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ABSTRACT

Twisted light, with spatially varying phase or polarization, has given rise to various applications, such as micro-particle manipulation, optical communication, and quantum information processing. In recent decades, to bring these applications into reality, various configurations such as conventional spiral phase plates, computer-generated holograms, metasurface-based setups, and on-chip devices have been explored for twisted light generation. In this Perspective, we focus on recent progress in generation twisted light from typical on-chip devices such as waveguides, plasmonic nanoslits, whispering gallery mode configurations, and meta-gratings. We aim at highlighting the key research advances and technical challenges in on-chip twisted light generation. Finally, we outlook the likely future trend of this emerging research field.

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I. INTRODUCTION

Optical vortices, the vortex solutions of the Maxwell–Bloch equations, are the electromagnetic analog of fluid vortices investigated in hydrodynamics. Ever since the definition of optical vortices (OVs) by Coullet *et al.* in 1989,[1] a huge number of strategies have been proposed to generate such beams based on free-space or on-chip configurations.[2] A vortex beam with orbital angular momentum (OAM) features a helical wavefront expressed as $\exp(il\varphi)$, where φ denotes the azimuthal angle and l is the topological charge. Recently, OAM beams have been widely applied in numerous fields, such as optical manipulation,[3,4] imaging and microscopy,[5,6] quantum information processing,[7,8] remote sensing,[9] micro/nanofabrication,[10] and chiroptical responses on micro/nanostructures.[11,12] In particular, due to the unbounded and orthogonal states of OAM, twisted beams have been regarded as the most promising candidates for high-capacity optical communications[13–16] and quantum information processing.[8,17–19] Therefore, compact and reliable ways to generate twisted beams are of vital essential for realizing these emerging photonic technologies.

Conventional approaches for generating OVs such as spiral phase plates,[20] forked holograms with spatial light modulator,[21] and q-plates[22] inevitably involve bulky configurations, hindering their miniaturization and integration. Emerging applications based on the OAM degrees of freedom will probably demand photonic integrated circuits and devices with miniature size, high performance, and novel functionality. For this purpose, various mechanisms such as metasurfaces and on-chip devices have been adopted to develop compact OV generators, offering an easy and robust solution to obtain vortex beams.[23–32] In addition to these compact OV generators that create integer-order OAM beams, other compact setups capable of generating fractional-order OAM beams have also been demonstrated.[33,34] Despite the great achievement of single setups for twisted light generation, much effort should be made toward the integration of these setups into a compound system.[35]

For on-chip vortex generation, initial efforts were devoted to fiber-based generation techniques in which the twisted beams can transmit longitudinally among on-chip waveguides.[36] Lately, considerable attention has been devoted to plasmonic nano-aperture structures; however, the generated OAM beams have the disadvantage of low efficiency due to the intrinsic Ohmic dissipation of metal.[37,38] To improve the efficiency, attention was switched to low-loss all-dielectric platforms, enabling a series of high-performance on-chip twisted beam generators.[15,23,39–41] These twisted beam generators feature narrow or wide-band characteristics that cater to

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different application requirements. Moreover, on-chip dynamically tunable vortex beam generators have been demonstrated as well for important applications in future OAM-multiplexing and quantum information processing systems.[42,43]

In this Perspective, we discuss the evolution of several typical setups for on-chip generation and processing of twisted beams. The corresponding evolution process, design principles, underlying mechanisms, and emerging applications are introduced. We also discuss the technical challenges for various design approaches, such as mode purity, mode number, and efficiency. Ultimately, we give our prospects of future development in this field.

II. OVERVIEW AND POTENTIAL CHALLENGES OF ON-CHIP TWISTED LIGHT GENERATION

To date, twisted light has provided a new degree of freedom for understanding a wide range of optical phenomena, prompting various novel applications ranging from optical communication to quantum processing. Large-scale applications of twisted light require the development of integrated devices to enable the generation, transmission, and processing of this new degree of freedom. Orientated by this requirement, researchers have proposed various setups for on-chip twisted light generation, such as waveguides, plasmonic nanoslits, nano-structures that support whispering gallery modes (WGMs), and meta-gratings (Fig. 1).

As we know, various on-chip configurations along with corresponding design strategies have been proposed for twisted light generation. Despite their thrilling capacity in on-chip twisted light generation, different approaches have their own challenges. Here, we summarized several potential challenges for on-chip twisted light generation, such as mode purity, higher-order mode, vortex number, efficiency, and bandwidth (Fig. 2).

(a) **Mode purity.** Mode purity is defined as the degree of agreement or similarity between the output mode and the target mode, which can be expressed as *Mode purity* = *Correlation*(*profile*$_{\text{out}}$, *profile*$_{\text{target}}$). Vortex beams from planar plates such as plasmonic nano-structures and meta-gratings often suffer from low purity, resulting from the diffraction and phase-only modulation. In particular, the generation of high order or multiple OAM beams would further reduce their mode purity. The adoption of high quality factor cavities or elaborately designed waveguides could result in vortex beams with a high mode purity.

(b) **Higher-order mode.** The waveguides are used for generating low-order vortex beams, and it is difficult to generate high-order vortex beams. The elaborately designed cavity is able to generate vortex beams with topological charge up to 156.[44] Moreover, the plasmonic nano-structures have the potential for generating vortex beams with topological charge number up to hundreds.

(c) **Vortex number.** For high-capacity optical communications, such as the recently developed OAM-multiplexing and demultiplexing techniques, the multiplexing channel number is a key issue. Due to the physical limitations, it is very difficult to generate multiple vortex beams simultaneously in a single waveguide or cavity. Integrated cavities or waveguide arrays would be alternatives for multiple vortex beam generation. However, these strategies lead to bulky configurations.

(d) **Efficiency.** Efficiency is a key indicator for evaluating the performance of the vortex beam generator. Plasmonic nano-aperture structures have been used for generating vortex beams, but with the disadvantage of low efficiency due to the intrinsic Ohmic dissipation of metal. Dielectric materials with low absorption are excellent alternatives to overcome this disadvantage. Additionally, the precision and error in the fabrication process could also deteriorate the efficiency.

(e) **Bandwidth.** Vortex beams from WGMs have ultra-narrow bandwidth due to the resonant nature of WGMs. Vortex beams with narrow bandwidths nevertheless restrict their practical applications such as wavelength- and frequency-division multiplexing techniques in high-capacity communication. The use of meta-gratings can expand the bandwidth up to several hundred nanometers, and new strategies are required for further expanding the bandwidth.

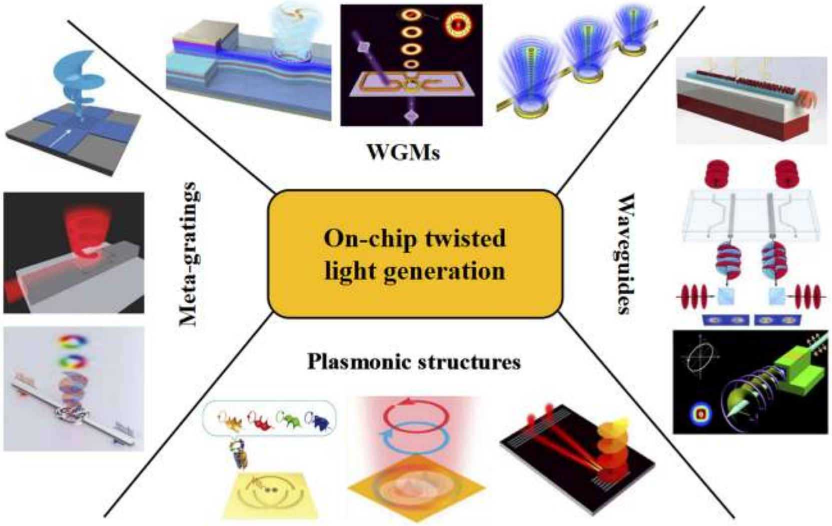

FIG. 1. Overview of recent developments of twisted beams from various on-chip devices such as waveguides, plasmonic nanoslits, WGMs, and meta-gratings. Here, for each kind of device, we show three typical representatives regarding twisted beam generation.

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FIG. 2. Demonstration of potential challenges for on-chip twisted light generation. Here, we summarize five potential challenges, namely, mode purity, efficiency, bandwidth, vortex number, and high-order mode.

III. THE EVOLUTION PROCESS AND DESIGN STRATEGIES OF ON-CHIP TWISTED LIGHT GENERATION

A. On-chip twisted light generation from waveguides

To generate and process on-chip twisted beams, initial efforts were devoted to fiber-based generation techniques.[36,45,46] In 1998, McGloin *et al.* demonstrated a stressed fiber-optic waveguide, which is able to convert a Hermite–Gaussian mode emitted from a laser into a well-defined twisted beam.[36] Soon after, a hybrid plasmonic waveguide is numerically demonstrated by Liang *et al.*, with the capacity of creating a vortex beam carrying spin and orbital angular momenta.[47] To achieve considerable birefringence, an asymmetric configuration is introduced in the hybrid plasmonic waveguide section [Fig. 3(a)]. Through elaborately designing the asymmetric geometry, a phase difference of $\pi/2$ between the quasi-TE and quasi-TM modes was achieved, producing a confined circularly polarized mode in the waveguide. Finally, through spin-to-orbital angular momentum conversion, a strong longitudinal OAM mode was generated in the waveguide. Lately, to create vortex beams from waveguides, different configurations have been proposed theoretically with the introduction of birefringence in the waveguide

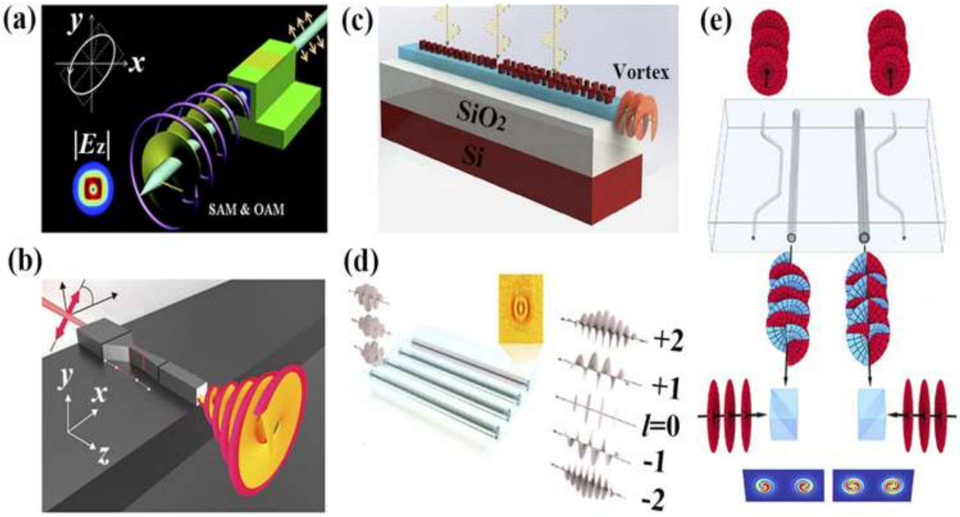

FIG. 3. On-chip twisted beams from optical waveguides. (a) Schematic of the hybrid plasmonic waveguide for generating a vortex beam carrying spin and orbital angular momenta. Reproduced with permission from Liang *et al.*, "Light beams with selective angular momentum generated by hybrid plasmonic waveguides," Nanoscale **6**, 12360 (2014). Copyright 2014 Royal Society of Chemistry. (b) Sketch of the on-chip integrated device for vortex beam generation. Reproduced with permission from Maltese *et al.*, "Towards an integrated AlGaAs waveguide platform for phase and polarisation shaping," J. Opt. **20**, 05LT01 (2018). Copyright 2018 IOP Publishing Ltd. (c) Schematic of the silicon-nanoantenna-patterned waveguide that directional couples free-space linearly y-polarized plane wave into right-propagating vortex beam. Reproduced with permission from Meng *et al.*, "Versatile on-chip light coupling and (de)multiplexing from arbitrary polarizations to controlled waveguide modes using an integrated dielectric metasurface," Photonics Res. **8**, 4000564 (2020). Copyright 2020 Chinese Laser Press. (d) Illustration of mapping twisted lights into and out of a photonic chip consisting of doughnut waveguides. Reproduced with permission from Chen *et al.*, "Mapping twisted light into and out of a photonic chip," Phys. Rev. Lett. **121**, 233602 (2018). Copyright 2018 American Physical Society. (e) Schematic of the asymmetric direction coupler comprising an OAM waveguide and a standard single-mode waveguide. Reproduced with permission from Chen *et al*., "Vector vortex beam emitter embedded in a photonic chip," Phys. Rev. Lett. **124**, 153601 (2020). Copyright 2020 American Physical Society.

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section.[48,49] In 2018, based on this mechanism, Maltese *et al.* experimentally demonstrated the generation of the vortex beam from an on-chip AlGaAs waveguide.[50] The scheme [Fig. 3(b)] involved a linearly polarized incident beam being passed through a waveguide and converted into a vortex beam carrying spin and orbital angular momenta.

For the above-mentioned waveguide-based vortex beam emitters, the incident light is all from one port of the waveguide, which somewhat restricts their potential applications. Recently, to solve this issue, a silicon-nanoantenna-patterned waveguide was proposed in which the free-space wave was converted into a waveguide-propagating vortex beam.[51] The silicon nanoantennae, patterned on the silicon-nitride waveguide, is optimized not only to couple directionally the free-space plane wave into the waveguide but also to endow the TE_{01} and TE_{10} modes with a phase difference of $\pi/2$ [Fig. 3(c)]. As a consequence, the free-space linearly y-polarized plane wave is converted into a right-propagating vortex beam. Moreover, considerable attention was paid to the mapping of twisted light into and out of a photonic chip using elaborately designed optical waveguides.[52,53] Chen *et al.* proposed and experimentally demonstrated the first laser-direct-written doughnut waveguides [Fig. 3(d)] that map OAM beams into and out of a photonic chip.[52] The states of OAM beams with topological charge −1, 0, +1 and their superpositions can couple into and transmit through photonic chips with a total efficiency of up to 60%. Very recently, an on-chip current device [Fig. 3(e)] has been developed into a vector vortex beam emitter.[53] This emitter comprises an OAM waveguide and a standard single-mode waveguide that can convert incident Gaussian beams into vector vortex beams with an efficiency up to 30%. With emitters integrated onto chips as an array, twisted light transmitting/emitting longitudinally in/from waveguides has the potential to advance immensely the development of high-capacity communication and quantum information processing.

B. Processing optical twisted beams via plasmonic nano-structures

To generate and process optical twisted beams in the near-field region, considerable attention has been paid to plasmonic Archimedes spirals.[54–57] In 2008, Gorodetski *et al.* experimentally demonstrated the generation of near-field vortex surface modes with spin-dependent topological charge via a plasmonic microcavity.[54] Shortly afterward, these created near-field vortex modes were selectively deployed for trapping or rotating particles.[55] Plasmonic Archimedes spiral nanoslits along with the created vortex field for optical macro-particle rotation were developed [Fig. 4(a)]. Apart from the Archimedes spiral nanoslits, other on-chip setups such as plasmonic vortex lenses and pinhole masks have also been used for generating near-field vortex modes.[58–60] The detailed spatiotemporal evolution of the vortex mode is explored by using time-resolved

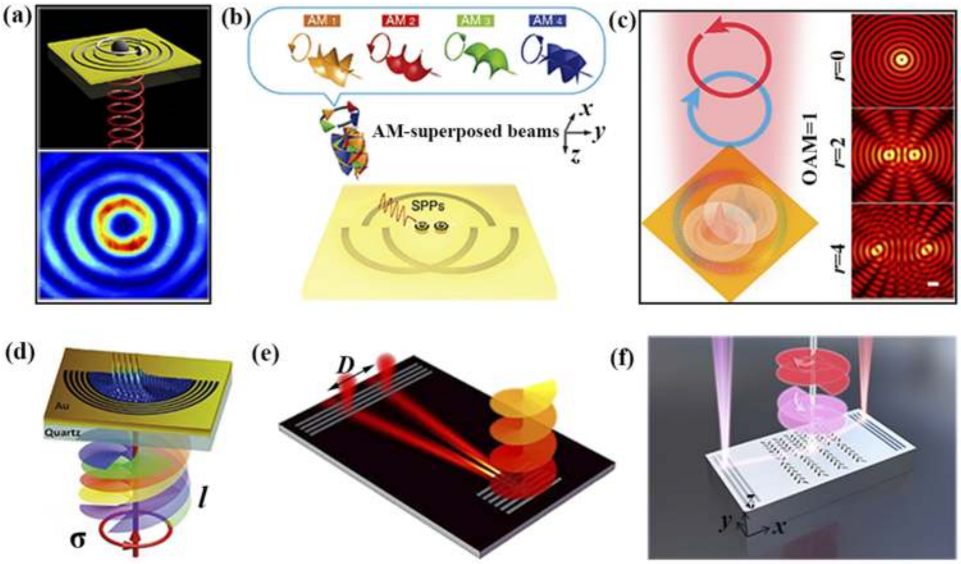

FIG. 4. On-chip twisted beams processing by plasmonic nano-structures. (a) Plasmonic Archimedes spiral nanoslits for optical macro-particle rotation. Reproduced with permission from Tsai *et al.*, "Selective trapping or rotation of isotropic dielectric microparticles by optical near field in a plasmonic archimedes spiral," Nano Lett. **14**, 547 (2014). Copyright 2014 American Chemical Society. (b) Schematic of the nano-ring aperture unit for on-chip noninterference AM multiplexing. Reproduced with permission from Ren *et al.*, "On-chip noninterference angular momentum multiplexing of broadband light," Science **352**, 805 (2016). Copyright 2016 AAAS. (c) Schematic illustration of the on-chip photonic spin Hall lens. Reproduced with permission from Du *et al.*, "On-chip photonic spin Hall lens," ACS Photonics **6**, 1840 (2019). Copyright 2019 American Chemical Society. (d) Schematic of the semi-circular sorter for launching and sorting multiplexed Laguerre–Gaussian beams. Reproduced with permission from Mei *et al.*, "On-chip discrimination of orbital angular momentum of light with plasmonic nanoslits," Nanoscale **8**, 2227 (2016). Copyright 2016 Royal Society of Chemistry. (e) Illustration of on-chip detection of OAM modes via elaborately designed grating. Reproduced with permission from Chen *et al.*, "On-chip detection of orbital angular momentum beam by plasmonic nanogratings," Laser Photonics Rev. **12**, 1700331 (2018). Copyright 2018 Wiley-VCH. (f) Schematic of the designed spin-Hall nano-grating capable of detecting both polarization and phase singularities. Reproduced with permission from Feng *et al.*, "On-chip plasmonic spin-Hall nanograting for simultaneously detecting phase and polarization singularities," Light: Sci. Appl. **9**, 95 (2020). Copyright 2020 Springer Nature.

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two-photon photoemission electron microscopy.[58] For high-capacity optical information technologies, twisted beams are often treated as the most promising candidates. However, the conventional bulky elements utilized for information retrieval impose a fundamental limit on realizing on-chip OAM multiplexing. To overcome this limitation, Ren *et al.* demonstrated noninterference OAM multiplexing via a mode-sorting nano-ring aperture with chip-scale footprint.[61] The distinctive OAM modes are selectively coupled out by the nano-ring slits, enabling on-chip parallel OAM multiplexing over a bandwidth of 150 nm [Fig. 4(b)]. In addition, we have proposed an on-chip photonic spin Hall lens [Fig. 4(c)], which generates spatially separated surface plasmon polariton vortices by changing the helicity of incident light.[62] For this lens, photonic spin routing and OAM-mode demultiplexing have been demonstrated, holding potential applications in on-chip and ultrafast photonic information processing.

On the other hand, to exploit the advantages of on-chip OAM beams, it is crucial to discriminate the OAM modes in a compact and reliable manner. For this regard, considerable effort has been devoted toward this objective with plasmonic configurations. An on-chip OAM detector [Fig. 4(d)], which is composed of multiple semi-ring plasmonic nanoslits, was fabricated.[63] Upon illumination with a specific twisted beam (with topological charge l), the OAM detector functions as a semi-circular source with an imparted azimuthal phase of $2l\pi$. Consequently, this OAM detector can focus twisted light with different OAM modes to different focal spots. However, this device depends on accurate alignment, bringing challenges in its practical application. To solve this issue, Chen *et al.* proposed an on-chip OAM detector [Fig. 4(e)] consisting of a plasmonic nano-grating.[64] This OAM detector couples an incident OAM beam into two separated surface beams with different splitting angles, and the incident OAM modes can be determined by recognizing the splitting angles. Very recently, based on the spin-Hall meta-gratings, Feng *et al.* demonstrated an on-chip plasmonic twisted beam detector.[65] Figure 4(f) shows the schematic of the proposed on-chip vortex detector with which the SAM and OAM of the incoming twisted beam can be simultaneously determined.

C. Optical twisted beams extracted from WGMs

As is well known, optical micro-cavities such as micro-disks or micro-rings support WGMs that carry high angular momenta and feature high quality factors.[66] The feasibility in selectively extracting a required WGM (via utilizing a proper coupler) opens new doors in designing integrated on-chip twisted beam emitters.[23,26,34,39,40,42,43,67,68] A significant advance toward an on-chip integrated vortex emitter [Fig. 5(a)] was demonstrated in experiments by Cai and co-workers experimentally with the generation of vortex beams with well-controlled OAM.[23] The integrated vortex emitter consists of an azimuthal periodic grating engraved along the inner wall of a micro-ring cavity and coupled to a bus waveguide for optical input. Under the angular phase-matching condition, a

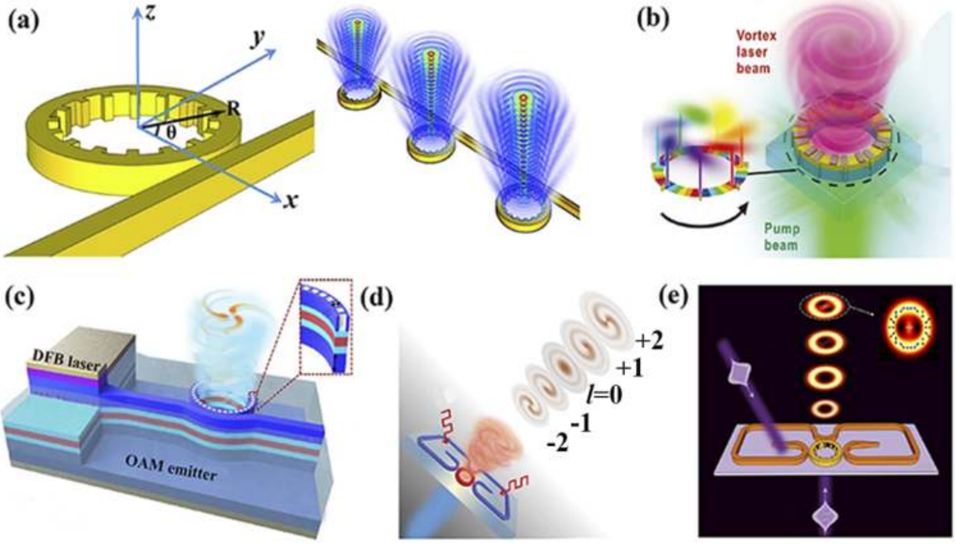

FIG. 5. On-chip twisted beams extracted from whispering gallery modes (WGMs). (a) Left panel: schematic of the vortex emitter with an azimuthal periodic grating engraved along the inner wall of a micro-ring cavity that is coupled to a bus waveguide. Right panel: Illustration of an array of three identical vortex emitters that scatter OAM beams into free space. Reproduced with permission Cai *et al.*, "Integrated compact optical vortex beam emitters," Science **338**, 363 (2012). Copyright 2012 AAAS. (b) Schematic of the OAM micro-laser on the InGaAsP/InP platform. The on-top alternating and periodically arrayed Ge and Cr/Ge introduces complex refractive index modulations and forms an exceptional point. Reproduced with permission from Miao *et al.*, "Orbital angular momentum microlaser," Science **353**, 464 (2016). Copyright 2016 AAAS. (c) Schematic of the monolithically integrated OAM laser composed of a laser diode and a micro-ring vortex emitter on InP substrate. Reproduced with permission from Zhang *et al.*, "An InP-based vortex beam emitter with monolithically integrated laser," Nat. Commun. **9**, 2652 (2018). Copyright 2018 Springer Nature.[39] (d) Schematic of the non-Hermitian-controlled vortex micro-laser capable of emitting OAM laser beam with switchable topological charges ranging from −2 to two. Reproduced with permission from Zhang *et al.*, "Tunable topological charge vortex microlaser," Science **368**, 760 (2020). Copyright 2020 AAAS. (e) Illustration of the vortex micro-laser for ultrafast control of FOAM. Reproduced with permission from Zhang *et al.*, "Ultrafast control of fractional orbital angular momentum of microlaser emissions," Light: Sci. Appl. **9**, 179 (2020). Copyright 2020 Springer Nature.[34]

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vortex beam with a controlled OAM value of $(p-q)\hbar$ is scattered into free space, where p is the order of the clockwise or anti-clockwise WGM in the micro-ring resonator, q is the number of equidistance gratings engraved along the inner wall of the micro-ring cavity, and $\hbar$ is Planck's constant h divided by 2π. By adding a resistive heater configuration on the above setup, a compact actively tunable vortex emitter is achieved with a switching rate of microseconds that is one to two orders faster than that of its bulky counterparts.[42] In such a device, active modulation of the emitted OAM mode, at a fixed wavelength, depends on the thermal-varying refractive index of the waveguide. Because of mirror symmetry in design, for a micro-ring with angular gratings, clockwise and anti-clockwise WGMs can be simultaneously excited, and hence, the emitted beams are cylindrical vector beams (CVBs).

To achieve a micro-ring OAM laser, a mechanism for unidirectional excitation of WGMs is needed that is similar to the conventional ring resonator lasers required to introduce non-reciprocal isolators. However, the realization of non-reciprocal isolators at the microscale is extremely challenging. To solve this issue, an exceptional point capable of realizing unidirectional power oscillation is introduced in the micro-ring laser.[67] The on-top alternating and periodically arrayed Ge and Cr/Ge layers introduce complex index modulations and form an exceptional point [Fig. 5(b)]. For this designed OAM micro-laser, single-mode OV laser beams with on-demand topological charges and vector polarization states have been experimentally demonstrated. In view of the practical on-chip applications, an OAM micro-laser was developed within a monolithically integrated OAM laser by adding a single-mode laser diode on the current setup.[39] Light from the distributed feedback laser [Fig. 5(c)] couples to the vortex emitter and resonates within the micro-ring, yielding a vertically emitted OAM laser beam.

However, the previously demonstrated on-chip miniaturized vortex laser at telecommunication wavelengths lacks reconfigurability, resulting from the single predetermined polarized OAM state at a fixed wavelength. To overcome this limitation, Zhang *et al.* demonstrated a tunable on-chip OAM micro-laser by judiciously applying an external non-Hermitian symmetry breaking setup.[43] The scheme for the non-Hermitian-controlled vortex micro-laser [Fig. 5(d)] enables the emission of an OAM laser beam with a switchable topological charge ranging from −2 to 2. The tunable OAM micro-laser consists of a micro-ring resonator coupled to an external feedback loop with two control waveguide arms. By pumping the control waveguide arm to either create gain or loss contrast, an asymmetric coupling between counter-propagating WGMs is achieved in the micro-ring, producing a specific OAM state with high purity. Moreover, together with a radial polarizer for optional on-chip spin-orbital conversion, an OAM laser beam with switchable topological charges from −2 and 2 is achieved. The dynamically tunable OAM micro-laser brings into reality emerging OAM-based technologies, such as OAM-multiplexed high-capacity information processing. Fractional OAM (FOAM) plays an important role in optical communication and computation applications; nevertheless, high-speed tunable FOAM is challenging. Very recently, by using the presented non-Hermitian-controlled vortex micro-laser platform [Fig. 5(e)], an ultrafast controllable FOAM vortex micro-laser was demonstrated.[34] In this setup, precise modulation of the time delay between the two femtosecond pump pulses leads to reconfiguration of the weighting of different OAM components, and consequently, a continuous FOAM sweep ranging from charge 0 to +2 within 100 ps is achieved.

D. On-chip twisted beams from meta-gratings

Despite their superior capacity of emitting twisted beams, WGMs have inherent narrow bandwidths that nevertheless restrict their practical applications such as wavelength- and frequency-division multiplexing techniques in high-capacity communication. To overcome this challenge, a series of strategies along with on-chip setups have been proposed. In this section, we review recently proposed on-chip meta-gratings for broadband on-chip twisted beam emission.

Conventionally, to generate broadband OV beams, an alternative method is the adoption of holographic fork gratings. Such a strategy could transplant into on-chip configurations, enabling broadband on-chip twisted beam emission.[41,69,70] Liu *et al.* proposed an on-chip vortex beam generator [Fig. 6(a)] consisting of a holographic fork grating patterned on a Si_3N_4 waveguide.[41] The guided modes in the waveguide can be coupled into specific free-space OAM beams through the elaborately designed holographic fork grating, within a wavelength band of 175 nm. In addition to the generation of single-mode OAM beams, the synthetization of OAM modes is of great interest for potential applications, such as OAM multiplexing and quantum state superposition. For this purpose, an on-chip silicon setup is demonstrated, with the capability to generate and synthesize OAM modes over an ultra-broad band.[69] The on-chip setup [Fig. 6(b)] is composed of a holographic fork grating patterned on a silicon waveguide. Input from one side of the waveguide leads to a specific OAM mode vertically converted to the free-space and the synthetization of them can be achieved upon inputs from both sides.

Nowadays, polarization has become a degree of freedom exploited in multiplexing techniques, and hence, polarization characteristics may be considered in the design of on-chip twisted beam emitters. Zhou *et al.* demonstrated an ultra-compact on-chip broadband polarization diversity twisted beam emitter based on a silicon configuration with a footprint of 3.6 × 3.6 μm^2.[71] The on-chip twisted beam emitter consists of a superposed holographic fork grating patterned on top of a cross-shaped silicon waveguide, enabling the coupling of waveguide modes to free-space OAM modes. Consequently, four different polarized OAM beams (x-polarized OAM_{+1}, x-polarized OAM_{-1}, y-polarized OAM_{+1}, and y-polarized OAM_{-1}) are emitted to the free-space under TE_0 guides mode incident from the four waveguide ports, with two of them being demonstrated [Fig. 6(c)]. To generate broadband OV beams, another alternative method is the inverse design strategy. By combining the genetic algorithm and annealing algorithm, we demonstrated an on-chip multiplexed twisted light emitter operating within an ultra-broadband from 1450 to 1650 nm.[15] The emitter consists of a synthesis of air and silicon meta-atoms [Fig. 6(d)], which are optimized by the joint phase control of the optical path and local resonances. Assisted by a 30-channel optical frequency combs (OFCs), the proposed emitter has been applied to an OAM communication with a data rate of 1.2 Tbit/s, providing a new method to further increase the capacity in OFC communication.

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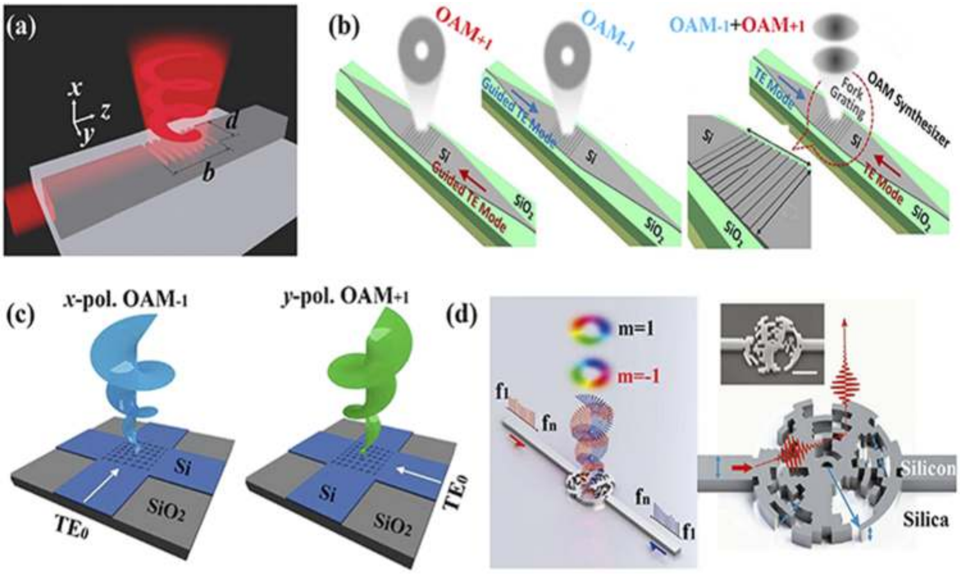

FIG. 6. Broadband twisted beams emitting from on-chip meta-gratings. (a) Schematic of the proposed vortex beam generator consisting of a holographic fork grating patterned on a Si_3N_4 waveguide. Reproduced with permission from Liu *et al.*, "On-chip generation and control of the vortex beam," Appl. Phys. Lett. **108**, 181103 (2016). Copyright 2016 AIP Publishing LLC. (b) Schematic of the on-chip platform for OAM beam generating and synthesizing. From left to right are the illustrations for generating OAM_{+1}, OAM_{-1}, and their synthesization. Reproduced with permission from Zhou *et al.*, "Generating and synthesizing ultrabroadband twisted light using a compact silicon chip," Opt. Lett. **43**, 3140 (2018). Copyright 2018 The Optical Society. (c) Illustration of the generation of broadband polarization diversity twisted beams: left panel for x-polarized OAM-1 and right panel for y-polarized OAM_{+1}. Reproduced with permission from Zhou *et al.*, "Ultra-compact broadband polarization diversity orbital angular momentum generator with 3.6 × 3.6 μm2 footprint," Sci. Adv. **5**, eaau9593 (2019). Copyright 2019 AAAS. (d) Left panel: schematic illustration of the on-chip multiplexed twisted light emitter. Right panel: detailed structure design. Reproduced with permission from Xie *et al.*, "Ultra-broadband on-chip twisted light emitter for optical communications," Light: Sci. Appl. **7**, 18001 (2018). Copyright 2018 Springer Nature.

IV. POTENTIAL APPLICATIONS FOR TWISTED LIGHT FROM DIFFERENT ON-CHIP SETUPS

For vortex beams from waveguides, the most intuitive application is OAM-multiplexing communication. In contrast to conventional optical communication, the OAM-multiplexing and demultiplexing communication technique has specific advantages in enhancing the communication capacity owing to the adoption of the new degree of freedom.[72,73] For high-capacity OAM communication, the multiplexing channel number is a key issue. Integrating waveguides to form an array would be an alternative strategy, but it will lead to bulky configurations. Moreover, it is difficult to generate high-order vortex beams by using waveguides, which, to some extent, restrict the development of high-capacity OAM communication in fiber systems. Another potential application is the optical fiber tweezers.[74] It overcomes the disadvantages of traditional optical tweezers, such as expensive and bulky configuration. The optical fiber tweezers are capable of non-invasive capturing and manipulating micro-particles, holding potential applications in the biological and biomedical fields.

Twisted beams from plasmonic nano-structures can be used as near-field optical tweezers. In contrast to conventional optical tweezers, near-field optical tweezers overcome the restriction of diffraction limit of optical resolution, achieving the capture and control of particles at the nanoscale. With a proper design, the plasmonic near-field optical tweezers can be used to simultaneously control of multiparticles.[75] Another potential application for these twisted beams is the OAM-multiplexing and demultiplexing communication technique. Moreover, the plasmonic nano-structures can be used to discriminate the OAM modes in a compact and reliable manner. Despite the capacity of processing OAM beams, however, the low efficiency due to the intrinsic Ohmic dissipation of metal would worsen the performance of devices, limiting their practical applications. Future attention could focus on exploring smart materials and ingenious strategies, facilitating efficient near-field twisted beam processing.

The twisted laser beams from the WGMs usually have high purity and efficiency, which have potential applications in the next generation of integrated optical devices for optical communications. Moreover, the twisted laser beams with tunable topological charge numbers open new opportunities in high-speed signal modulation and multiplexing in telecommunications. Another potential application for these twisted laser beams is the high-dimensional quantum communication. The single photon beam with OAM generation from this platform awaits further exploration. Twisted laser beams from the WGMs have ultra-narrow bandwidth due to the resonant nature of WGMs. The narrow bandwidth nevertheless restricts their practical applications such as wavelength- and frequency-division multiplexing techniques in high-capacity communication.

Twisted light beams from on-chip meta-gratings have the characteristic of broadband, which is compatible with wavelength- or frequency-division multiplexing high-capacity communications.

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However, the efficiencies of the generated beams from the meta-gratings are low owing to the diffraction effect. The fast-developing inverse design approach such as genetic algorithm and deep learning algorithm can be adopted to enhance the efficiency and further broaden the bandwidth of the generated twisted beam.

V. CONCLUSIONS AND OUTLOOK

Twisted lights carrying OAMs have provided a new degree of freedom in light–matter interactions, enabling numerous advanced applications in modern photonics. In this Perspective, we have briefly reviewed the recent progress in the field of on-chip twisted light generation from typical setups such as waveguides, plasmonic nanoslits, WGM configurations, and meta-gratings. We have summarized the evolution process, design principles, underlying mechanisms, technical challenges, and emerging applications for on-chip twisted light generation. Despite the fact that there are already quite a lot of achievements in on-chip twisted light generation, much effort could be devoted toward solving the challenges of on-chip twisted light generation. We envisage that, with the emerging of smart materials and ingenious design strategies along with rapid development in nanofabrication, the emerging OAM-based photonic technologies and applications will be implemented in the near future.

Despite the great achievement in on-chip twisted light generation, most of the current demonstrated twisted light generators are static in nature. The loss of tunability would, to some extent, restrict their potential applications in specific fields. Nowadays, various modulation mechanisms have been proposed to achieve dynamically tunable devices, such as optical control,[76–78] thermal control,[79,80] electrical gating,[81–84] and mechanical actuation.[85–87] Correspondingly, numerous tunable functional materials, such as graphene,[81,88–90] phase-change materials,[91–94] and liquid crystals,[95–98] have been employed in these modulation mechanisms. These modulation mechanisms along with specific materials could be adopted to design on-chip twisted light generators with tunability and reconfigurability, opening up new doors for the development of the next generation multi-dimensional OAM-multiplexing technology.

Nowadays, the inverse design approaches such as gradient-based algorithm,[99] genetic algorithm,[100] and deep learning algorithm[101–103] have been used for nanodevice design. As we know, by using the inverse design approach, one can achieve comparable performance with that of the typical direct design approach. More importantly, the inverse design approach can be utilized to achieve specific functionalities that prove difficult to be implemented by the direct design approach. We believe that the booming inverse design approach would definitely accelerate the development of high-performance and versatile on-chip twisted light generation.

Twisted light holds potential in numerous applications in the field of photonics. Here, we foresee several certain promising fields that may be further alighted by the development of on-chip twisted lights: (1) high-capacity optical communications enabled by the recent advances in OAM-multiplexing and ultrafast vortex modulation, (2) optical tweezing enabled by tunable twisted light in the spatiotemporal domain, and (3) quantum optics applications enabled by vortex beams with improved efficiency and purity. Moreover, the summarized strategies and mechanisms for on-chip twisted light generation may also benefit the research of analog in electron, neutron, acoustic, and magnetic domains.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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