LASERS AT 60 YEARS

Supertwisted Light from a **Metasurface Laser**

A new metasurface laser emits high-purity, nonsymmetric superchiral light with unprecedented control over angular momentum at the source.

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Structured light refers to the tailoring or shaping of light in all its degrees of freedom. The recent development of structured light supports applications such as optical communications, enhanced resolution in imaging, and optical trapping and tweezing. Chiral light is foremost among the family of structured light fields that carries spin angular momentum ($\pm\hbar$ per photon, depending on the handedness) and orbital angular momentum (OAM, $\ell\hbar$ per photon, where ℓ is an integer).

An open challenge in this field is arbitrary control of light's chirality — spin and orbital — at the source. So far, advancements have been limited due to fundamental symmetry restrictions and spatial resolution of the optical elements[1,2]. Results from the former always perform zero in the total angular momentum (TAM), and the latter restricts the purity and efficiency while generating a higher OAM value. Superchiral light with high angular momentum is known to be important in many fundamental and applied studies. Arbitrary angular momentum control of light at the source has remained elusive.

It is believed that this research is the first to demonstrate that a laser can produce any desired angular momentum state with an intracavity metasurface. The research has shown new high-purity OAM states with quantum numbers reaching 100 and nonsymmetric vector vortex beams that lase simultaneously on independent OAM states as much as a quantum numbers difference of 90 (10 and 100 demonstrated)[3]. This laser conveniently outputs in the visible, offering a compact and power-scalable source that harnesses intracavity structured matter for the creation of arbitrary chiral states of structured light. The result opens new avenues for innovation and applications based on metasurface lasers.

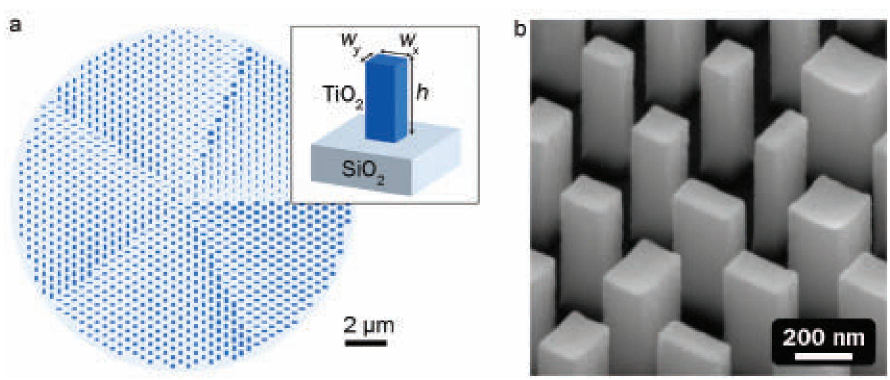

Figure 1. A schematic image of typical J-plate design for OAM (*m, n*) = (1, 5) operating in the linear polarization basis **(a)**. A tilted scanning electron microscope image of a few typical nanopillars constituting a J-plate **(b)**.

Courtesy of Reference 3.

Metasurface J-plate

Technologies such as the Q-plate are one of the common methods used to generate OAM-carrying beams in free space. Q-plates, based on the Pancharatnam-Berry (PB) phase, perform the transformation $|L\rangle \rightarrow e^{i2q\varphi}|R\rangle$ and $|R\rangle \rightarrow e^{-i2q\varphi}|L\rangle$, where the circular polarizations (spin) are flipped to output states with opposite OAM, $\pm 2q\hbar$. These techniques thus only produce two possible output states, adding a fixed amount of OAM to one spin state and an equal and opposite amount to the opposite spin state. The result is that the TAM adds to zero. Q-plates are mainly realized using liquid crystals, such as a spatial light modulator (SLM) that allows the production of dynamic diffraction patterns. However, the relatively large pixel size limits the beam quality, effciency, and capability of generating high OAM states.

Metasurfaces, on the other hand, are composed of subwavelength artificial structures and enable spatial modulations of phase and polarization on demand. This allows high-effciency spin-orbital conversion and generation of vortex beams with high topological charges. The metasurface J-plate, with J referring to the photon's TAM, is a metasurface device based on both the propagation phase and PB phase and performs the transformation $|\lambda^+\rangle \rightarrow e^{im\varphi}|(\lambda^+)^*\rangle$ and $|\lambda^-\rangle \rightarrow e^{in\varphi}|(\lambda^-)^*\rangle$[4]. The inputs $|\lambda^+\rangle$ and $|\lambda^-\rangle$ are orthogonal basis, and the corresponding outputs $|(\lambda^+)^*\rangle$ and $|(\lambda^-)^*\rangle$ have opposite handedness. Notably, the conversion works for arbitrary orthogonal bases (any elliptically polarized state) and imparts two arbitrary OAM states ($m\hbar$ and $n\hbar$ can be independent), overcoming restrictions of Q-plates.

The J-plates used in the laser cavity

(Figure 1) are a dielectric metasurface made of amorphous TiO_2 nanopillars with rectangular sections (Figure 1a, inset) on a fused glass substrate. Each pillar has a height of 600 nm while the width and length (w_x, w_y) change in order to impart a different phase delay to the propagating visible light at 532 nm. More specifically, each nanopillar imparts an overall phase delay to the propagating light and a phase delay difference between the field in the x and y components[5]. The phase delay difference only depends on the shape of the pillars and is called form birefringence. Note that symmetric sections such as squares or circles do not show form birefringence.

Figure 1a shows the schematic image of the central part of a J-plate that converts two orthogonal linear polarization states ($|\lambda^+\rangle = |H\rangle$ and $|\lambda^-\rangle = |V\rangle$) into helical modes with the same polarization state and OAM $(m, n) = (1, 5)$. Figure 1b shows a tilted scanning electron microscope image of another J-plate designed for OAM $(m, n) = (10, 100)$ in the linear polarization basis. The light propagates through the tiny pillars of the metasurface, causing the geometric phase of the light to be altered. This produces a corkscrew variation of the wavefront in the output. One thus produces so-called intertwined twists of light, while simultaneously controlling its polarization.

Metasurface laser

The laser, shown schematically in Figure 2a, is a frequency-doubled cavity that converts the infrared fundamental frequency of Nd:YAG ($\lambda = 1064$ nm) to the second-harmonic green ($\lambda = 532$ nm) through an intracavity nonlinear crystal (KTP). Each time the light passes through the J-plate, a particular twist is added to the beam's wavefront. Due to the reciprocity of both light and the metasurface device, light returns to its initial state after every round trip inside the laser, and the conservation of the TAM inside the system is maintained. The output modes from the cavity can then simply be altered by only rotating the J-plate with angle θ, which is equivalent to changing the effective polarization state "seen" by the metasurface. Consequently, a desired mode combination is generated, $sin\theta|m, H > + cos\theta|n, V >$, which constitutes the most general OAM-to-spin paired state — a state that has never been produced from a laser before.

In the general case of $(m, n) = (10, 100)$, the metasurface was crafted to generate nonsymmetrical OAM states. Figures 2b, c, and d show the calculated beam profiles with various rotation angles of the J-plate. Such generation of supertwisted light, OAM state of $\ell = 100$, has not been

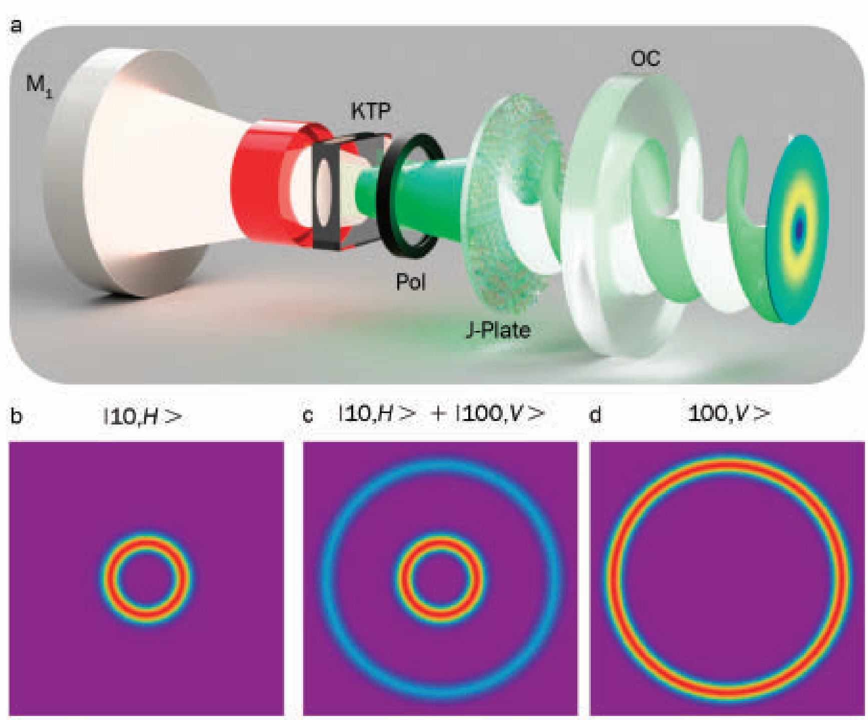

Figure 2. An illustration of a laser cavity with an intracavity nonlinear crystal (KTP), polarizer (Pol), and metasurface (J-plate), excited by an infrared pump, with the green light emerging from the output coupler (OC) mirror **(a)**. Calculated states from the laser with OAM order 10 **(b)**, OAM order 100 **(d)**, and the superposition **(c)**.

Figure 2(a) courtesy of Reference 3. Figure 2(b,c,d) courtesy of Hend Soor.

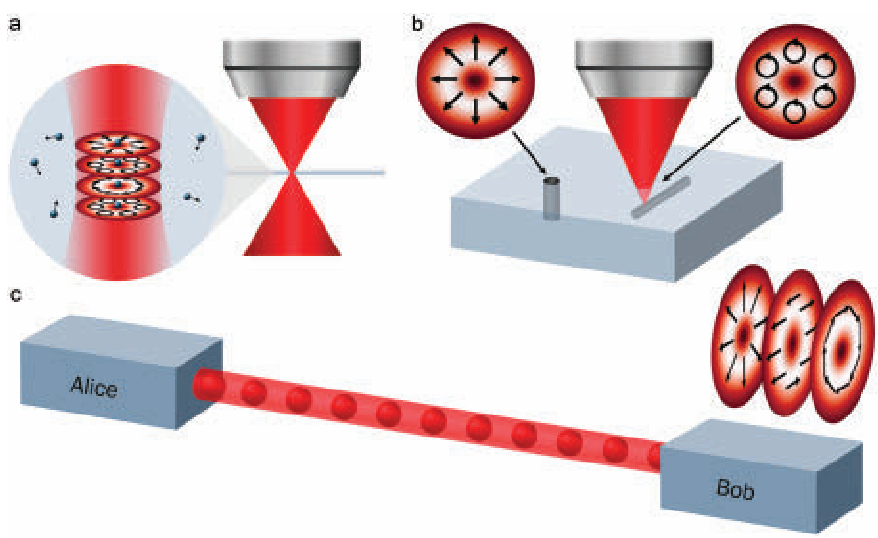

Figure 3. Supertwisted light applications. Optical trapping and tweezing with selection **(a)**, optical spanner for nanomanufacturing **(b)**, and optical communication and quantum protocols **(c)**.

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observed from lasers until now. The metasurface resolution (of nanometer scale) has made it possible to create these modes with higher quality. Alternative technologies such as Q-plates and SLMs have not even come close to these values of OAM, let alone purity. Additionally, the metasurface laser output states can contain a large OAM difference, as much as $\Delta\ell = 90$ apart, which is an extreme violation of previous symmetric spin-orbit lasing devices. Another interesting feature is that these modes are in fact very different in size when they come out of the laser. When they travel around the cavity, however, they converge to a similar shape and size, where they experience optical gain. This allows for a coherent mode — a telltale sign of lasing — even though the actual beams look spatially separated.

The metasurface laser is attractive for many reasons. For example, it can be used in different designs, meaning it can be tailored to better fit the physical parameters of where it is implemented. Due to the high damage threshold of the metasurface device, the gain intracavity can be increased to produce bulk lasers with higher power, or even compressed to make use of monolithic/microchip designs. In both cases, the resonant mode would be controlled by the pump's polarization, and thus no additional intracavity elements are required, other than the metasurface itself.

Outlook and opportunities

The metasurface laser is a new milestone in the history of structured light lasers because it breaches spin-orbit coupling symmetry and enables new high-purity OAM states from a laser. The laser design, together with the metasurface previously described, enables unprecedented control over light's total angular momentum (chirality) at the source.

This approach lends itself to many laser architectures. For instance, this type of light can be used to optically drive gears in situations where physical mechanical systems would not work, such as in microfluidic systems to drive flow (Figure 3a). There is currently strong interest to control chiral matter with twisted light; for this to work, light with very high twist is needed. Nonsymmetrical output modes can also be applied to optical trapping to separate cells or particles because of the various associated scattering forces of the beam. This type of light can be used as an optical spanner for nanomanufacturing (Figure 3b). Furthermore, information can be packed into states for optical communications (Figure 3c) and exploited for quantum protocols.

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Acknowledgments

We thank Bereneice Sephton (University of the Witwatersrand, South Africa), Adam Valles (Chiba University, Japan), Vincent Ginis (Vrije Universiteit Brussel, Belgium), Cheng-Wei Qiu (National University of Singapore, Singapore), Antonio Ambrosio (Fondazione Istituto Italiano di Tecnologia, Italy), Federico Capasso (Harvard University, U.S.), and Andrew Forbes (University of the Witwatersrand, South Africa).

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