as dye molecules and engineered fluorescent protein tags. Development of single-molecule detection and super-resolved FL imaging resulted in the 2014 Nobel Prize in Chemistry awarded to Eric Betzig, Stefan W Hell, and William E Moerner. The *J. Opt.* represented developments in super-resolved FL imaging including such methods as stimulated emission depletion [237, 238], single molecule localization [239–242], structured illumination [243, 244], multi-conjugate adaptive optics [245], confocal microscopy [246], and super-resolution optical fluctuation imaging [247]. The development of super-resolved FL microscopy was a resounding success story due to the ability to 'highlight' the structures inside a living cell with extremely high optical contrast. In the past two decades, a rapid development of a label-free super-resolution (LFSR) microscopy not using FL markers took place [248, 249]. Such imaging promises practically unlimited applications spanning from visualization of subcellular structures to nanostructure characterization in materials science. However, it must rely on subtler light-scattering processes in nanoscale objects with lower optical contrasts in comparison with the FL imaging. Rapid development of this area stems from several advancements including understanding of imaging as an information science problem, use of structured illumination with superoscillatory optical beams [125, 250, 251], plasmonic hot spots [252], photonic nanojets, vertices or hyperstructured beams, as well as the use of superlenses, hyperlenses and microspherical lenses with a super-resolution capability [253, 254]. Other approaches to LFSR imaging represented in *J. Opt.* are based on using optical nonlinearity [255], gradient index media [256], coherent diffractive imaging [257], DH [258–260] and quantum optics [261–263] effects. Over the years, Journal of Optics consistently represented progress in the imaging area including the special issues on 'Transformation Optics' in 2016 [264], 'High-Resolution Optical Imaging' in 2013 [265], 'Optoacoustic Imaging and Sensing' in 2017 [266], 'Enhanced Quantum Imaging' in 2019 [261], 'Hyperspectral Imaging in Biomedical Applications' in 2019 [267], and 'Computational Imaging and its Applications' ongoing in 2025. This area has also been represented in the roadmaps on 'Transformation Optics' in 2018 [268] and on 'Superoscillations' in 2019 [251]. The progress in this field turns super-resolution imaging into one of the frontiers of modern optics and photonics which brings researchers from the physics and biomedical optics communities under the same umbrella.

11. DH and quantitative phase imaging (QPI)

In holography [269], light diffracted from an object (an object wave) is interfered with a reference wave and recorded as a 2D interference pattern—the hologram. The object can be formed holographically by passing the same reference wave through the hologram. In the past, the recording was done physically with real objects and photographic plates. Today it is done digitally with the aid of a computer: the hologram is either digitally recorded with an image sensor or computed, and an object is numerically reconstructed. We refer to this as DH, a topic actively researched within sub-areas such as 3D image sensing, complex amplitude recording, and QPI techniques. The *J. Opt.* has published a large number of high-quality articles related to DH techniques and various applications for 25 years.

DH is a quantitative 3D sensing technique and therefore a 3D shape of an object is measured with DH and the calculations of diffraction integrals [270]. DH also allows interferometric reconstruction of images, making it suitable to depth-resolved 3D imaging by adopting optical coherence tomography. Depth-resolved 3D measurements have been performed [271] and refractive index and thickness distributions have been measured simultaneously by the combination of DH and optical coherence tomography [272]. Because of digital recording of a hologram and numerical calculation with a computer, various computational methods have been developed to improve the specification of DH. Selective reconstruction of multiple objects has been demonstrated by developing an automatic decomposition method [273]. To solve the problem of the noise due to the aliasing error in the calculation of the diffraction integral, Shimobaba *et al* have presented a method for reducing the aliasing and then improving the quality of the reconstructed image [274]. DH has also been researched for the application to optical security. A digital hologram generally has a random-like intensity distribution, and researchers have applied DH to optical security for implementing multidimensional encryption [275–278]. In the *J. Opt.* many researchers have gathered and summarized optical security techniques including DH and their roadmap [279]. Speckle is a random-like intensity distribution that acts as a source for noise when attempting image reconstruction in DH. Denoising is important for the image-quality improvement and techniques for denoising have been investigated [280]. Spatially incoherent DH is another method to obtain a speckleless holographic image and an experimental demonstration with spatially incoherent single-pixel DH termed optical scanning holography has been performed [281]. 3D measurement of particles is another prospective application in DH. To improve the depth resolution in 3D intensity imaging and to observe objects aligned along the depth direction clearly, two-view DH methods have been presented [282, 283]. Super-resolution is an active research theme in general imaging systems and has also been actively researched in DH. To improve the resolution in digital holographic microscopy, the shift of an image sensor and a microsphere are applied to digital holographic microscopes [259, 284]. One of the unique features in holography is the holographic multiplexing of multiple holograms. Exploiting the holographic multiplexing, 200 holograms are multiplexed in a numerically generated digital hologram and 200 light waves are simultaneously reconstructed from the hologram [26]. Holographic multiplexing is exploited also in digital holographic recording, and unique holographic multiplexing technique was proposed in the *J. Opt.* [285]. QPI is important and highly useful for accurate 3D measurement and quantitative sensing of transparent objects. Quantitative measurement is required for scientific research and evaluations. DH, interferometry, and transport of intensity equation (TIE) are representative QPI techniques. The merits of DH and TIE in QPI are to obtain both intensity and quantitative phase images and to reconstruct quantitative phase images with extended depth of focus by applying diffraction integrals. QPI has been investigated by numerous researchers in the world and been performed by DH [271, 286] and TIE with numerical methods [287, 288] in the *J. Opt.*. Phase measurement accuracy is an important factor in QPI and evaluated using a digital holographic microscope [289]. A laser light source is generally required to obtain an interference fringe image with high visibility in DH, as demonstrated in the studies described above. However, QPI with a light-emitting diode (LED) has been performed by rigorous adjustment of a two-arm interferometer [290, 291]. Furthermore, DH with daily-use light can be implemented with spatially incoherent DH with a self-interference interferometer, and single-shot incoherent DH with an image sensor was proposed towards incoherent 3D motion-picture imaging in the *J. Opt.* [292, 293]. These interferometers are robust against external vibrations because of the common-path optical configuration. It is difficult to conduct QPI in an incoherent self-interference interferometer. However, it is reported that holographic QPI with a common-path interferometer and an LED is realized by engineering spatial coherence of an LED and changing phase masks from figure 3 of [292], and therefore QPI in 3D space with a highly robust LED interferometer is ready to use [294]. The combination of holographic multiplexing and incoherent DH is also experimentally demonstrated as a filter-free lens-free incoherent four-dimensional (3D + polarization) imaging technique [295].

DH has been actively researched from various viewpoints by the researchers around the world. QPI in 3D space is one of the promising applications of DH, and other QPI techniques such as TIE are also actively developed for the social implementation. A laser light source is not mandatory to obtain a digital hologram now. Developments of the applications of monocular 3D image sensing, QPI in 3D space, and light-wave control will be important research themes towards next 25 years.

12. Dielectric resonant nanophotonics

Although the Mie theory, which predicts the resonant behaviors of subwavelength particles with high refractive indices, has been in existence for over a century, the significant interest in the optical properties of dielectric resonant nanostructures has emerged only recently [297]. In sharp contrast to their plasmonic counterparts that rely on the free electron responses, the optical resonances of dielectric nanostructures come from the displacement currents due to bounded electron oscillations [298]. Consequently, they are nearly free from nonradiative losses and the accompanying Joule heating damage, which is crucial for high-performance optical devices.

From the individual nanoantennas to the periodically arranged metasurfaces, the high-index low-loss dielectric materials have revolutionized nanophotonics. The *J. Opt.* has been central to this revolution, capturing significant advances in its topic review articles [299–302]. The resonant modes, including magnetic [303], electric [304], toroidal multipoles and their interferences anapoles [305, 306], as well as the Fano resonance [307, 308], the electromagnetically induced transparency [309], and the emerging physics of bound states in the continuum [310–312], have been well observed in

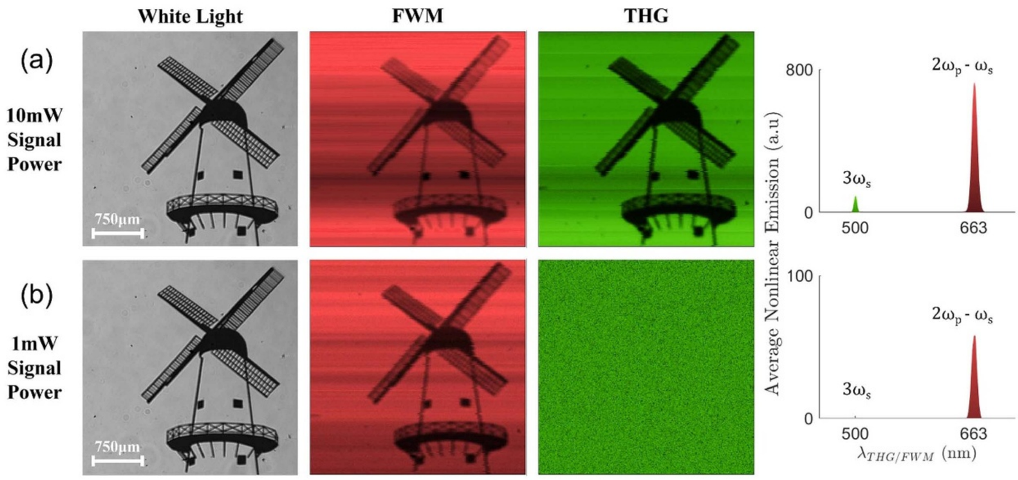

Figure 8. Nanophotonic-enabled imaging. Infrared imaging with a nonlinear silicon resonator governed by high-quality factor resonant states. Reproduced from [296].

dielectric nanostructures, deepening the understanding of the light–matter interaction. Optical absorption and modulation using these resonances have also been reported [313]. Beyond linear optical phenomena, dielectric resonant nanostructures with negligible nonradiative loss, are increasing popular in nonlinear optics [183, 314]. The *J. Opt.* have documented this trend by publishing both of theoretical and experimental results, staying abreast of current trends in the field [296, 315], with an illustrative example given in figure 8. A recent report in the collection of Emerging Leaders 2024 highlighted the first realization of resonantly enhanced four-wave mixing process within individual silicon resonators, further applied in infrared imaging technique leveraging these subwavelength resonators [296].

13. Plasmonics

The field of plasmonics studies the physics and applications of surface plasmon polaritons (SPPs), the surface waves that can exist at the interface of a conductor and a dielectric [316]. These are fascinating and useful for several reasons, among others because optical energy is highly confined, plasmon wavelengths are much smaller than their free-space counterparts, and the light–matter interaction can be greatly enhanced [317–319]. SPPs exist in various material platforms, as the conductors can be (noble) metals, transparent conducting oxides [320], doped semiconductors [321], or 2D materials (‘graphene plasmonics’) [322]. Plasmonics finds applications in areas that include refractive-index and bio-sensing, photovoltaics, surface-enhanced Raman scattering, structural colors, plasmonic waveguiding, thermoplasmonics including for medical treatment [323], and catalysis. In some applications, the lossy nature of conductors can nearly be neglected, while in others, plasmonic absorption is exploited [324].

Research in plasmonics has seen a tremendous theoretical and experimental activity, as exemplified by hundreds of related articles in the *J. Opt.*, including several influential reviews and roadmaps [179, 216, 217, 219, 317, 325–327]. Here we will highlight a few subthemes of plasmonics that were represented in the journal, beginning with light focusing and field concentration [328–330] and plasmonic absorption control and enhancement [331–335]. Both of these topics make plasmonics interesting for optical energy conversion [219], including photovoltaics [325, 336]. It was studied how plasmonics enhances light–matter interactions [337–340], enabling surface-plasmon lasing (’spasers’) and other nonlinear processes [179, 341]. Finally, we highlight as a subtheme of plasmonics the science and applications of graphene plasmons [342–345]. In summary, the *J. Opt.* has played and continues to play its part in the development of plasmonics, not in the least part by showing the way in the recent roadmaps [179, 216, 327].

14. Attosecond science

The first demonstration of attosecond pulse generation in 2001 [346, 347] marked the birth of attosecond science, a new discipline that has seen remarkable breakthroughs over the past quarter-century. Enabled by advances in ultrafast optics [65], laser physics, and quantum dynamics, attosecond science has provided unprecedented insights into the fundamental interactions between light and matter [348–350]. The fundamental issue of attosecond science is to probe and to control the electron dynamics. Attosecond electron dynamics of multiphoton ionization, tunneling ionization, non-sequential double ionization [351] and high-harmonic generation (HHG) etc, has been well studied. The generation of attosecond pulses is based on the HHG process, as illustrated in figure 9, where ultrashort intense laser pulses interact with a medium, usually a gas, to produce light at harmonic frequencies much higher than the original laser frequency [352]. Attosecond spectroscopy based on HHG allows the investigation of electron dynamics at their natural timescales, enabling the observation and control of ultrafast processes in atoms, molecules, and solids. Several pivotal works published in the *J. Opt.* over the last 25 years highlight the progress and promise of this transformative

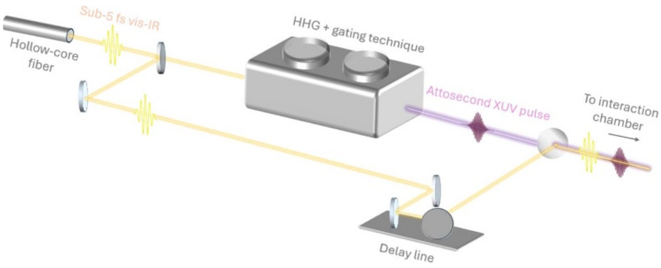

Figure 9. Attosecond pulses. General scheme of a typical attosecond pump–probe spectroscopy experiment: isolated attosecond pulses are generated through high-order harmonic generation and combined with a short infrared pulse.

area of research. In the last decades, the scientific community has devoted much effort to developing novel attosecond light sources. One of the most significant advancements has been the generation of attosecond pulses in the 'water window' [189], a spectral region between 280 eV and 530 eV highly relevant for biological imaging. This achievement has been enabled by the development of high-energy mid-infrared lasers [186, 187], which allow for extending the cut-off in HHG [188]. Another pivotal development in the field has been the generation of attosecond pulses with circular polarization, which has been extensively reviewed in [353]. Circularly polarized light is indispensable for studying chiral molecules and magnetic materials, as it allows for the direct probing of spin and angular momentum dynamics. Recent innovations, including the manipulation of HHG processes with tailored driving fields and bichromatic laser setups [354], have facilitated the production of circularly polarized attosecond pulses. Potential applications of such pulses include spectroscopy [355], ultrafast magneto-optics or stereochemistry. Beyond circularly polarized harmonics, there is a growing interest in the generation of structured XUV light pulses. HHG enables the transfer of spatial properties, including OAM, from infrared laser beams to XUV pulses, producing harmonics with OAM that scales linearly with the harmonic order and driving field's topological charge. The generation of vortex XUV pulses thus needs an accurate description of the spatio-temporal properties of the driver [69]. Several techniques have emerged in attosecond spectroscopy over the past 25 years. Originally developed for temporal characterization of XUV pulses, attosecond streaking [346, 356] and reconstruction of attosecond beating by interference of two-photon transitions [347] have provided detailed information into photoemission time delays in atoms and molecules [357–359] or inelastic scattering time in dielectrics [360]. Attosecond photoelectron/ion spectroscopy has also provided invaluable insights into the mechanisms governing ultrafast dynamics in molecules [361–363] and solids. Another widespread technique is transient absorption/reflection spectroscopy, which has allowed, for example, the observation of valence electron motion [364] and electron correlations in atoms [365, 366], charge dynamics in solids [367–370] or molecular dynamics during ring-opening reactions [371, 372]. These advancements not only deepen our fundamental understanding of matter but also hold promise for the development of new technologies ranging from ultrafast electronics to tailored photochemical reactions. Recently, attosecond pulses have been generated at free-electron lasers (FELs) [373–375]. This achievement has significantly enhanced the capabilities of attosecond spectroscopy, complementing the unprecedented temporal resolution with unprecedented high intensities. The ability to produce high-energy attosecond pulses in the x-rays enables researchers to probe intricate processes with chemical sensitivity, also enabling nonlinear approaches that were previously inaccessible to elucidate light–matter interaction. In this field, the development of ultrafast technologies, such as the study of state-of-the-art broadband multilayer optics [376], and the exploration of innovative spectroscopic approaches, like XUV-assisted HHG experiments at FELs [377], undoubtedly play an important role. Collectively, these advancements highlight the remarkable evolution of attosecond science over the past 25 years. The field continues to push the boundaries of our ability to generate, control, and apply the shortest bursts of light, offering a powerful lens through which to study the ultrafast dynamics shaping the quantum world.

15. Intelligent adaptive metasurfaces

The manipulation of electromagnetic waves using aritificially engineered structures not only overcomes the limitations of traditional optics, but is also crucial for addressing the demands of emerging applications. The advent of metamaterials, first conceptualized in the late 20th century, marked a groundbreaking shift in controlling electromagnetic waves through man-made structures with unprecedented material properties [378–380]. Building upon this foundation, metasurfaces emerged as 2D analogs, offering compact and versatile platforms for manipulating wavefronts with subwavelength precision, facilitating a variety of exciting phenomena and novel applications [381]. Reconfigurable metasurfaces offer a promising solution for addressing the early version of passive metasurfaces enabling dynamic control of electromagnetic functionalities for multiple purposes. Moving forward, intelligent metasurfaces (shown schametiically in figure 10) have gain much attention by integrating deep learning into metasurfaces, which can accelerate the automated exploration of vast parameter spaces and adaptive control of metadevices [382–385]. Such synergy has transformed metasurface development, unlocked novel functionalities, and paved the way for intelligent wave manipulation systems. For intelligent metasurfaces, tunable metasurfaces are the physical foundation, and deep learning is the internal driving force. Their fusion is poised to give rise to radically intelligent devices that adapt to the changing electromagnetic waves and user demand autonomously. Intelligent adaptive metasurfaces would interact with the environment by perceiving and responding to external stimuli, while adjusting their internal properties to enable a precise customization of scattering field. A typical example is the intelligent self-adaptive invisibility cloak that exhibits a millisecond response time to a changing incident wave and the surrounding environment without human intervention [386–388]. In the last 25 years

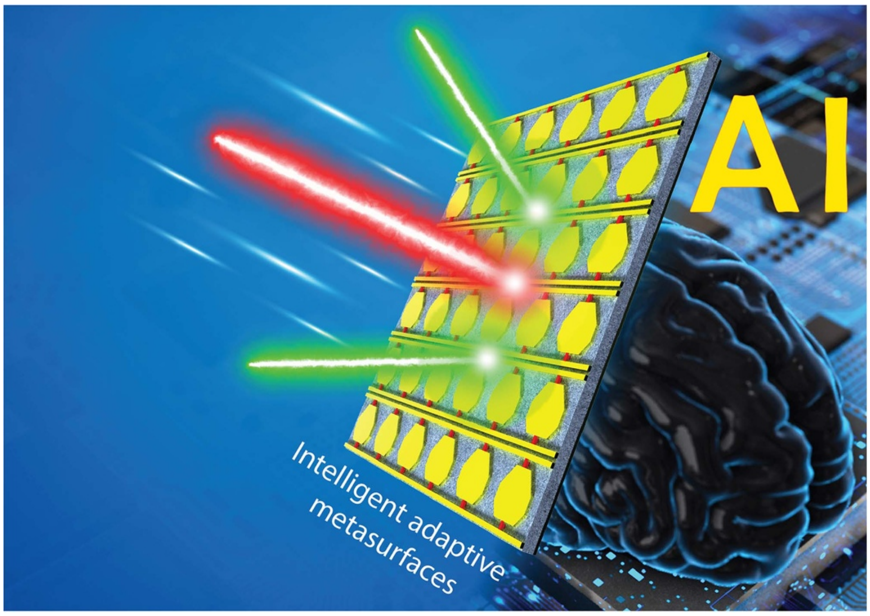

Figure 10. Concept of intelligent adaptive metasurfaces. Tunable metasurfaces serve as the physical foundation, while artificial intelligence acts as the internal driving force. Together, they empower intelligent metasurfaces to facilitate a wide range of adaptive applications autonomously, without the need for human intervention.

journey of metamaterials, the *Journal of Optics* has captured many advances of the field in several reviews [137, 264, 389]. For instance, in the review article, the authors present emerging fronts in areas of optical metamaterials that could contribute and apply to other research communities [389]. In another review article, the authors cover the physics behind the metasurfaces and their applications to realize electromagnetic devices [137]. Furthermore, in a tutorial-style article, the authors cover essential concepts, survey the field, and provide guidelines for the creation and deployment of artificial neural network architectures tailored to optical problems [390]. Journal of Optics has also play an important role in publishing research related to cascaded metasurfaces a spatial multiplexing encryption technique allowing multiple users to simultaneously access independent encryption information [391]. In an other example, a continuously tunable varifocal metalens has been designed based on optical phase changing materials [392]. The phase-gradient modulation concept proposed in the article helps to realize reconfigurable metasurfaces with simplified control architectures. Recently, in a perspective-style article, the authors foreground the rise of data-driven metasurfaces that are renovating our understanding and utilization of metasurfaces, moving away from human-based control towards automatic control based on real-time detection and updates of application requirement [393].

16. Concluding remarks

The *J. Opt.* has a rich history spanning 25 years in its present form, and over 100 years since first inception. Over the years it has evolved to remain topical and relevant, with the present scope covering topics as diverse as nanophotonics and plasmonics, metamaterials and metasurfaces, quantum photonics, biophotonics, nonlinear and ultrafast optics, structured light, integrated optics, optical communication, topological photonics, information optics, THz optics, light matter interaction, and photovoltaics and energy harvesting. This perspective accompanies a larger special issue to that attempted to touch on examples of the seminal work captured by the journal in modern topics across optics, celebrating the journal's role in past advances and pointing to a bright future.

Data availability statement

There is no data for this study. The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Andrew Forbes https://orcid.org/0000-0003-2552-5586
Mohamed Swillam https://orcid.org/0000-0002-7962-2341
Kayn A Forbes https://orcid.org/0000-0002-8884-3496
Yijie Shen https://orcid.org/0000-0002-6700-9902
Chao He https://orcid.org/0000-0001-9654-830X
Shuyuan Xiao https://orcid.org/0000-0002-4446-6967
Jörg B Götte https://orcid.org/0000-0003-1876-3615
Goutam K Samanta https://orcid.org/0000-0002-2611-6808
Tatsuki Tahara https://orcid.org/0000-0001-9560-1041
Boris Malomed https://orcid.org/0000-0001-5323-1847
Carmelo Rosales-Guzmán https://orcid.org/0000-0002-0321-0877
Peter Bermel https://orcid.org/0000-0001-7140-0667

Martijn Wubs https://orcid.org/0000-0002-8286-7825
Rocio Borrego-Varillas https://orcid.org/0000-0002-4499-0558
Caterina Vozzi https://orcid.org/0000-0002-0212-0191
Celia Rowland https://orcid.org/0009-0009-5872-6326
Elisa Pappalardo https://orcid.org/0000-0001-6881-9176
Lynn Paterson https://orcid.org/0000-0003-0493-5041
P H Souto Ribeiro https://orcid.org/0000-0002-0060-1717
Hongsheng Chen https://orcid.org/0000-0003-3573-3338

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