Long-range spatio-temporal correlations in multimode fibers for pulse delivery

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Long-range correlations play an essential role in wave transport through disordered media, but have rarely been studied in other complex systems. Here we discover spatio-temporal intensity correlations for an optical pulse propagating through a multimode fiber with strong random mode coupling. Positive long-range correlation arises from multiple scattering in fiber mode space and depends on the statistical distribution of arrival times. By optimizing the incident wavefront of a pulse, we maximize the power transmitted at a selected time, and such control is significantly enhanced by the long-range spatio-temporal correlation. We provide an explicit relation between the correlation and the power enhancement, which agrees with experimental results. Our work shows that multimode fibers provide a fertile ground for studying complex wave phenomena. The strong spatio-temporal correlation can be employed for efficient power delivery at a well-defined time.
Cohort transport of classical and quantum waves in disordered media exhibits long-range correlations, which exist in space, angle, frequency, time, and polarization. Such correlations, resulting from the crossing of wave paths, are responsible for the formation of highly transmitting channels in diffusive systems. In the frequency domain, long-range correlations enable broad-band enhancement of transmission through disordered media by waveform shaping. Spatially, long-range correlations significantly increase the efficiency of wave focusing to a target of size much larger than the wavelength in strongly scattering media. However, long-range correlations also increase the background when optimizing the energy delivered to a single speckle grain for continuous waves and pulses.

From the aspect of scattering, a multimode fiber (MMF) with strong mode mixing shares similarities with a disordered medium. Inherent imperfections and environmental perturbations introduce random mode coupling in an MMF, and its effect grows with the length of the fiber. Such coupling can be regarded as scattering in the fiber mode space, leading to energy transfer from the input mode to the other transverse modes. An MMF has a significant difference from the disordered medium: negligible reflection and low propagation loss leading to near-unity transmission. For a continuous wave input, energy conservation dictates that the intensity increase in one mode must be accompanied by intensity decreases in other modes, resulting in negative correlation among the transmitted spatial modes, similar to those found in weakly continuous wave input, energy conservation dictates that the low propagation loss leading to near-unity transmission. For a...
width at half maximum (FWHM) of 2.0 nm (temporal FWHM = 2.6 ps). The input bandwidth is 10 times of the spectral correlation width of the fiber. Thus for random input wavefronts the transmitted pulse would be 10 times longer than the input pulse.

The total output intensity at time $t$ is $\langle \psi_{\text{out}}(t) | \psi_{\text{out}}(t) \rangle = \langle \psi_{\text{out}} | u(t)^* u(t) | \psi_{\text{out}} \rangle$. The mean eigenvalue of $u(t)^* u(t)$ (blue solid line, left axis) representing the transmitted intensities of random spatial inputs. The two curves are normalized to have the same area. (c-e) Magnitudes of the measured time-dependent transmission matrices at three arrival times (marked by red arrows in (b), showing strong mode mixing in the fiber. The transmission matrices are measured in $k$ space at input and real space $r$ at output, and subsequently converted to the fiber mode basis.

**Fig. 1** Time-dependent transmission matrix of an MMF. (a) Schematics of experimental setup for both transmission matrix measurement and wavefront shaping. A laser beam with tunable frequency is collimated, and its horizontal polarization is selected and split into two arms, with one being the reference and the other propagating through the MMF after reflecting off a spatial light modulator (SLM). The SLM is demagnified and imaged onto the MMF facet. Light transmitted through the MMF is recombined with the reference plane wave, and its horizontal polarization is imaged onto a CCD camera. The path lengths of the two arms are matched by tuning the delay line formed by mirrors M1-M3. L, lens; BS, beam splitter; PBS, polarization beam splitter. (b) Temporal shapes of the input pulse (black dotted line, right axis) and the mean eigenvalue of $u(t)^* u(t)$ (blue solid line, left axis) representing the transmitted intensities of random spatial inputs. The two curves are normalized to have the same area. (c-e) Magnitudes of the measured time-dependent transmission matrices at three arrival times (marked by red arrows in (b), showing strong mode mixing in the fiber. The transmission matrices are measured in $k$ space at input and real space $r$ at output, and subsequently converted to the fiber mode basis.

**Spatio-temporal correlations.** We calculate the spatio-temporal correlations $C(\Delta r, t, t')$ from the measured time-dependent transmission matrices, replacing the ensemble average in Eq. (2) with an average over random input spatial profiles. Figure 2a, b plot $C(\Delta r, t) \equiv C(\{\Delta r\}, t, t = t)$ and two cross sections of it along $\Delta r$ at $t = -17.3$ ps and $t = 3.7$ ps. We observe a short-range correlation that starts from one and vanishes at the speckle size of about 3 μm, beyond which we see a long-range correlation that is approximately constant with respect to $\Delta r$. This indicates $C(\Delta r, t) = F(\Delta r) C_1(t) + C_2(t)$, consistent with Eq. (1). Figure 2c shows the arrival-time dependence of the long-range correlation $C_2(t)$; it is small at the central arrival time but increases toward early or late arrival times.

The time dependence of $C_2(t)$ can be understood through the optical path-length distribution in the multimode fiber. Due to strong mode coupling, there are numerous paths that light can take to travel through the fiber. By exciting the fiber with many random incident wavefronts, all paths are explored and the averaged temporal shape of transmitted pulse in Fig. 1b reflects the number of propagation paths with varying lengths. For the middle delay times, there are a large number of propagation paths, thus $C_2(t)$ is very weak. The larger $C_2(t)$ at early and late arrival times is consistent with the lower number of paths for such times. Conceptually, if there is only one path of length corresponding to the arrival time $t$, the output intensities $I(r, t)$ at different positions $r$ must be fully correlated: varying the incident wavefront can only change how much light is coupled into that one path, which will increase or decrease $I(r, t)$ at all positions in the same way. Therefore, the fewer paths for the arrival time $t$, the stronger $C_2(t)$.
between spatio-temporal speckle grains at different arrival times. This is quantified by \( C(\Delta r, t, t') \) as defined in Eq. (2). At large \( |\Delta r| \), this quantity again becomes independent of \( |\Delta r| \) and approaches the asymptotic value \( C_2(t, t') \). In Fig. 2d, we show \( C_2(t, t') \) for different arrival times \( t \) and \( t' \). In Fig. 2e, we show three cross-sections. Near the central arrival time \( (t' = 3.7 \text{ ps}) \), \( C_2(t, t') \) is close to zero at all \( t \). Meanwhile, at \( t = -17.3 \text{ ps} \), \( C_2(t, t') \) peaks at \( t = t' \) and decays away from it, eventually becoming negative. The trend, however, is opposite at \( t' = 16.1 \text{ ps} \). The correlation is negative at early delay times and becomes positive at late arrival time. Such a negative correlation is a result of the conservation of transmitted pulse energy, which requires an increase of spatially integrated intensity (power) at arrival time \( t = t' \) to be compensated by a decrease of power at other arrival times.

**Pulse delivery.** The positive spatio-temporal correlation \( C_2(t) \) at early or late arrival times will lead to a higher achievable enhancement at such times. Because the matrix \( u^i(t_0) u(t_0) \) is Hermitian, the global optimum, which determines the maximum power that can be delivered at time \( t_0 \), is given by the largest eigenvalue of \( u^i(t_0) u(t_0) \), and the corresponding eigenvector is the desired incident wavefront. By shaping the incident wavefront with the SLM, we can enhance the total transmitted power at a target arrival time and compensate for the strong modal dispersion in the fiber. Experimentally, we determine such optimal transmission channels from the measured time-dependent transmission matrices, and then generate the desired wavefront using computer-generated phase holograms to simultaneously modulate the phase and amplitude profiles. By scanning the wavelength and Fourier transforming the spectral measurements to the time domain, we obtain the

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**Fig. 2** Spatio-temporal correlations in MMF with strong random mode mixing. **a** Intensity correlations \( C(\Delta r, t) = C(\Delta r, t; t' = t) \), revealing a short-range component \( C(t) \approx 1 \) at spatial distance within one speckle (\( \Delta r \approx 3 \mu m \)) and a long-range component \( C_2(t) \) that persists at large distance. **b** Two cross-sections of \( C(\Delta r, t) \) at arrival times \( t = -17.3 \text{ ps} \) and \( t = 3.7 \text{ ps} \). **c** Time dependence of the long-range component \( C_2(t) \), averaging over \( \Delta r \) for \( \Delta r > 5 \mu m \). The error bars represent the standard deviation among four measurements of the fiber in different bending configurations. **d** Long-range correlations \( C_2(t, t') \) between spatio-temporal speckle grains at different arrival times \( t \) and \( t' \). **e** Cross sections of \( C_2(t, t') \) at \( t' = -17.3 \text{ ps} \), \( 3.7 \text{ ps} \) and \( 16.1 \text{ ps} \) (marked by white dashed lines in **d**).
spatially integrated temporal pulse shapes of such optimal transmission channels.

The pulses optimized for arrival times $t_0 = -5\text{ ps}$ and $t_0 = 16.1\text{ ps}$ are shown in Fig. 3a, b (red solid curve), in comparison to the averaged pulse of random spatial inputs (black dash-dotted curve). The sharp peak at the selected arrival time, as marked by the vertical black dotted line, illustrates that the transmitted power can be effectively enhanced at different target times, even in the presence of strong modal dispersions in the fiber. The peak width equals the input pulse width. The spatial intensity patterns of the optimized pulse and the non-optimized one at the target arrival times, shown in Fig. 3a, b, are obtained from the Fourier transform of the frequency-resolved field patterns measured with the optimized and random incident wavefronts. It is distinct from spatio-temporal focusing\textsuperscript{24,44-48} where only one speckle is enhanced. Figure 3b shows that the transmitted power after the target time increases, but well before the target time it increases. Such changes are determined by correlation $C_2(t, t')$ shown in Fig. 2e. The negative correlation at early arrival time suppresses the background and the positive correlation at late arrival time enhances the background. Figure 3c plots the pulse shapes optimized for different arrival times from $t_0 = -20\text{ ps}$ to 25 ps. The peak follows the target time $t_0$, and notably, the background also shifts with the target time.

To evaluate the effectiveness of the transmitted power optimization, we define an enhancement factor $\eta(t_0) \equiv I_{\text{enh}}(t_0)/I_{\text{random}}(t_0)$, where $I_{\text{enh}}(t_0)$ and $I_{\text{random}}(t_0)$ are the spatially integrated intensities of the optimized pulse and the random pulse at the target time $t_0$. We plot the measured enhancement factor $\eta$ (blue square) in Fig. 3d. The standard deviation of the enhancement between measurements on four different days is shown by the error bars. The deviation is larger at early or late arrival times as the weaker pulse intensities there lead to smaller signal-to-noise ratio. The average enhancement is about four times around the central arrival time, which is what one expects through the quarter-circle law for the singular values of a square random matrix with uncorrelated elements\textsuperscript{49}. At early or late arrival times, we achieve power enhancements much $>4$; such increase is consistent with the long-range correlation $C_2(t)$ that we observed (Fig. 2c).

**Power enhancement.** Finally, we provide a quantitative connection between the long-range spatio-temporal correlation $C_2(t)$ and the enhancement factor $\eta(t_0)$ of transmitted power at arrival time $t_0$. We use a heuristic model similar to that employed in ref. \textsuperscript{21}, capturing the correlation between output channels at arrival time $t_0$ through a reduction in the effective number of output channels. Specifically, we consider an effective random matrix with $N$ input channels and $N^{(\text{eff})}(t_0)$ output channels, and we consider all elements of this matrix to be identically independently distributed. The enhancement $\eta$ is determined by the largest eigenvalue, which is related to the spread of the eigenvalues characterized by the eigenvalue variance. As detailed in the Supplementary Note 1, the normalized eigenvalue variance associated with the reduced matrix is given by the Marchenko–Pastur distribution\textsuperscript{19} to be $N/N^{(\text{eff})}(t_0)$, while that associated with the actual time-resolved transmission matrix is...
1 + NC₂(t₀). Therefore, we choose

\[ N^{(\text{eff})}(t₀) = \frac{N}{1 + NC₂(t₀)} \]  

(3)

to match the two corresponding eigenvalue variances. This relation quantifies how long-range correlation effectively reduces the number of output channels. The enhancement is the normalized maximal eigenvalue, which for an uncorrelated matrix is

\[ \tau_{\text{max}} / \tau = \left(1 + \sqrt{N / N^{(\text{eff})}(t₀)}\right)^2 \]  

(ref. 49). Inserting Eq. (3), we obtain a simple equation

\[ \eta(t₀) = \left(1 + \sqrt{1 + NC₂(t₀)}\right)^2 \]  

(4)

that relates the maximal enhancement to the long-range spatio-temporal correlation.

In Fig. 3d, we compare the measured enhancement to the enhancement predicted through the measured C₂(t) via Eq. (4) (black circles). Overall, the two curves agree well, especially around the central arrival time. Some differences at early or late arrival times may be due to the fact that the time-dependent transmission matrix is not as isotropic as that at the central time (as shown in Fig. 3c–e). We further generalize the relationship in Eq. (4) to predict the whole output pulse (both the peak at the target time and the background) via C₂(t, t’) (see Supplementary Note 1). In Fig. 3a, b, we plot the predicted temporal shapes (blue dotted curves) of the optimized pulses with t₀ = −5 ps and t₀ = 16.1 ps on top of the measured pulse shapes. As C₂(t, t’) changes from positive correlation for the arrival time t close to the target time t₀ to negative correlation for t far from t₀, the transmitted power is enhanced near the peak at t₀ and suppressed away from the peak. Consequently, the background shifts toward the peak due to long-range correlation.

**Discussion**

Local and nonlocal correlations have been studied extensively in scattering media, but there are few observations in other complex photonic systems. Short-range correlation introduces the rotational memory effect that has been observed in a MMF with weak mode coupling⁵⁰,⁵¹. Here we observe long-range spatio-temporal correlation in a multimode fiber with strong mode mixing when a pulse propagates through the fiber. The correlation not only determines the effectiveness of enhancing the transmitted power at a target time, but also capture the temporal shape of the resulting pulse. We provide a qualitative explanation for the long-range spatio-temporal correlations using the optical path-length distribution in the multimode fiber with random mode mixing. This simple model reveals the possibility of physically turning the spatio-temporal correlations by tailoring the path-length distribution in the fiber via a careful design of the fiber configuration.

Enhancing the transmitted power in time can be utilized in many fiber applications from communication to imaging. The maximum eigenmode (EM) of the time-resolved transmission matrix provides the incident wavefront for focusing the transmitted pulse to a chosen delay time. This method is effective for any input pulse with arbitrarily broad spectrum, and it guarantees the maximal power delivery at any selected time. Especially when the spectral width of an input pulse is much larger than the spectral correlation width of the fiber, the EM outperforms the principal mode⁵²–⁵⁴ and super-principal mode⁵⁵ in achieving the highest peak power of the transmitted pulse (see Supplementary Note 2 for detailed discussion and direct comparison).

**Data availability**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions
H.C. initiated and led the study. W.X. performed the experiment and numerical simulation. C.W.H. provided analytical derivation. All authors contributed to data analysis and the manuscript.

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