High-fidelity spatial mode transmission through multimode fiber via vectorial time reversal

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The large number of spatial modes supported by multimode fibers constitutes a promising platform for a multitude of quantum and classical applications. However, the practical use of multimode fibers is severely hampered by modal crosstalk and polarization mixing. Here we show that high mode fidelity can be achieved for a large number of spatial modes propagating through a 1-km-long, standard, graded-index, multimode fiber by using vectorial time reversal. Vectorial time reversal is accomplished digitally by means of a single-shot measurement for each mode of interest, without the need to probe the entire transfer matrix of the fiber. We characterize the crosstalk for 210 modes, in each of the Laguerre-Gauss and Hermite-Gauss basis sets. Through the use of vectorial time reversal, we show an average mode fidelity above 80% for fiber without thermal or mechanical stabilization. Our method presents a practical tool for enhancing fiber-based quantum and classical applications.

The spatial degree of freedom in multimode fibers has long been recognized as a resource for applications such as mode-division multiplexing1–7, quantum teleportation8, entanglement distribution9,10, and high-dimensional quantum key distribution (QKD)11–14. However, the inevitable mode crosstalk in multimode fibers is a persistent obstacle to the practical applications of spatial modes. Tremendous efforts have been devoted to attempts to mitigate the effects of spatial mode crosstalk, such as the development of multiple-input-multiple-output algorithms15, adaptive optics correction16, specially designed fibers or waveguides17–19, mode-group excitation17–19, transfer matrix inversion20–23, principal mode identification24, and optical phase conjugation25–30. However, all existing techniques exhibit one or more of the following deficiencies: inapplicable to quantum applications that require operations at the single-photon level; the use of exotic modes; the need of nonstandard fibers; computationally intensive algorithms; slow response time; a limited number of usable spatial modes; or a short propagation distance.

To overcome all the above deficiencies simultaneously, we propose and demonstrate digital vectorial time reversal to construct a long-distance fiber link, which allows for the transmission of a large number of spatial modes with low crosstalk. Time reversal is also referred to as phase conjugation in the literature31 and has been used to compensate aberrations for biological tissues32–35 and more recently for multimode fibers25–30. The concept of time reversal is illustrated in Fig. 1(a). The wavefront of an optical beam is distorted by an aberrating medium as shown in the left panel. Reflecting the beam by an ordinary mirror is not helpful as the wavefront becomes distorted more severely (see the middle panel). In contrast, a time-reversing mirror reverses the wavefront of the reflected beam, and consequently wavefront distortion can be exactly corrected after propagating through the same aberrating medium31 (see the right panel). Although we use a simple plane wave to illustrate the concept, it should be noted that time reversal is also applicable to spatial modes such as the Laguerre-Gauss and Hermite-Gauss modes. Therefore, by pre-shaping the wavefront of an optical beam to be the reversed wavefront of an aberrated spatial mode, a high-fidelity spatial mode can be obtained at the receiver after transmission through the aberrating medium. This method can be readily extended to transmit a large number of high-speed data streams through mode-division multiplexing25; by separately pre-shaping individual wavefronts of multiple high-speed-modulated signal beams, high-fidelity spatial modes can be recovered at the receiver, and thus the data streams can be demultiplexed with low crosstalk. Nonetheless, a perfect realization of time reversal should account for all degrees of freedom of an optical beam (i.e., the polarization, spatial, and temporal degrees of freedom). Due to experimental difficulty, very few realizations have included both the spatial and polarization degrees of freedom32. Most experiments25–30,33–35 reported in the literature are solely based upon scalar time reversal which only accounts for the spatial degree of freedom while ignoring polarization. Although scalar time reversal could work for nearly isotropic samples, its performance would be severely limited due to unavoidable birefringence and polarization mixing in multimode fibers.

Based upon recent advances in vectorial beam manipulation36, here we demonstrate a simple and powerful scheme of digital vectorial time reversal to build a 1-km-long link that allows for transmitting 210 high-fidelity modes from Alice to Bob. As a proof-of-principle experiment, we implement digital vectorial time reversal for one spatial mode at a time, but we emphasize that our method can be readily used to multiplex a large number of modes25. The conceptual schematic of our experiment is shown in Fig. 1(b). Bob prepares a spatial mode of interest and transmits it to Alice through a 1-km-long, standard, graded-index, multimode fiber (Clearcurve OM3,
Figure 1. Illustration of experiment. (a) The concept of time reversal. (b) Schematic of the experiment to send high-fidelity spatial modes from Alice to Bob. Bob generates a specific mode of interest (denoted by red beams) and sends it to Alice. Alice then performs vectorial off-axis holography on her received light beam and generates the corresponding time-reversed beam (denoted by blue beams). |H⟩ and |V⟩ stand for the horizontal and vertical polarization state respectively. See Supplementary Information for details.

Figure 2. Mode fidelity measurement. (a, b) The measured amplitude, phase, and polarization of the vectorial speckle pattern and time-reversed mode for horizontally polarized LG(3,2) and HG(4,4) mode respectively. (c, d) The unnormalized mode fidelity for time-reversed Laguerre-Gauss modes and Hermite-Gauss modes. A single index is used to denote the two mode indices for simplicity, and the light and dark blue bands denote the odd and even mode group number respectively (see Supplementary Information).

Corning). The fiber is comprised of two 500-m-long bare fibers that are spliced together and are free of any specialized thermal or mechanical isolation. The polarization of the spatial mode transmitted by Bob can be adjusted by a half-wave plate. After transmission through the fiber, the mode received by Alice has a scrambled spatial and polarization profile. Alice then performs vectorial off-axis holography to measure the spatial and polarization profile of the received speckle pattern. First, Alice uses a polarizing beam displacer to coherently separate the horizontally and vertically polarized components of the received speckle pattern into two co-propagating beams; these two co-propagating beams are then combined with a coherent reference plane wave at a beamsplitter, and the resultant interference pattern is recorded by a camera. Through off-axis holography[37], the amplitude, phase, and polarization of the received speckle pattern can be simultaneously determined with a single-shot measurement[36]. Alice then uses a single spatial light modulator to generate the time-reversed co-propagating beams, one for each polarization[36]. The two co-propagating beams are combined coherently by the same polarizing beam displacer and form a vectorial time-reversed speckle pattern. After passing through the same multimode fiber, the time-reversed speckle pattern becomes the mode originally transmitted by Bob with a reversed wavefront. Vectorial off-axis holography is then performed by Bob to quantitatively characterize the spatial and polarization profile of the received time-reversed beam. A 780 nm laser is used as the light source in the experiment, and more experimental details are provided in Supplementary Information.

Figure 2(a, b) shows two examples of experimentally measured vectorial fiber speckle patterns received by Alice and the time-reversed modes received by Bob for horizontally polarized LG(3,2) and HG(4,4) modes, where the mode indices of Laguerre-Gauss mode are denoted by LG(p,l) and that of Hermite-Gauss mode are denoted by HG(m,n). For each time-reversed mode received by Bob, we digitally project the mode to an orthonormal spatial mode basis set to calcu-
We experimentally characterize the fidelity of the spatial mode within the 210-mode-subspace has an average of 91.5% for (see Supplementary Information). The full 210 individual spatial modes (see Supplementary Information for details). It can be seen that the experimental generation fidelity, which is presented as solid lines in Fig. 2(c, d) for individual spatial modes (see Supplementary Information), which suggests that both the spatial mode and polarization scrambling can be well suppressed through vectorial time reversal. These high-fidelity results directly indicate that the polarization-based QKD protocol can be performed through multimode fibers, and the secure key rate can be significantly boosted by mode-division multiplexing. Furthermore, based on the fact that high-fidelity results can be obtained over spliced fiber, we expect that the vectorial time reversal is also applicable in a much longer fiber. We also calculate the crosstalk matrix for the vectorial speckle pattern received by Alice, and the average unnormalized mode fidelity is ≈1% for both Laguerre-Gauss modes and Hermite-Gaussian modes (see Supplementary Information), which shows the strong mode scrambling in fiber and by contrast highlights the effectiveness of our method.

To overcome environmental instability, vectorial off-axis holography needs to be performed repeatedly in real time, and the phase pattern on the spatial light modulator should be updated accordingly. In the following, we evaluate the response time of our vectorial time reversal system. To perform off-axis holography, we need to retrieve a single-shot image from the camera (which takes 2.6 ms) and execute fast Fourier transforms and interpolations as digital data processing (which takes 18 ms on a desktop computer, see Supplementary Information). It should be noted that the data processing time can be significantly reduced by using a dedicated digital signal processor or even eliminated by careful experimental design and alignment as discussed in Supplementary Information. The response time of our system is therefore only constrained by the refresh rate of spatial light modulator, which is 4 Hz in our experiment. However, this constraint can be readily removed by using a commercially available fast digital micromirror device (above 10 kHz refresh rate36) or a high-speed spatial light modulator (sub kHz refresh rate36). In addition, we emphasize that the transmission data rate using each spatial mode is not limited by the response time of the time-reversal system25, and the system response time only needs to be faster than environmental fluctuation rate in order to overcome instability. A classical communication protocol for mode-division multi-

Figure 3. System performance evaluation. (a) The normalized crosstalk matrix in the polarization subspace for horizontal (H), vertical (V), diagonal (D), and anti-diagonal (A) polarizations for LG(0,2), LG(1,2), LG(2,2), and LG(3,2) modes. (b) Stability test for vectorial time reversal. The unnormalized mode fidelity is measured as a function of time. The shaded area corresponds to mode fidelity between 80% and 90%. The solid lines represent the results when the spatial light modulator is under active control and the dashed lines represent the results without active control. (c) Bandwidth measurement by tuning the laser frequency. The unnormalized mode fidelity is measured as a function of laser frequency detuning.
plexing is discussed in Supplementary Information, where we show that the speed of a spatial light modulator does not limit the signal modulation rate. To test the operation stability of our system, we also measure the unnormalized mode fidelity as a function of time while the spatial light modulator is actively updated, which is depicted by the solid lines in Fig. 3(b); here the dashed lines represent the mode fidelity in the absence of active control of the spatial light modulator. The autocorrelation $R(\Delta t) = \langle |\langle \phi(t) | \phi(t+\Delta t) \rangle |^2 \rangle$ is calculated according to these data, where $\langle \phi(t) \rangle$ is the time-reversed mode at time $t$ and $\langle \cdot \rangle$ is the time average. The time for $R(\Delta t)$ to drop to $1/e$ is approximately 120 s for LG(0,2) and 100 s for LG(3,2). These results clearly show that our system is able to overcome environmental instability even though the 1-km-long bare fiber is placed on an optical table that has not been floated and is free of any thermal or mechanical isolation (see Supplementary Information). We believe that by using a fast spatial light modulator, real-time crosstalk suppression can be achieved even in a harsh environment through a much longer fiber. We also characterize the spectral bandwidth of our system by monitoring the unnormalized mode fidelity when tuning the laser frequency as shown in Fig. 3(c) (see Supplementary Information for details). It can be seen that the full-width at half-maximum bandwidth is 22 GHz for LG(0,2) and 5 GHz for LG(3,2), which suggests that the vectorial time reversal can continue to work when the signal is modulated at a rate of several GHz. The commercially available OM4 fiber is an immediate solution to increase the bandwidth because its effective modal bandwidth is twice as large as that of the OM3 fiber that we used. Furthermore, the temporal degree of freedom can also be taken into account in vectorial time reversal to overcome the modal dispersion.

In summary, we have demonstrated that, through the use of vectorial time reversal, we can establish a high-fidelity, 1-km-long communication link that supports 210 spatial modes of a standard multimode fiber. Both spatial mode crosstalk and polarization scrambling in multimode fiber can be well suppressed, which demonstrates the possibility of boosting the communication rate of both classical communication and polarization-based QKD protocol by either mode-division multiplexing or high-dimensional encoding. Bandwidth measurements reveal that our method can readily support a modulation rate of several GHz, and there is still room to further enhance the bandwidth. Given the simplicity of the experimental implementation and high fidelity of the data, our technique presents a practical platform to a multitude of quantum and classical applications ranging from mode-division multiplexing to entanglement distribution.

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Competing interests

The authors declare no competing interests.

Author contributions

Y.Z. conceived and performed the experiment with assistance from B.B., Z.S., R.Z., J.Z., and R.W.B. All authors contributed to the discussion of the results and the writing of the manuscript. A.E.W., Z.S., and R.W.B. supervised the project.

Data and materials availability

The data supporting this study are available in the manuscript and Supplementary Information. If needed, other relevant data may be available upon reasonable request.

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