Mapping Twisted Light into and out of a Photonic Chip

Yuan Chen,¹,² Jun Gao,¹,² Zhi-Qiang Jiao,¹,² Ke Sun,¹ Lu-Feng Qiao,¹,² Hao Tang,¹,² Xiao-Feng Lin,¹,² and Xian-Min Jin¹,²

¹State Key Laboratory of Advanced Optical Communication Systems and Networks, Institute of Natural Sciences & Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China
²Synergetic Innovation Center of Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui 230026, China

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Twisted light carrying orbital angular momentum (OAM) provides an additional degree of freedom for modern optics and an emerging resource for both classical and quantum information technologies. Its inherently infinite dimensions potentially can be exploited by using mode multiplexing to enhance data capacity for sustaining the unprecedented growth in big data and internet traffic, and can be encoded to build large-scale quantum computing machines in high-dimensional Hilbert space. While the emission of twisted light from the surface of integrated devices to free space has been widely investigated, the transmission and processing inside a photonic chip remain to be addressed. Here, we present the first laser-direct-written waveguide capable of supporting OAM modes and experimentally demonstrate a faithful mapping of twisted light into and out of a photonic chip. The states OAM₀, OAM₋₁, OAM₊₁ and their superpositions can transmit through the photonic chip with a total efficiency up to 60% with minimal crosstalk. In addition, we present the transmission of quantum twisted light states of single photons and measure the output states with single-photon imaging. Our results may add OAM as a new degree of freedom to be transmitted and manipulated in a photonic chip for high-capacity communication and high-dimensional quantum information processing.

An optical beam with a spatial degree of freedom of OAM is twisted like a corkscrew around its axis of travel and the cancellation of light waves at the axis itself results in a “doughnut” intensity profile. The twisted light has a helical wave front with an azimuthal phase term eⁱℓφ [11], with which every photon can carry an OAM of ℓℏ ( ℓ is topological charge, φ is azimuthal angle, and ℏ is Planck constant h divided by 2π ). Having the special features of intensity structure (“doughnut” intensity), phase structure (spiral phase front) and dynamic characteristic (carrying OAM), the twisted light has been widely applied into the field of optical manipulation [2], optical trapping [3,4] and optical tweezers [5].

In recent years, OAM has shown the great potential in communication systems to overcome the channel capacity crunch [6,7]. The unlimited topological charges and the inherent orthogonality may provide tremendously resources for mode multiplexing. The inherently infinite dimensions potentially can also be exploited to deliver high-dimensional quantum states with larger alphabets and to build quantum computing machines in high-dimensional Hilbert space [8,12].

Large-scale applications of OAM beyond proof-of-principle demonstrations require developing integrated devices to enable the generation, transmission and processing of such new degree of freedom. Previous works have demonstrated on-chip generation twisted light with integrated star couplers [13], micro-ring resonators [14] and controlled phase arrays [15]. While the emission of twisted light from the surface of integrated devices to free space has been widely investigated, the transmission and processing inside a photonic chip remain to be solved. In this letter, we demonstrate a faithful mapping of twisted light into and out of a photonic chip by prototyping “doughnut” waveguides with femtosecond laser direct writing [16,17]. We couple the states OAM₀, OAM₋₁, OAM₊₁ and their superpositions into and out of the photonic chip with a total efficiency up to 60% and verify the output states by interference with Gaussian reference beam. In addition, we present the transmission of single-photon quantum twisted light and measure the output states with single-photon imaging.

In conventional waveguides, the effective index nₑff is much too small to isolate near-degenerate OAM states from one another. A solution to this problem is to enhance the vector splitting through a choice of waveguide structure. It is known that the typical transverse intensity pattern of a OAM beam is “doughnut” shaped. The waveguides with such shaped cross section, being cylindrically symmetric structure, may support OAM modes. The key physical problem of OAM propagating in cylindrically symmetric structure is that, during total internal reflection, phase shifts at index discontinuities critically depend on polarization orientation of an incident wave [18]. To translate this physical problem into a mathematical problem, it can be expressed by a full vectorial solution of the Maxwell equations. By means of a first-order perturbative analysis, it is found that an “doughnut” waveguide would be more suitable for supporting OAM states [18].

We realize constructing such three-dimensional (3D) structure by using femtosecond laser direct writing technique (see Methods). Fig. 1a inset shows the cross section image of the fabricated waveguide. We prepare the twisted light in different OAM modes and couple them into the “doughnut” waveguide embeded in the photonic chip and expect to observe well-preserved output states. As is shown in Fig. 1b, the probe is switchable to both coherent light and heralded single photon (see Methods). After mapping out of the photonic chip, we

* xianmin.jin@sjtu.edu.cn
FIG. 1: Experimental implementation. a. Schematic diagram of mapping twisted light into and out of a photonic chip. The inset shows the cross-section image of a femtosecond laser-written “doughnut” waveguide. The OAM modes are generated externally, then coupled into “doughnut” waveguide, and finally analyzed after chip. b. The experimental setup with classical and quantum probes in OAM degree of freedom (see Methods). Comp: half wave plate and 1-mm-thick BBO crystal together are used to compensate temporal and spatial walk-off of the photon pair; BS: beam splitter; PBS: polarization beam splitter; SLM: spatial light modulator; BF: band-pass filter (780 nm ± 6 nm); ICCD: intensified charge coupled device camera.

measure the intensity profile with CCD camera. The total efficiency is obtained by measuring the probe power before and after the chip, which is up to 60%.

The observed intensity profiles of OAM$_{-1}$, OAM$_{0}$, OAM$_{+1}$ modes are shown in Fig. 2a. The prepared states before mapping into the chip are shown in the first column and the output states are shown in the second column. We define similarity to benchmark the ability of preserving the spatial structure of OAM. The obtained similarity for $\ell = \pm 1$ reaches up to 96.6% and 96.2% respectively (see Methods). The polarization of the output OAM$_{-1}$ and OAM$_{+1}$ modes are found unchanged with the extinction ratio up to 80:1.

By inserting a beamsplitter, we are able to measure the interference with a Gaussian reference beam. The yielded interference pattern shown in the third column of Fig. 2a can be employed to verify the topological charge of the output OAM modes. The high-visibility clockwise (counterclockwise) spiral interference pattern are observed for OAM$_{+1}$ (OAM$_{-1}$) state, which indicates a great ability to maintain the topological charge of the twisted light.

Besides individual pure states, we further look into the ability to support general superposition states. We can construct matrices to describe the superpositions of OAM$_{\pm \ell}$ and their transformations on two-dimensional subspaces [19] that can be represented by a Bloch sphere, equivalent to the Poincaré sphere for polarization [20]. By tuning the relative phase and the magnitude of the superposition components on a spatial light modulator, we can access states distributed over the entire Bloch sphere [21]. We show the results of mapping six universal states on Bloch sphere into and out of the photonic chip, which indicate great capacity to simultaneously support all superposition states (see Fig. 2b). Interestingly, we also observe a purification effect that output states possess even better spatial structure than the input states. It can be understood that the unwanted components of the imperfect input states can be spatially filtered out by the waveguide that only supports well-defined OAM modes.

Such a purification effect are also observed when we try to map higher-order OAM modes. As is shown in Fig. 3a, while the sign of positive and negative topological charges are unchanged, the states are all mapped out with their corresponding first-order OAM modes, which are clearly revealed by the chirality and the number of arms in the measured interference patterns. In our experiment, the coupling objective is optimized for mode matching of OAM$_{-1}$, OAM$_{0}$, OAM$_{+1}$ between free-space beam profile and waveguide cross section. We do observe that the total efficiency can reach 60% for OAM$_{\pm 1}$ and drop below 10% for OAM$_{\pm 6}$ (see Fig. 3b).
FIG. 2: Experimental results of mapping OAM\(_{-1}\), OAM\(_{0}\), OAM\(_{+1}\) and their superpositions. a. The measured intensity profiles of OAM\(_{-1}\), OAM\(_{0}\), OAM\(_{+1}\) modes before (after) the chip are shown in the first (second) column. Measured interference patterns shown in third column clearly confirmed faithful preservation of topological charges \(\ell\). b. Experimental results of OAM superposition states for \(\ell = 1\). The holograms applied to SLM and the measured intensity profiles for six universal states are presented visually pointing to Bloch sphere.

FIG. 3: Experimental mapping of higher-order OAM modes. a. The measured intensity profiles and interference pattern on the output of the chip for high-order topological charges \(\ell\) up to 6. b. The obtained total efficiency \(\eta\) versus topological charge \(\ell\). c. The maximum intensity diameter \(D\) defined by our coupling systematic parameters versus topological charge \(\ell\). d. The normalized optical intensity in the focal plane along the radial direction for OAM\(_{\pm 6}\).

By fixing the input coupling optical system, the diameter of maximum optical intensity in the focal plane can be derived according to Collins-Huygens integral to analytically describe propagation of a “doughnut” beam [22], and would tend to scale linearly with the topological charge [22] (see Fig. 3c). For example, as is shown in Fig. 3d, the diameter of OAM\(_{\pm 6}\) is as large as 30 \(\mu\)m, which far exceeds the mode diameter of the waveguide. Besides the spatial filtering induced selection...
of OAM modes, the “doughnut” waveguide itself also tends to support certain order twisted light [24] and further contribute to the observed purification/filtering effect.

The inherently infinite dimensions potentially can be exploited as an alternative resource to prepare high-dimensional Hilbert space quantum states, hyper-entanglement for instance, to boost the computational power of quantum computing and quantum simulations, rather than to prepare quantum states with higher photon number. The resource of photonic dimensions seems more scalable than photon number [25], but requires complex processing circuits and phase-level stability, i.e. is physically unscalable. Quantum integrated photonics would be an elegant solution for such demands. We make the step forward for OAM-based high-dimensional quantum information processing by demonstrating mapping single-photon quantum twisted light into and out of photonic chip. Thanks to the rapid progress in imaging technologies over the last few years, CCD cameras has become an interesting option for single-photon detection in quantum optics experiments, since the large spatial information [26, 27] is directly accessible. In this experiment, we directly visualize quantum twisted light in thermal states and heralded single-photon states before and after photonic chip by employing an ICCD camera. The obtained intensity profiles are shown in Fig. 4 without any Fourier-transformation-based noise filtering and background reduction. It should be noticed that the high-quality imaging of heralded single-photon states are achieved because we utilize the detection signal of another photon to trigger ICCD with a time window as narrow as 10 ns.

In summary, we demonstrate a faithful and highly efficient mapping of twisted light into and out of a photonic chip by prototyping “doughnut” waveguides with femtosecond laser direct writing. The simultaneous support of the states OAM$_{-1}$, OAM$_{0}$, OAM$_{+1}$ and their superpositions suggests that it is possible to transmit and manipulate OAM states inside a photonic chip. We also show the compatibility of single-photon quantum twisted light to the photonic chip and measure the output states with single-photon imaging, which may promise OAM based integrated high-dimensional quantum information processing. Multi-channel all-on-chip sender (receiver) can be conceived to encode (sort) OAM with large alphabet information [28], for both classical and quantum communications. The combined use of different degrees of freedom of a single photon, such as spin and orbital angular momentum, enables the on-chip implementation of entirely new quantum information systems in a high-dimensional space [10, 12, 29] for quantum supremacy.

**Methods**

3D Fabrication of “doughnut” waveguides: The “doughnut” waveguide proposed to support OAM modes on a photonic chip is very different from using a single-mode fiber. Its cylindrically symmetric structure requires 3D fabrication capacity, which is very challenging to be realized with conventional methods of silicon photonics. We employ femtosecond laser direct writing technique to realize such 3D capacity. The wafer materials only absorb energy in a scope of micrometer level and a short time slot of hundreds of femtoseconds due to the nonlinear effects, and therefore their refractive index can be modified in a very small scale [16, 17, 30]. Continuous scanning the wafer and/or focal spot of the laser allows us to manufacture a very thin line. Multiple writing in such way can construct the proposed “doughnut” waveguide piece by piece, just like a “surgery operation”. The wafer materials only absorb energy in a scope of micrometer level and a short time slot of hundreds of femtoseconds due to the nonlinear effects, and therefore their refractive index can be modified in a very small scale [16, 17, 30]. Continuous scanning the wafer and/or focal spot of the laser allows us to manufacture a very thin line. Multiple writing in such way can construct the proposed “doughnut” waveguide piece by piece, just like a “surgery operation”. The wafer is a 1 × 20 × 20 mm borosilicate glass. The fabrication laser centred at 513 nm with pulse duration of 290 fs possesses a pulse energy of 70 nJ and a repetition rate of 1 MHz. The pulses are focused 170 μm under the sample surface using an objective with a numerical aperture of 0.7, while the sample is translated at constant speed of 5 mm/s by high-precision positioning stages. The refractive index contrast and birefringence are estimated...
at the order of $10^{-3}$ and $10^{-5}$, respectively. The diameter of the “doughnut” is set at $8 \, \mu m$. The optimal number of scanning is $12$ while we apply an additional scan through the middle.

**Classical and quantum twisted light preparation:** As is shown in Fig. 1b, a Ti: Sapphire Oscillator centred at 780 nm is divided into three beams by inserting two beamsplitters. One of the beams is relatively weak and serves as reference to measure the interference patterns. A translation stage is added in order to tune the phase for high-contrast interference fringes. The second beam as coherent light, weak as well, is utilized to prepare classical twisted light. The third beam, the strongest one, is employed to produce a 390 nm laser up to 1.2 W via second harmonic generation (SHG). We feed the up-converted laser into a 2-mm-thick BBO crystal tuned for type II, non-collinear down-conversion to prepare a photon pair. The obtained single-channel count rate and two-channel coincidence count rate are 1875000 and 237500 respectively. The up-converted laser is sent to ICCD to open a window of 10 ns for taking the image of the heralded single-photon OAM state. The single photon and coherent light can be switched easily by fiber flanges to an individual set-up for converting single-mode beam to the twisted light. The total efficiency of the prepared classical and quantum twisted light can reach 60%.

**Similarity analysis:** To compare the output with the input pattern, we convert the measured images to binary images by employing threshold transform method, which sets the amplitude of every pixel to 0 or 1 by judging their value either above or below a certain threshold. In this way, we are able to digitally compare two converted binary images pixel by pixel. It should be noticed that the imaging systems for the intensity profile measurement are different, and therefore may lead to different sizes and positions though they may share a similar shape. To reveal the genuine similarity value, we repeat the comparison test by scanning the relative position and size to find the optimal value.

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