Record-length transmission of photons entangled in orbital angular momentum (OAM)

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Abstract: We demonstrate, for the first time, transmission of photons entangled in orbital angular momentum, over km-lengths of a specially designed optical fiber, representing a thousand-fold improvement of transmission-distance over previous reports.

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Polarization and time-bin entanglements are well established ways for transmission of the entanglement over long distances [1-3]. Recent results have suggested the use of orbital angular momentum (OAM) of light as another degree of freedom, which is potentially unlimited in the number of achievable orthogonal states [4-6]. However, OAM carrying light (also called vortex states) tend to be inherently unstable in transmission, mixing with other modes and breaking into the linearly polarized (LP) modes [7]. So far, OAM-based experiments have been demonstrated only over few meters in the lab setting in free space [5-6].

Using a specialty optical fiber [7**]** that serves to lift modal degeneracies that make OAM states inherently unstable in conventional fibers**,** we have recently demonstrated successful transmission of two OAM classical states carrying topological charges $l = \pm 1$ and showed that they preserve purity of more than 94% after propagation over a fiber length of 0.9 km [8-9]. To probe the reach of successful entanglement transport when one photon propagates in OAM modes, we have replaced one of the channels with our specialty few-mode vortex fiber. By measuring the density matrix of the photon pair at the output, and we extracted the concurrence of C=0.76 and the maximally possible S-parameter [10] of S=2.47. This clearly shows that the photon pair preserves entanglement even after one of the photons has been converted to, a back from, an OAM carrying state.

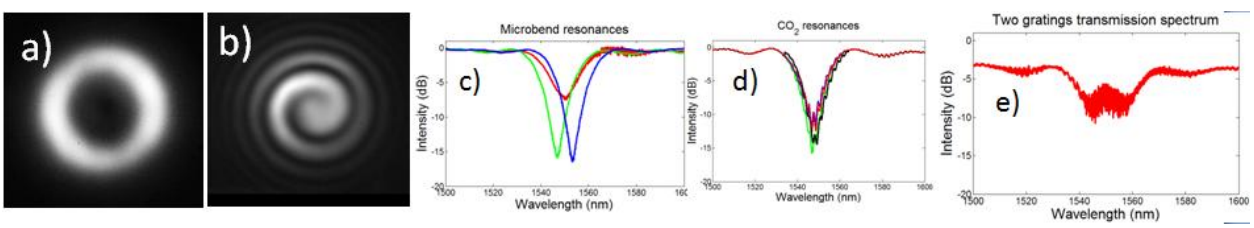

Figure 1: a) Intensity and b) phase of the OAM mode imaged with the camera (setup was described previously [8-9]). c, d, e) Polarization dependent transmission spectra for c) microbend grating d) CO_2 laser induced grating and e) combined transmission spectra of two gratings on each fiber end.

The image and spectral output from the vortex fiber is characterized with a narrow-band laser source in conjunction with the camera reveal the intensity and phase of the OAM mode, respectively (Fig 1a and 1b). A broad-band source (LED) was used to record the transmission spectra of the mode converting gratings as well as the overall transmission of the module (Fig1c-1e). Strong (~ 90%) mode conversion was achieved with a combination of a permanent grating, written by CO_2 laser inscription, and a mechanical microbend respectively (Fig. 1d and 1s, respectively). The combined conversion efficiency of the gratings was 80%-90% depending on a polarization, with a total loss of the system being 7dB. A majority of this loss is related to imperfect splices, as the fiber propagation loss was itself of the order of ~ 3 dB/km. Multi path interference (MPI), which is a measure of the amount of energy in an unwanted mode, was estimated from the spectral ripples in the transmission module [11], and was 14.2 dB.

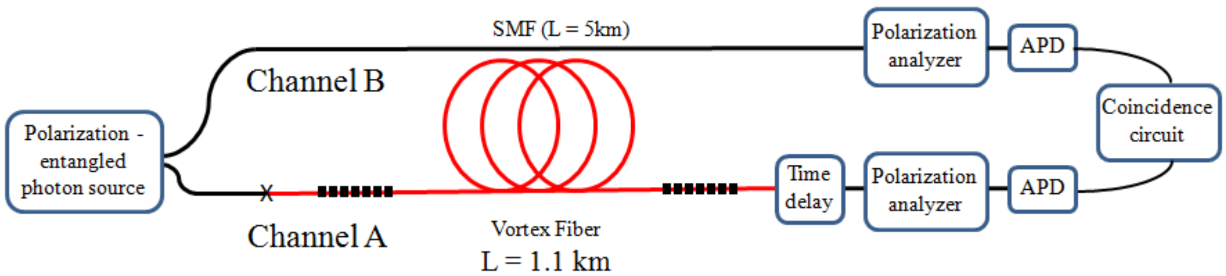

Figure 2: Schematic of experimental setup. Polarization-entangled photons (1550nm and 1558nm) are sent in two different channels A and B. 1.1km long channel A used two gratings to convert between fundamental and OAM mode with >80% efficiency. Channel B consisted of 5km long single mode fiber (SMF); Time delay was tuned to target coincidence of channel A photons (traveled in a fundamental mode) and channel B photons (traveled in the OAM mode). Density matrix of entangled state was measured at the output.

Schematic of the entanglement transmission system is shown in Figure 2. Two polarization-entangled photon pulses were produced (1550nm and 1558nm, 50MHz repetition rate) and launched in the two different channels, (channel A: 1.1 km vortex fiber, channel B: 5km single mode fiber). At the receiving end a complete quantum state tomography is performed. The results have shown that the output state preserved entanglement with the maximally possible Bell parameter of S = 2.47

In summary, we have shown that, using specially designed optical fibers, OAM states can preserve entanglement over kilometer lengths, which is the first demonstration, to the best of our knowledge, of using this potentially higher-dimensional coding scheme with optical fibers, thereby enabling practical implementation of QKD networks. This was critically enabled by a novel specialty optical fiber that preserves OAM in fibers, and resulted in a 1000-fold improvement in distances over which entangled OAM photons have been transmitted to date. We expect that such fibers would become the platform of choice for higher-dimensional encoding of information in both quantum and classical networks.

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