Long-range fiber-transmission of photons with orbital angular momentum

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Abstract: We demonstrate propagation of light possessing orbital angular momentum over record fiber-lengths (~km) with minimal cross-talk (<20-dB). This yields a novel degree of freedom for encoding information in fibers for quantum or classical communication links.

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Since the recognition by Allen et al. [1] that light carries orbital angular momentum (OAM), so-called vortex beams have generated widespread scientific and technological interest [2]. Mair et al. showed that entangled photons have correlated OAM [3], which led to the demonstration of a qutrit quantum [4], and the OAM classical [5] communication links. OAM data encoding has the potential to address the rapidly approaching capacity crunch in classical communications channels, while also offering the means to dramatically improve the security of quantum encryption networks, by enabling information multiplexing in multiple orthogonal spatial modes. Unfortunately, light beams with OAM are susceptible to atmospheric scintillation, and are conventionally considered to be completely unstable in optical fibers. Thus, free space [5] or fiber-based [6, 7] demonstrations of generation and maintenance of OAM states have been limited to length scales of the order of one meter.

Here, we report the successful transmission of two distinct OAM states of light (with orbital angular momentum of $\pm\hbar$ per photon) through 0.9 km of a specialty optical fiber, representing a thousand-fold improvement in the relevant length-scale. Measured cross-talk at the output was <20dB, thereby demonstrating, for the first time to the best of our knowledge, a new modal basis set with which information can be encoded over practical length scales. The demonstration was enabled by our specially designed "vortex" fiber which strongly separates the propagation constants of the antisymmetric vector modes. This design avoids intermodal couplings that have thus far inhibited propagation of OAM states. The limitation of our demonstration to 0.9 km was dictated not by any fundamental instabilities, but rather by the length of fiber available to us.

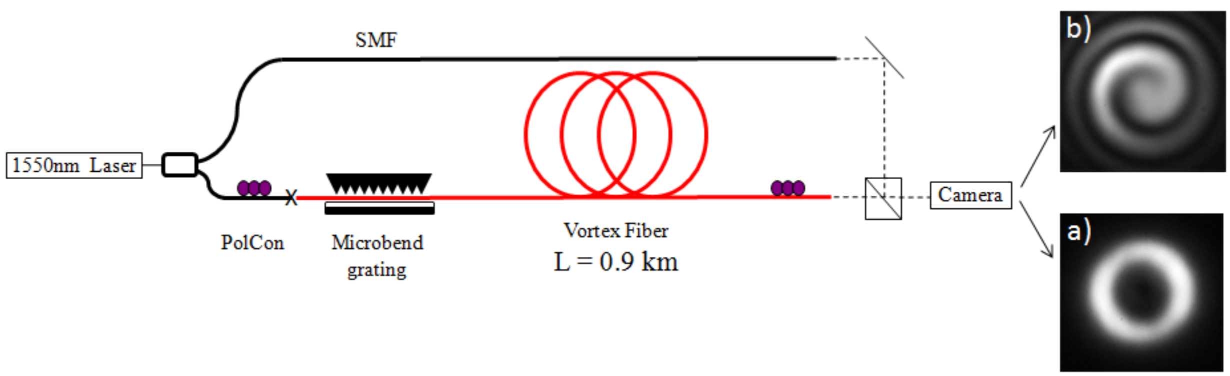

Figure 1: Schematic of experimental setup. Microbend grating creates optical vortex (@1550nm) which can then be a) imaged directly on a camera, or b) interfered with a Gaussian mode in the reference arm.

OAM states with $\pm\hbar$ orbital angular momentum are true eigenmodes of an optical fiber, and can be represented as $\pi/2$-phase-shifted linear combinations of the vector modes HE_{21}^{even} and HE_{21}^{odd} [8]. Unfortunately, the TE_{01} and TM_{01} modes are nearly degenerate with the HE_{21} modes, which destroy any OAM state in most standard fibers. Previously we demonstrated a fiber in which the TE_{01} and TM_{01} modes can propagate stably, but the desired OAM states were not observed [9]. Our current demonstration is enabled by the realization that, in analogy to polarization multiplexed signal transmission in SMFs, bends and twists leading to birefringence may phase-shift the two HE_{21} modes that combine to yield the OAM state, but do not destroy their orthogonality. This is true as long as polarization mode dispersion is low, and our demonstration of OAM transmission, *with low cross talk* (< 20 dB), confirms that.

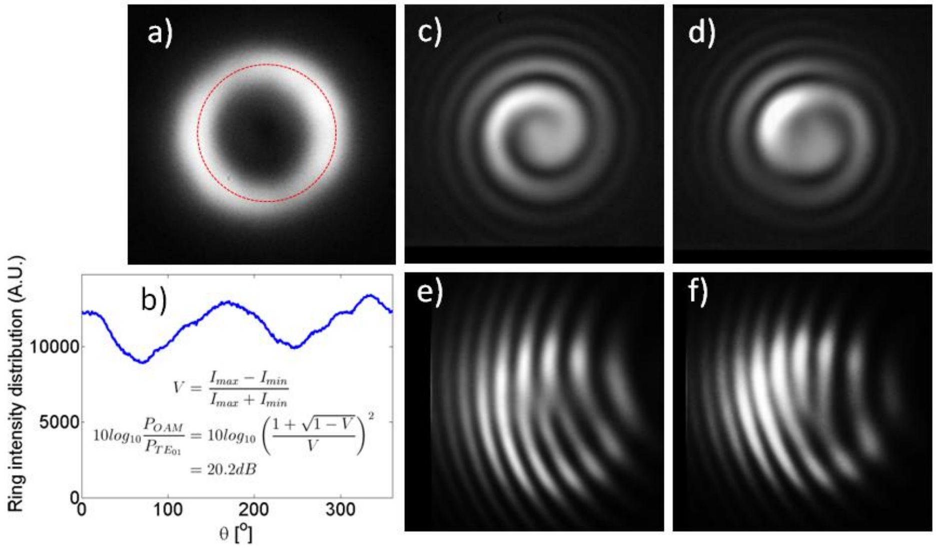

Fig. 2: (a) OAM mode intensity profile and (b) a line profile along the ring showing the >20dB mode purity. (c-f) Interference patterns between the $OAM^{\pm}$ mode and the fundamental mode for (c, d) collinear case (spiral patterns) and (e, f) non-collinear case (fork holograms).

The measurement setup is shown in Fig. 1. A narrowband (100kHz) laser, tuned to 1523 nm, was spliced to the input of the vortex fiber. Conversion from the fundamental mode into the $OAM^{\pm} = HE_{21}^{even} \pm iHE_{21}^{odd}$ modes was achieved using a microbend fiber grating with period of ~500 µm [10]. Using polarization controller before the microbend grating, we ensured high mode conversion efficiency (>99%) to the $OAM^{\pm}$ modes (not shown in the figure, an LED and OSA multiplexed to this setup were used to characterize the grating spectrum). After 0.9-km propagation in the fiber, the mode was imaged or interfered with a reference beam on a camera (InGaAs SWIR) in order to obtain information about mode's intensity (Fig. 2a) or phase (Figs. 2c-f) respectively.

When directly imaged, the mode intensity profile had a familiar 'doughnut' shape (Fig. 2a) expected of OAM states. When the OAM mode was collinearly interfered with a slightly defocused reference beam, a spiral pattern was observed, confirming an OAM phase profile of exp $(\pm i\varphi)$. The sign of the OAM state we observed at the output (left-handed or right-handed spiral) was determined by the state we chose at the input (with polarization controller before the grating). Similarly, the expected fork hologram was observed in the case of interference at an angle. The high visibility of the fringes close to the dislocation point indicates high modal purity. Finally, we quantify the modal purity by measuring the azimuthal intensity distribution (Fig. 2b) of the mode output itself (Fig. 2a) – a calculation based on the visibility of this pattern reveals that mode purity was >20 dB.

In summary, we demonstrated fiber propagation of optical vortices with $\pm\hbar$ OAM per photon over kilometer length scale which indicates their suitability for metropolitan links, either for expanding the capacity of classical communications channels or increasing the dimensionality (and hence security) of quantum encryption links. Cross talk levels were below 20 dB, and our length scale limitation was due to availability of the fiber rather than any fundamental stability constraint. Our demonstration represents a thousand-fold improvement in the length over which OAM states have been transmitted to date. We expect that minor modifications to the fiber design would enable further decrease in cross-talk, while also enabling scaling to a larger basis set of orthogonal spatial modes uniquely defined by the angular momentum that the light beam carries.

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