

25-Pb s⁻¹ extreme-multiplexed fiber-optic communications enabled by orbital angular momentum physics

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S1. MIMO-complexity calculations of space-division multiplexed systems

In space-division multiplexed (SDM) systems, digital MIMO equalizers are used to mitigate differential mode delay (DMD) by applying filter taps over the coupled modes. The total number of filter taps required can be quantified as^{1,2}:

$$N_{MD} = \Delta T_{MD} r_{os} R_s \quad (1)$$

Here, ΔT_{MD} denotes the DMD span across all spatial modes, R_s represents the symbol rate, and r_{os} is the oversampling factor, typically set to 1 or 2.

For SDM systems using single-carrier modulation, the number of taps N_{MD} expressed in terms of sampling points, with each symbol sampled at r_{os} intervals. A $D \times D$ MIMO equalizer that handles D sequences, each of length N_{MD} , must perform $N_{MD} D^2$ complex multiplications. Since this corresponds to processing symbols, the average number of complex multiplications per symbol is:

$$RNCM_{per\ symbol, sc, TDE} = r_{os} N_{MD} D \quad (2)$$

The MIMO dimension D is typically equivalent to the number of spatial modes being jointly processed. To fairly evaluate the computational burden across different SDM systems with varying transmission capacities, this complexity is normalized per unit capacity. Dividing by the number of bits per symbol N_{bit} , we obtain the number of complex multiplications required per bit:

$$RNCM_{per\ bit, sc, TDE} = \frac{r_{os} N_{MD} D}{N_{bit}} \quad (3)$$

This normalization provides a consistent basis for comparing the efficiency of equalization schemes across systems with different modulation formats and spatial channel counts.

Table S1 Parameters used in the calculations for 10-km OAM-SDM systems with modular 4×4

R_s	12.5 GBaud	D	4
r_{os}	1	N_{bit}	2/3.945
N_{MD}	35	$RNCM/symbol$	140

S2. The effective refractive indices of the 19-RCF across S, C and L band

Based on the designed refractive index profiles (RIP), the modal effective refractive indices of all guided modes within the S + C + L bands (1480–1620 nm) were calculated using a commercial finite element solver (COMSOL Multiphysics). As shown in Fig. S1, a total of five mode groups are supported: OAM $|l| = 0$, OAM $|l| = 1$, OAM $|l| = 2$, LP₀₂, and OAM $|l| = 3$. For OAM mode groups with $|l| \geq 1$, the differential effective refractive index (Δn_{eff}) between adjacent mode groups (MGs) remains greater than 1.5×10^{-3} across the entire wavelength range, ensuring sufficient modal separation. Meanwhile, as illustrated in Fig. S2, each OAM MG contains four highly degenerate modes ($\pm l$, each supporting two orthogonal polarizations). Representative results at five wavelengths—1480 nm, 1500 nm, 1540 nm, 1580 nm, and 1620 nm—are presented for reference.

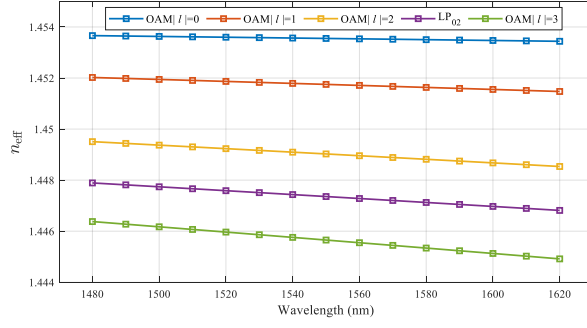


Fig. S1 Modal effective refractive index versus wavelength in the fibre core.

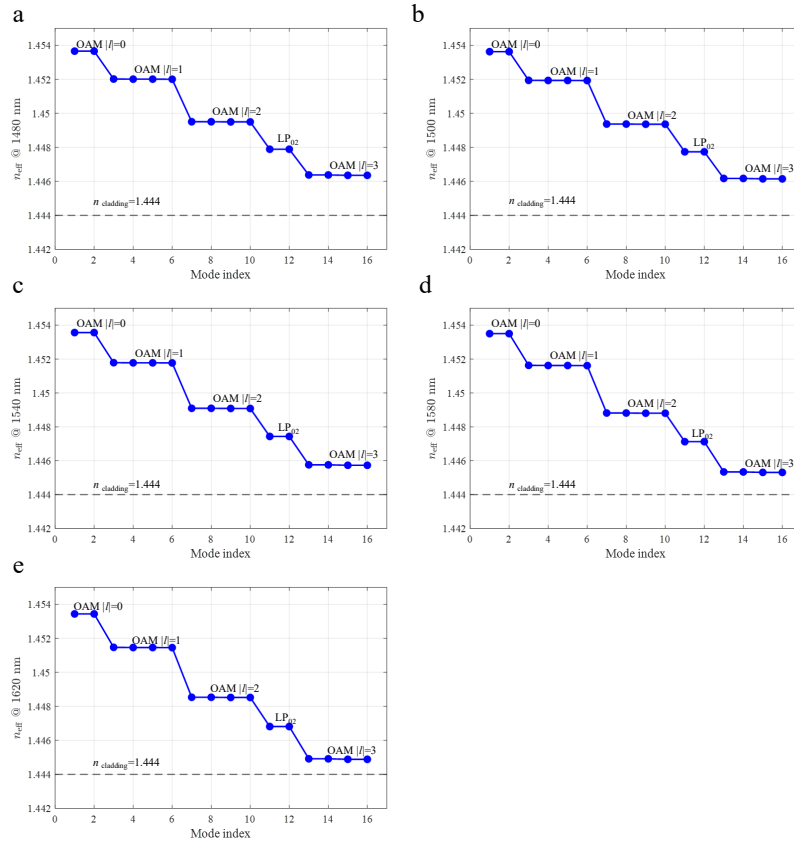


Fig. S2 Effective refractive indices of eigen-modes at wavelengths of a 1480 nm, b 1500 nm, c 1540 nm, d 1580 nm and e 1620 nm.

S3. Perturbation analysis and azimuthal selection rules

While ideal OAM modes defined by $u_l(r, \phi, z) = A(r) \exp(il\phi) \exp(i\beta_l z)$ are strictly orthogonal, realistic fibers exhibit dielectric perturbations $\Delta n(r, \phi, z)$. We analyze the coupling mechanism by expanding the perturbation into its azimuthal Fourier components:

$$\Delta n(r, \phi, z) = \sum_m \Delta n_m(r, z) \exp(im\phi) \quad (4)$$

According to coupled-mode theory, the coupling coefficient $k_{ll'}$ between two OAM modes with topological charges l and l' is proportional to the overlap integral of their fields with the perturbation:

$$k_{ll'} \propto \int_0^{2\pi} \exp(-il'\phi) \left[\sum_m \Delta n_m \exp(im\phi) \right] \exp(il\phi) d\phi = 2\pi \delta_{ll'} \quad (5)$$

The angular integration yields a non-zero result only when the phase matching condition is met: $m = l - l'$. This establishes an azimuthal selection rule: significant coupling only occurs when the perturbation contains specific azimuthal harmonics matching the topological charge difference Δl .

S4. Measurement of mode attenuation in the 10-km 19-core RCF based on OTDR

To characterize the propagation loss of OAM mode groups ($|l| = 0-3$) in the 10-km 19-core ring-core fiber, we adopted a two-stage protocol (mode verification—OTDR measurement). First, a narrow-linewidth continuous-wave laser was launched through the same coupling optics and vortex phase plate (VPP) used for measurement, injecting the target OAM order into a selected core; near- and far-field imaging was employed to confirm that only the intended mode was efficiently excited, after which the optical alignment was fixed. Without altering the alignment or VPP settings, the light source was then switched to the OTDR to inject probe pulses into the same core and record the Rayleigh backscattering trace. For each core–MG pair, the launch transient and discrete Fresnel reflections were masked, and the attenuation coefficient ($\text{dB} \cdot \text{km}^{-1}$) was extracted by linear regression over the quasi-steady logarithmic region. The procedure was repeated across all 19 cores and $|l| = 0-3$, with the setup and workflow shown in Fig. S3 and the core- and MG-resolved statistics summarized in Fig. S4.

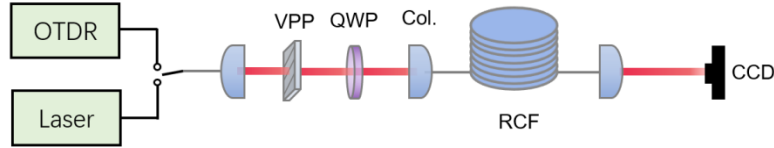


Fig. S3 Mode attenuation measurement setup of the 10-km 19-RCF at 1550 nm based on OTDR. OTDR: optical time-domain reflectometer; Col.: collimator; VPP: vortex phase plate; QWP: quarter-wave plate.

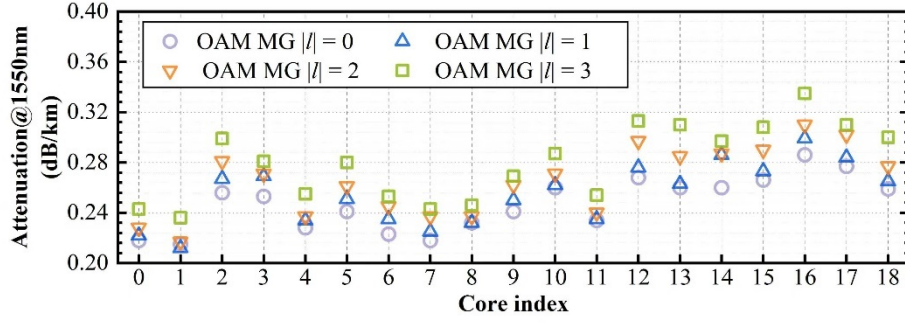


Fig. S4 Measured mode-dependent attenuation of 10-km 19-RCF.

S5. Experimental characterization of the crosstalk between adjacent MG using SWI-based impulse response measurement

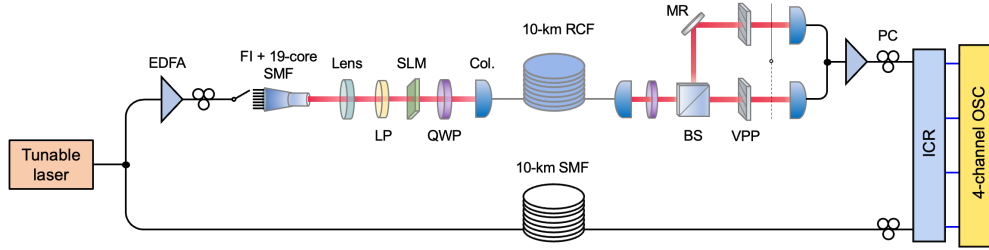


Fig. S5. SWI-based impulse response measurement setup for determining mode coupling in a fiber. EDFA: erbium doped fiber amplifier; PC: polarization controller; Col.: collimator; LP: linear polarizer; SLM: spatial light modulator; QWP: quarter-wave plate; BS: beam splitter; VPP: vortex phase plate; ICR: integrated coherent receiver; OSC: oscilloscope.

A tunable laser was employed to generate the optical carrier, configured with a wavelength sweep range of 0.2 nm and a sweep rate of 2000 nm/s. The light was split into a reference arm and a probe arm using a 50:50 optical coupler. In the probe path, the signal was amplified by an EDFA and subsequently modulated by a spatial light modulator (SLM) to generate spatial modes corresponding to topological charges of $l \in \{0, 1, 2, 3\}$. These modes were then collimated and coupled into the 10-km 19-core fiber. At the receiver end, the transmitted optical fields were demultiplexed using vortex phase plates (VPPs) with conjugate topological charges and coupled into a dual-polarization integrated coherent receiver (ICR). The electrical signals were acquired by a 4-channel real-time oscilloscope for offline digital signal processing. Through the SWI method, the impulse response matrices for representative cores of the 19-core fiber were retrieved. The SWI-measured impulse response matrix for all supported OAM modes at 1550 nm of core #0, core #3, core #12 and core #13 of the 10-km 19-core RCF can be obtained. Finally, the accumulated inter-mode crosstalk was quantified by calculating the ratio of the temporal integrals of the differential mode group delay (DMGD) plateau to the excited mode peak. (Specific calculation methods can be obtained from [3]).

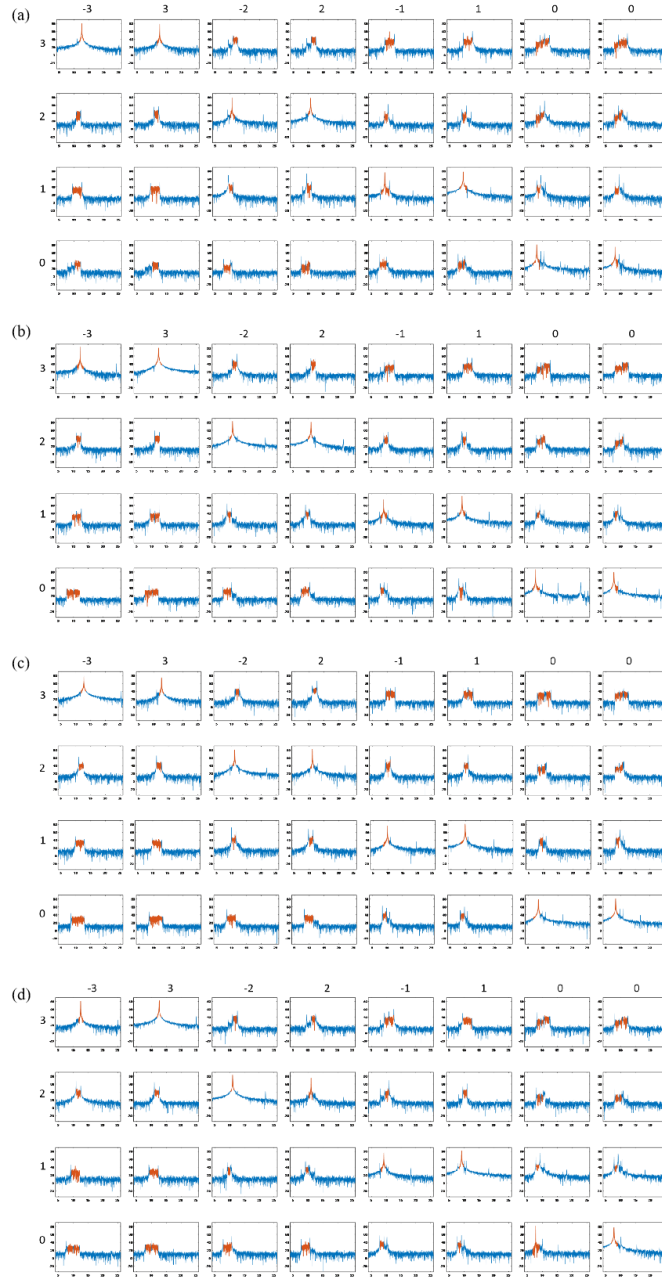


Fig. S6 The SWI-measured impulse response matrix of (a) core #0, (b) core #3, (c) core #12 and (d) core #13 at 1550 nm.

S6. Measurement setup of differential group delay using a vector network analyzer

To measure the differential group delay (DGD) for each core of the 19-RCF, a vector network analyzer (VNA)-based impulse-response setup was used. As the experimental setup illustrated in Fig. S7, the radio-frequency (RF) signals with a frequency range from 10 MHz to 2 GHz generated by the VNA drive the Mach-Zehnder modulator (MZM) to modulate

the optical light from a narrow-linewidth laser. The modulated light was amplified by an erbium-doped fiber amplifier (EDFA), collimated into a free-space path, linearly polarized to match the working axis of the spatial light modulator (SLM), and converted to an OAM mode with topological charge l ($|l| = 0$ to 3). After a quarter-wave plate (QWP) set the beam to circular polarization, the light was coupled into a selected core of the 10-km 19-RCF. At the receiver, the transmitted OAM mode was converted to a Gaussian beam by a vortex phase plate (VPP) with order $-l$, coupled into an SMF pigtail, detected by a photodetector (PD), and the resulting RF signal was returned to the VNA. The VNA acquired the complex transfer function $S_{21}(f)$; an impulse response was then obtained in the time domain. The group delay of each guided OAM MG was read from the impulse peak time, and the DGD was defined as the delay relative to OAM MG $|l| = 0$. This procedure was repeated for $|l| = 0 - 3$ for every fiber core.

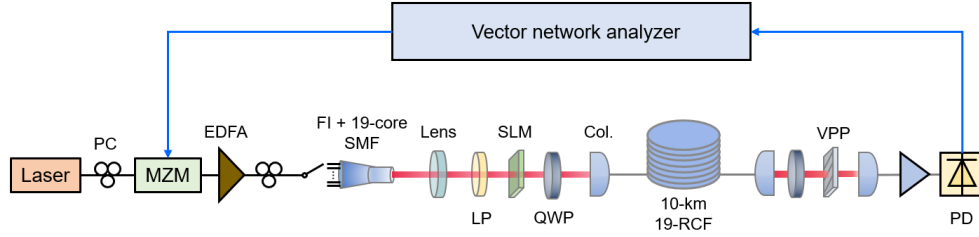


Fig. S7 VNA based impulse response measurement setup for determining DGD in a fibre. VNA: vector network analyzer; PC: polarization controller; MZM: Mach-Zehnder modulator; EDFA: erbium doped fiber amplifier; FI: Fan in; LP: linear polarizer; SLM: spatial light modulator; QWP: quarter-wave plate; Col.: collimator; VPP: vortex phase plate; PD: photodetector.

As shown in Fig. S8, large DGD with values of more than 6 ns km^{-1} between adjacent pairs of OAM MGs of topological charge $|l| \geq 0$ can be achieved in each fibre core for all four selected wavelengths. The large inter-MG DGD, totalling $\sim 20 \text{ ns km}^{-1}$ over the length of the link, serves to maintain low optical coupling among these higher-order MGs but does not impact the tap count of the DSP.

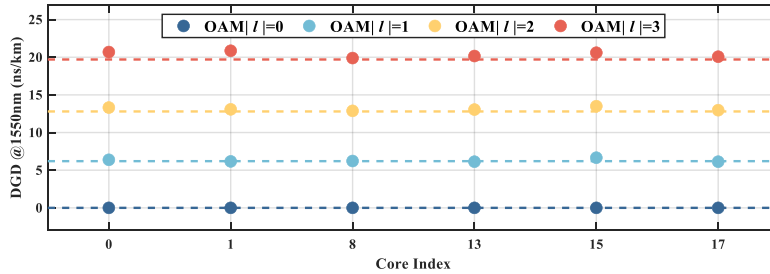


Fig. S8 The measured and simulated DGD of the designed fibre (dashed lines represent the simulated results).

S7. Experimental parameters of the ‘19-to-19’ coupling scheme

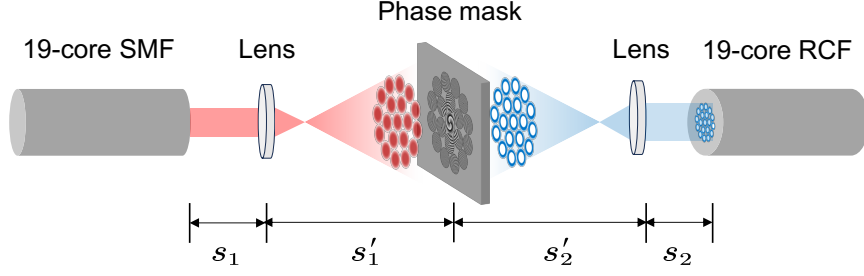


Fig. S9 Schematic diagram of the ‘19-to-19’ scheme for OAM mode excitation in the 19-core RCF.

Figure S9 illustrates the schematic of free-space OAM mode excitation based on the 19-core fibre configuration. During the multi-core coupling process, in order to ensure effective excitation of all cores and supported modes—as well as to maximize coupling efficiency—the incident optical field must be precisely matched to the spatial positions and modal structures of the 19-core ring-core fibre. Specifically, the transformed beams injected into the fibre must align with the core pitch, rotational orientation, and modal field characteristics of the fibre, including both intensity distribution and phase profile.

To achieve the required spatial and phase alignment, a spatial light modulator (SLM) is employed as a common reference plane for both the forward- and backward-propagating beams. On this plane, the Gaussian beams emitted from the 19-core single-mode fibre (forward direction) and the OAM modes emerging from the 19-core ring-core fibre (backward direction) are spatially overlapped in intensity. Based on this overlap, spiral phase distributions (for OAM modulation) and a quadratic phase profile (for wavefront shaping) are loaded onto the SLM. These allow simultaneous mode transformation of the forward beams and phase compensation of the backward-propagating OAM modes. The implementation principle is described as follows:

The rotational matching can be achieved by mounting the optical components on precision rotational stages. In this section, we primarily focus on matching the core pitch and beam size of the forward- and backward-propagating beams on the phase-mask plane. According to the thin lens imaging equation, the projected core pitch on the phase-mask plane can be controlled by selecting a lens with an appropriate focal length and adjusting the relative positions of the fibre end facet, the lens, and the phase mask. These parameters are governed by the following equations:

$$\frac{1}{s_i} + \frac{1}{s'_i} = \frac{1}{f_i} \quad (6)$$

$$V_i = -\frac{s'_i}{s_i} \quad (7)$$

According to the thin lens imaging equation and the definition of magnification, the following relationships hold:

$$s_i = f_i + \frac{f_i}{V_i} \quad (8)$$

$$s'_i = V_i f_i + f_i \quad (9)$$

Here, s_i denotes the distance from the fibre end facet to the lens (as illustrated in Fig. S9), where $i = 1$ corresponds to the 19-core single-mode fibre (SMF) and $i = 2$ corresponds to the 19-core ring-core fibre (RCF). f_i represents the focal length of the lens, and V_i denotes the imaging

magnification. With the condition $V_1 p_1 = V_2 p_2$, the projected core pitch of the 19-core SMF on the phase mask can be precisely matched to that of the 19-core RCF.

Once the intensity overlap is achieved, phase compensation using the spatial light modulator (SLM) must be considered. Treating the 19 beams as a single composite optical field, we assume that the field emitted from the 19-core SMF, after passing through the collimating lens and propagating from its focal point, can be described by the following expression:

$$U_{smf}(x, y) = A \exp(ikd_1) \exp\left(j \frac{k(x^2 + y^2)}{2d_1}\right) \quad (10)$$

Similarly, the optical field emitted from the 19-core ring-core fibre (RCF) can be expressed as follows:

$$U_{rcf}(x, y) = A' \exp(-ikd_2) \exp\left(-j \frac{k(x^2 + y^2)}{2d_2}\right) \quad (11)$$

Here, d_1 and d_2 represent the distances from the focal planes of the collimating lenses to the imaging plane (i.e., the liquid crystal surface of the SLM). According to Equation (9), we have:

$$d_1 = s'_1 - f_1 \quad (12)$$

Accordingly, a transfer function can be defined as follows:

$$t(x, y) = \frac{U_{rcf}(x, y)}{U_{smf}(x, y)} = \frac{A'}{A} \exp[-ik(d_2 - d_1)] \exp\left[-j \frac{k(x^2 + y^2)}{2(d_1 + d_2)}\right] \quad (13)$$

Neglecting constant coefficients and global phase terms, the expression simplifies to:

$$t'(x, y) = \exp\left[-j \frac{k(x^2 + y^2)}{2} \left(\frac{1}{d_1} + \frac{1}{d_2}\right)\right] \quad (14)$$

As shown in Equation (13), based on the Gaussian imaging formula for a lens, the transfer function is equivalent to the phase transformation term introduced by a lens, which can be simply expressed as:

$$t'(x, y) = \exp\left[-j \frac{k(x^2 + y^2)}{2F}\right] \quad (15)$$

Here, F denotes the focal length of the lens. Therefore, to compensate for the phase mismatch between the optical fields from the 19-core single-mode fibre and the 19-core ring-core fibre at the SLM plane, a global lens phase with focal length F can be applied to the entire optical field via the SLM. Details of the multiplexed optical path and the parameters of the phase masks loaded onto the SLM are summarized in Table S2.

Table S2: Experimental parameters of the ‘19-to-19’ coupling scheme.

19-core SMF	core pitch	μm	65
	focal length f_1	mm	11
	scaling factor V_1		31
19-core RCF	core pitch	μm	44
	focal length f_2	mm	11

scaling factor V_2			46
vortex order			0, +1, -1, +2, -2, +3, -3
Phase mask	pitch of vortex phase	μm	2015
	focal length of the Fresnel lens	mm	206

S8. Rotation invariance and parameter transferability experiments

The experimental setup is illustrated in Fig. 3a of the main text. The signal-modulated light is launched into a 19-core fan-in/fan-out device and emitted into free space in the form of 19 Gaussian beams. After passing through a linear polarizer, the beams become linearly polarized and are incident on a spatial light modulator (SLM). They are subsequently modulated into orbital angular momentum (OAM) or linearly polarized (LP) modes and coupled into a 19-core ring-core fiber. At the fiber output, a second SLM is employed to demodulate the transmitted OAM or LP modes. Finally, a charge-coupled device (CCD) is used to detect the intensity of the demodulated Gaussian beams, which characterizes the mode purity during transmission in the fiber.

To test rotation invariance, phase maps with varying rotation angles are loaded onto the transmission SLM. It should be noted that this rotation is applied exclusively around the central axis of each individual OAM/LP beam, rather than as a global rotation of the entire phase plate. Meanwhile, the phase map on the receiver SLM is kept constant, and the variations in the intensity of the received Gaussian beams are recorded.

For the parameter transferability experiment, adaptive optimization is initially performed at the transmitter for a beam of a specific mode order. Subsequently, only the topological charge is varied while retaining all other adaptively optimized parameters. The phase map at the receiver is synchronously adjusted to match the corresponding topological charge for demodulation, followed by detecting the intensity variation of the Gaussian beams at the receiver.

S9. Adaptive control principle of free-space optical multiplexing based on intensity feedback

As described earlier, the basic principles and implementation details of the free-space mode multiplexing process have been presented. However, in practical operation, this process typically relies on manual experience for mode alignment and adjustment, which limits its stability and generalizability—posing challenges for system-level engineering and automation. To address this issue, we propose an adaptive free-space multiplexing scheme based on feedback from the demodulated spot at the receiver side. The overall system architecture is illustrated in Fig. S10.

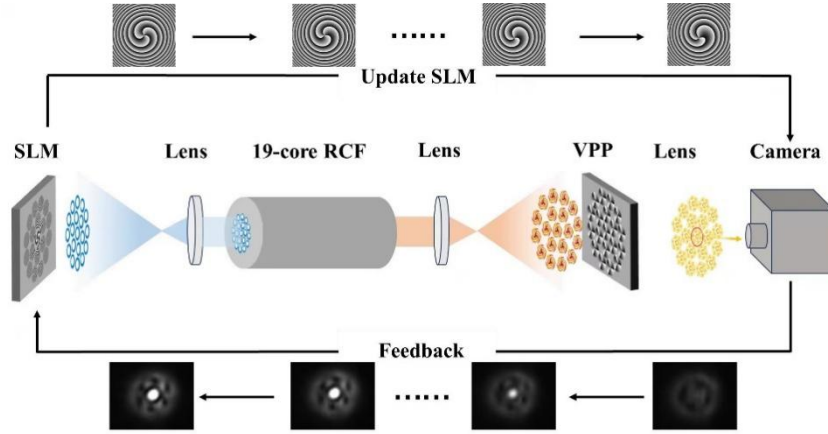


Fig. S10 Schematic diagram of the adaptive multiplexer optimization system.

The core idea of the proposed scheme is to dynamically optimize the phase mask loaded onto the spatial light modulator (SLM) at the transmitter side by analyzing the modal purity of the received optical field after fibre transmission, thereby improving the overall multiplexing precision and robustness. The adaptive process consists of two key components: (1) real-time evaluation of the modal purity of the output spot; and (2) feedback-driven optimization of the SLM phase mask based on the evaluation result.

To address the first challenge, it is necessary to extract phase information from the received optical field. Traditional methods typically rely on interferometric setups involving reference beams and interference imaging, which are complex and highly sensitive to environmental fluctuations—thus unsuitable for real-time operation. To overcome these limitations, we adopt a target-mode matched filtering strategy. At the receiver side, a vortex phase plate (VPP) corresponding to the desired OAM mode is applied to perform a conjugate phase transformation. If the incoming beam exactly matches the target mode, the transformed beam will collapse into a Gaussian-like spot with focused central intensity. This enables the replacement of complex phase retrieval with a simple intensity-based measurement, using the central intensity as an indicator of mode matching. This approach not only simplifies the system structure significantly but also offers improved real-time response and stability.

For the optimization strategy, we employ a simulated annealing algorithm for global search. By introducing random perturbations to the local phase distribution on the SLM surface, and using the negative of the detected Gaussian spot intensity at the receiver as the objective function, the SLM phase mask is iteratively optimized. This method does not rely on gradient information and has the ability to escape local optima, making it well-suited for the high-dimensional, nonlinear optimization problems encountered in this system.

In summary, the proposed adaptive multiplexing scheme combines intensity-to-phase mapping for modal purity evaluation with simulated annealing-based optimization, forming a closed-loop adaptive control framework for the free-space optical multiplexing system.

S10. Principle of the SAA for the adaptive optimization system

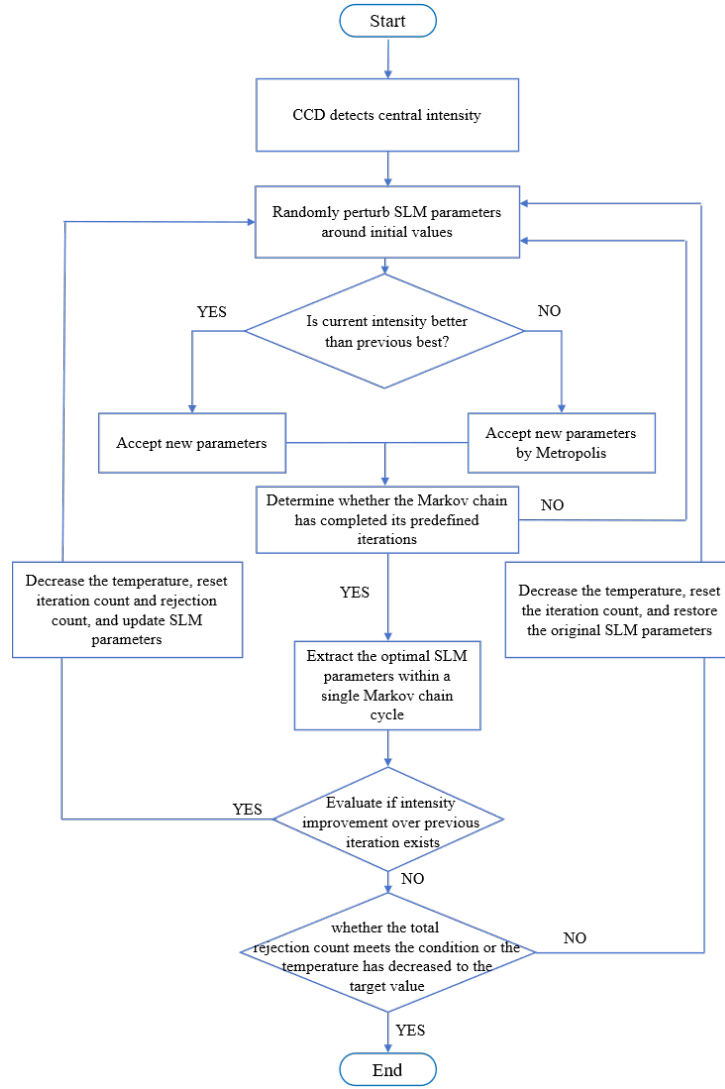


Fig. S11 Flowchart of the SAA for the adaptive optimization system.

Figure S11 illustrates the adaptive optimization algorithm process developed in this study. The system employs a simulated annealing algorithm (SAA) incorporating a multi-step Markov chain mechanism to optimize the control parameters of the spatial light modulator (SLM), including linear phase, global phase, and local phase, with the objective of maximizing the optical intensity detected by a CCD camera within the target region. The algorithm operates within a closed-loop framework, where the real-time optical intensity serves as the objective function for dynamic evaluation.

SAA is a global optimization method based on stochastic perturbations and a probabilistic acceptance criterion. Its core concept lies in gradually narrowing the acceptance range of candidate solutions by controlling the “temperature” parameter, thereby enabling a smooth transition from global exploration to local convergence. The temperature is typically updated according to an exponential decay law, expressed as:

$$T_k = \alpha T_0 \quad (16)$$

where T_0 denotes the initial temperature, T_k is the temperature at the k iteration, and α is the temperature decay factor.

The algorithm starts from an initial set of SLM parameters. At each temperature level, a Markov chain of length 5 was executed, in which candidate solutions were generated by applying stochastic perturbations to the SLM control parameters, and their corresponding CCD image intensities were measured in real time. The acceptance of a candidate solution follows the Metropolis criterion:

$$P = \begin{cases} \exp\left(-\frac{E_{new} - E_{old}}{T_k}\right), & E_{new} - E_{old} > 0 \\ 1, & E_{new} - E_{old} \leq 0 \end{cases} \quad (17)$$

where E_{new} and E_{old} denote the cost function values of the new and current solutions, respectively. Since the task aims to maximize optical intensity, the cost function was defined as the negative of the intensity, thereby reformulating the problem into a minimization form compatible with the SAA. Within each Markov chain, the parameter set yielding the highest intensity was retained as the initial solution for the subsequent temperature iteration.

In the experimental configuration, the initial temperature was set to 100, the termination temperature to 0.01, and the temperature decay factor to $\alpha = 0.9$. The algorithm was terminated early if no new solution was accepted over five consecutive temperature levels (a total of 25 iterations) to avoid unnecessary computation.

The SLM initial parameters and perturbation mechanism were defined as follows: the focal lengths of both the global and local phases were initialized to 206 mm, with random perturbations of ± 5 mm applied in each iteration; the linear phase was defined by two angular offset parameters (θ_x and θ_y), both initialized to zero and randomly adjusted within ± 0.01 radians after each iteration. This perturbation scheme ensures adequate exploration of the solution space while maintaining local continuity of the solutions.

S11. The experimental setup for OAM-SDM-WDM data transmission.

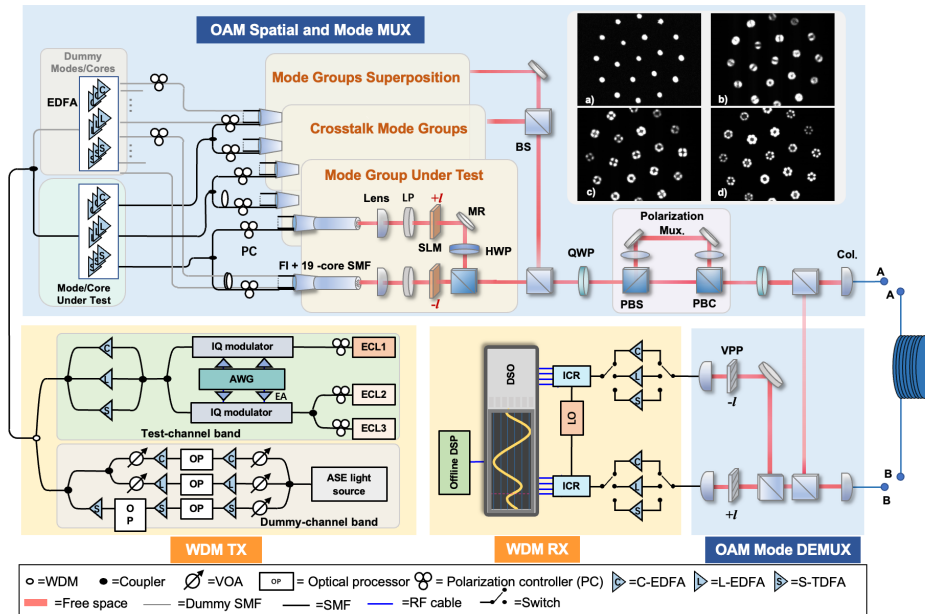


Fig. S12 Experimental setup. ECL, external cavity laser; AWG, arbitrary waveform generator; EA, electrical amplifier; EDFA, erbium-doped fiber amplifier; LP, linear polarizer; SLM, spatial light modulator; MR, mirror; HWP, half-wave plate; BS, beam splitter; QWP, quarter-wave plate; PBS, polarization beam splitter; PBC, polarization beam combiner; Col., collimator; VPP, vortex phase plate; ICR, integrated coherent receiver. The intensity profiles of OAM MGs with $|l| =$ (a) 0, (b) 1, (c) 2 and (d) 3.

Figure S12 illustrates the setup for the 25 Pbps OAM-SDM-WDM data transmission experiment, which mainly consists of five parts: a WDM signal generator with 16QAM/QPSK modulation, a 19-core OAM spatial and mode multiplexing (MUX) module, the 10 km 19-core RCF, an OAM mode demultiplexing (DEMUX) module and coherent optical receivers followed by DSP including the offline 4×4 MIMO equalization.

At the transmitter, a high optical signal-to-noise ratio (OSNR) sliding test channel band and a low OSNR dummy channel band are implemented simultaneously to produce the 1240 WDM channels using limited device resources. Three optical carriers, spaced at 0.1 nm/12.5 GHz, from three tunable external cavity lasers (ECLs) serve as sliding test channels. The primary test wavelength is modulated by a dual-polarization IQ (DP-IQ) modulator, with a roll-off factor of 0.01, carrying a 12-Gbaud probabilistically shaped 16QAM signal in the C/L bands and QPSK in the S band. The primary channel is multiplexed with two additional wavelengths, which are modulated by another DP-IQ modulator with the same format. Both modulators are driven by a four-channel (AWG), generating signals of a $2^{18}-1$ pseudo-random binary sequence (PRBS). The dummy channels, derived from amplified spontaneous emission (ASE), is amplified by a thulium/erbium-doped fiber amplifier (T/E-DFAs) and shaped by optical processors (OPs), setting the launch power of each WDM channel to 0 dBm.

The generated WDM signals are subsequently split into two branches via a 1:9 optical power splitter. 90% optical power is used to generate mode channels with high OSNR in the fibre core under test, while the remaining 10% optical power, which is further amplified by high-power T/E-DFAs, is used to implement low OSNR channels in the dummy cores. After passing through the T/E-DFAs, power splitters and optical DLs, the produced test and dummy spatial/mode channels are directed to the associated input port of the 19-core OAM mode multiplexing module. The excitation of OAM modes in the 19-core fibre is implemented using a free-space optical coupling approach. At the transmitter side, a 19-core single mode fan-in/fan-out (FIFO) module simultaneously generates 19 Gaussian beams, which are first collimated by a collimation lens and then directed into the free-space optics system. These Gaussian beams are subsequently modulated into 19 OAM beams by a spatial light modulator (SLM) loaded with a phase mask specifically designed for the 19-core configuration. All the desired OAM modes, including both the test modes and crosstalk-inducing modes, are combined via a beam splitter (BS), converted into circular polarization by a quarter-wave plate (QWP), and then injected into a 4-f polarization multiplexing system composed of two lenses with identical 150 mm focal lengths. The 4-f configuration ensures that the spatial pitch and optical axes of the orthogonally polarized OAM beam arrays remain unchanged during propagation, enabling efficient beam combining and accurate coupling into the 19-core ring-core fibre. Each mode group (MG) thereby carries four OAM modes: $\langle +l, X \rangle$, $\langle +l, Y \rangle$, $\langle -l, X \rangle$, and $\langle -l, Y \rangle$ ($l = 0-3$). (Further details on the free-space optical path and the SLM-loaded phase patterns can be found in Supplementary Section S7). After generation, all mode channels are equally split by a 50:50 BS into two optical paths, which are then injected into both ends of the fibre to emulate bidirectional transmission. This configuration is adopted due to equipment limitations in the laboratory. For the same reason, all channels are categorized into three types to emulate a realistic transmission environment: test channels, adjacent crosstalk-inducing channels, and low-crosstalk background channels. In the C+L bands, all test channels are launched with identical input power. In the S band, however, constrained by hardware availability, only the test channels and their adjacent crosstalk channels are assigned equal input power, while the low-crosstalk background channels are still excited but with significantly

lower power. Prior studies confirm that inter-core crosstalk is negligible, ensuring minimal impact on communication signals⁴.

After 10 km transmission through the 19-core ring-core fibre, all OAM modes are collimated and directed into free space for mode demultiplexing. The output beam profiles are shown in Fig. S12 (a)–(d). At the demultiplexing end, the collimated beams are split into two paths by a 50:50 beam splitter (BS), and each path is directed to a vortex phase plate (VPP) with opposite helical phase distributions to demodulate the $\pm l$ order orbital angular momentum (OAM) modes. The resulting Gaussian-like beams are then coupled into two single-mode fibres and subsequently delivered into dual-polarization integrated coherent receivers (ICRs) for detection. Due to equipment constraints, only one mode group (MG) in a single fibre core can be demultiplexed and received at a time to go through the 4×4 MIMO equalization that compensates the intra-MG modal crosstalk. To evaluate all spatial channels, signals corresponding to different OAM mode groups (MGs) and fibre cores are demultiplexed, received, and tested sequentially in an asynchronous manner. The output electrical waveforms from the dual-polarization ICRs are captured by an eight-channel real-time oscilloscope operating at a sampling rate of 50 GSa/s and are stored for offline digital signal processing (DSP) and bit-error rate (BER) analysis. The offline DSP procedures primarily consist of timing phase recovery, frequency offset compensation, carrier phase estimation, and 4×4 MIMO equalization based on the conventional blind constant modulus algorithm (CMA) to mitigate intra-MG modal crosstalk.

S12. Measurement of inter-MG crosstalk and the inter-core crosstalk of the entire transmission system and the 10-km 19-RCF

The inter-MG crosstalk (XT) within the same fiber core and the inter-core XT of the transmission system consists of the 10-km 19-RCF, the OAM MUX and DEMUX are experimentally characterized utilizing power measurements.

A. The measurement of inter-MG crosstalk of the entire SDM transmission system

Three OAM MGs with topological charges 0, 1, 2 and 3, after propagation in one 10-km fibre core, are split into two branches, with each branch passing through a commercial vortex phase plate (VPP) with opposite topological charges l and $-l$, respectively (see Fig. S13). With this arrangement, only the OAM MG whose topological charge equals $|l|$ is demultiplexed, converted to a Gaussian beam and coupled into the two SMFs. For a fixed $|l|$, we first transmit MG $|l|$ and record the average power $P_{|l|}$ (dBm) at the ends of the two SMFs (mean of the two outputs). Without changing the receiver setting, the transmitter is then switched to MG $|m| \neq |l|$, and the corresponding average power $P_{|m|}$ is recorded at the same SMFs. The crosstalk from OAM MG $|m|$ to OAM MG $|l|$ is calculated as

$$XT_{|l|,|m|} = P_{|m|} - P_{|l|} \quad (18)$$

where $|m|, |l| = 0-3$. The measured results of the inter-MG crosstalk of all cores at the wavelengths of 1550 nm in the 10-km 19-RCF is shown in the Fig. S14.

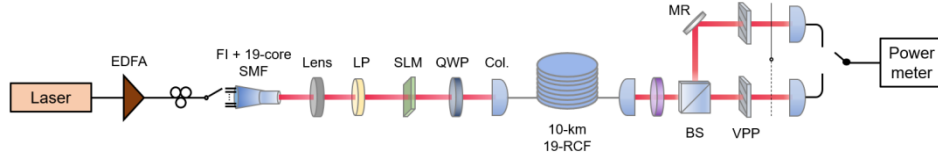


Fig. S13 The setup of the inter-MG crosstalk and the inter-core crosstalk measurement. PC: polarization controller; EDFA: erbium doped fiber amplifier; FI: Fan in; LP: linear polarizer; SLM: spatial light

modulator; QWP: quarter-wave plate; Col.: collimator; BS: beam splitter; VPP: vortex phase plate; PD: photodetector.

Following the above test method, we measured the inter-mode crosstalk of 19 fiber cores. The test results are shown below, indicating that the crosstalk between adjacent mode groups is approximately -14 dB. In addition, we also evaluated the inter-mode crosstalk at different wavelengths across different bands, and the results demonstrate that the inter-mode crosstalk exhibits good stability over wavelength.

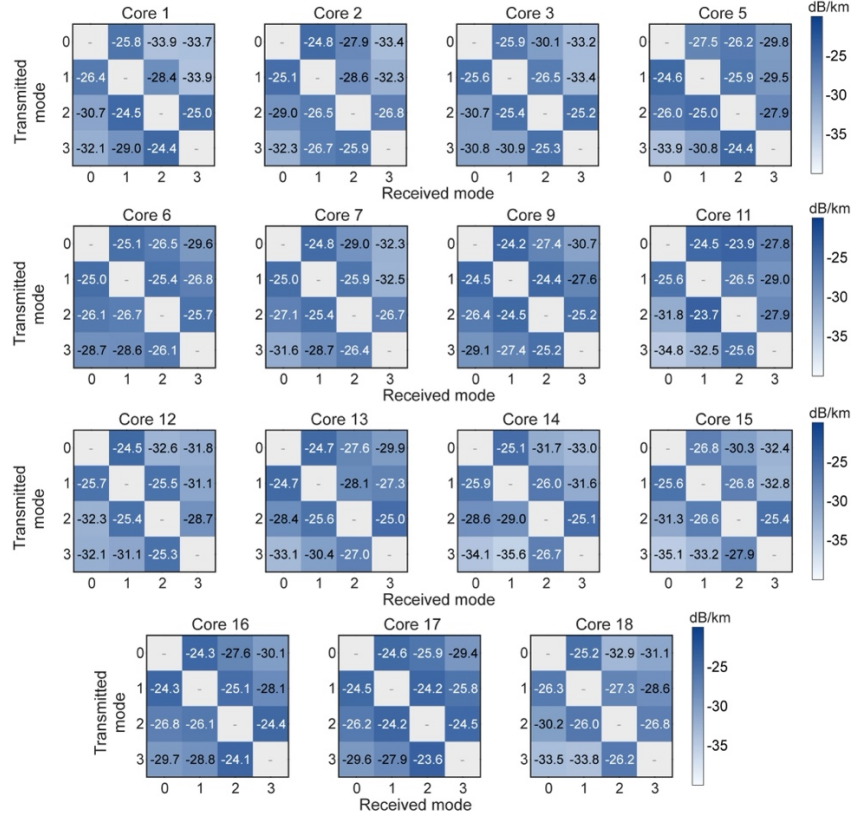


Fig. S14 Measured inter-mode crosstalk values for different cores (in dB km⁻¹).

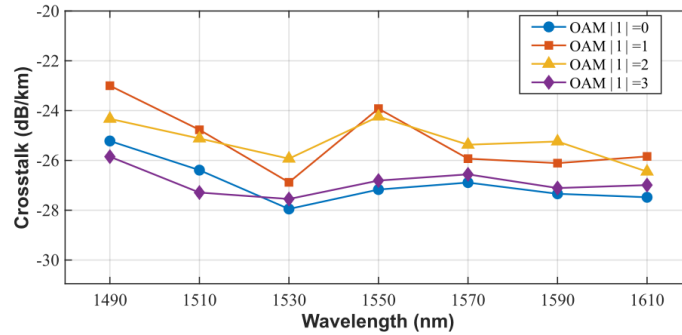


Fig. S15 Total crosstalk received from other modes for different OAM modes over the wavelength range of 1490 nm to 1610 nm.

B. The measurement of inter-core crosstalk of the transmission system

As illustrated in Fig. S16, to measure inter-core crosstalk for OAM MGs with $|l| = 0-3$, an OAM beam modulated with topological charge $|l|$ is coupled into core # m ($m = 0-18$) of the 10-km 19-RCF. The average output power from the incident core is recorded as P_m (dBm), and the average output power simultaneously detected at another core $n \neq m$ is recorded as P_n (dBm). The inter-core crosstalk of MG $|l|$ from core # m to core n is defined as:

$$XT_{mn} = P_n - P_m \quad (19)$$

This procedure is repeated for $|l| = 0-3$ and all core pairs $n \neq m$ ($m, n \in \{0, \dots, 18\}$).

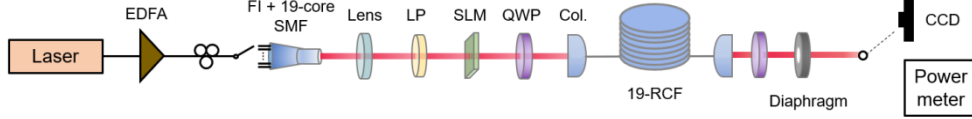


Fig. S16 The setup of the inter-core crosstalk measurement. PC: polarization controller; EDFA: erbium doped fiber amplifier; FI: Fan in; LP: linear polarizer; SLM: spatial light modulator; QWP: quarter-wave plate; Col.: collimator; BS: beam splitter; PD: photodetector; CCD: charge coupled device.

S13. Influence of Rayleigh Backscattering noise in the transmission over multimode fiber with coherent detection

Considering a high-speed communication system, if the fluctuation of the laser source is far slower than the modulated signal, the linearly polarized electrical field of the optical signal can be approximately described as⁵:

$$\vec{e}_s(t) = \text{Re}[\vec{\tilde{e}}_s(t)e^{j\omega_0 t}] \quad (20)$$

where the ω_0 is the carrier frequency and the $\vec{\tilde{e}}_s(t) = \vec{p}_s \gamma(t) \exp[j\phi(t)]$ is the complex amplitude vector. Here, $\gamma(t) = a(t) \exp[j\theta(t)]$ represents the variations of the complex amplitude $\vec{\tilde{e}}_s(t)$ due to amplitude modulation $a(t)$ and angle modulation $\theta(t)$. $\phi(t)$ describes the inherent laser phase noise, and the Jones matrix $\vec{p}_s$ indicates the state of polarization of the field. $P_s = \langle \gamma(t) \rangle^2$ is the average power of the optical signal.

With the attenuation coefficient α , the propagation constant β , and the group velocity v , the complex amplitude vector of the incident field at location z is:

$$\vec{e}_i(t) = \mathbf{P}(z) \vec{\tilde{e}}_s \left(t - \frac{z}{v} \right) e^{-\frac{\alpha z}{2}} e^{-j\beta z} \quad (21)$$

The Jones matrix $\mathbf{P}(z)$ indicates the polarization state transfer of the electrical field along the longitudinal direction. Divide the fiber with length L into N scatter sections, and the $\Delta L = L/N$ is the scatter section length. Then the Rayleigh backscattering (RB) signal $\Delta \vec{e}_{RB}(t, z)$ received at the fiber input from a scatter section at z is described as:

$$\Delta \vec{e}_{RB}(t) = \mathbf{M}(z) \vec{\tilde{e}}_s \left(t - \frac{2z}{v} \right) e^{-\alpha z} e^{-j2\beta z} \Delta \rho(z) \quad (22)$$

The unitary Jones matrix $\mathbf{M}(z) = \mathbf{P}^T(z) \mathbf{P}(z)$, which describes the change of polarization state⁶. The backscattering coefficient $\Delta \rho(z)$ is the fraction of the backscattered field from a scatter section at location z . Thus, the total RB field at the fiber input can be described as:

$$\vec{e}_{RB}(t, s) = \sum_{n=1}^N \Delta \vec{e}_{RB}(t, n\Delta L) = \int_0^L \mathbf{M}(z) \vec{\tilde{e}}_s \left(t - \frac{2z}{v} \right) e^{-\alpha z} e^{-j2\beta z} \rho(z) dz \quad (23)$$

Where $\rho(z) = \lim_{\Delta L \rightarrow 0} \Delta \rho(z) / \Delta L$. Considering the RB as a random process, $\rho(z)$ can be modeled as a delta-correlated zero-mean circular-complex-Gaussian random variable, which can be

described by $\langle \rho^*(z_1)\rho(z_2) \rangle = 2\sigma^2\delta(z_1-z_2)$, where σ^2 is variance of $\rho(z)$ ⁷. Therefore, in the SMF, the average RB power at the fiber input can be approximately described as⁸:

$$\langle P_{RB} \rangle = \frac{2\alpha_s S P_s (1 - e^{-2\alpha L})}{2\alpha} \quad (24)$$

Where S is the recapture factor, which is related to the fiber structure, and α_s is the attenuation coefficient due to RB. Eqs. (24) has been confirmed to be applicable in the case when the optical light is modulated⁹.

However, when it comes to multi-mode fibers (MMFs), the recapture factor of RB needs to be corrected considering the mode coupling. Assuming that the average input signal intensity of mode i is I_s , the average RB power from mode i in one transmission direction recaptured by mode j in the other transmission direction can be calculated as¹⁰:

$$\langle P_{RB,ij} \rangle = \frac{2\alpha_s B_{ij} P_s (1 - e^{-2\bar{\alpha}L})}{2\bar{\alpha}} \quad (25)$$

where $2\bar{\alpha} = \alpha_i + \alpha_j$, α_i and α_j are the attenuation coefficients of mode i and j . α_s is the attenuation coefficient due to the RB, which can be assumed that $\alpha_s \approx \bar{\alpha}$ while the fiber attenuation is mainly attributed to RB. B_{ij} is the recapture factor, indicating the proportion of the total scattered power of the mode i in one transmission direction recaptured by the mode j in the other transmission, which can be calculated by the mode field overlap integration¹¹:

$$B_{ij} = \frac{3\pi}{2(kn)^2} \frac{\iint \varphi_i^2 \varphi_j^2 ds}{\iint \varphi_i^2 ds \iint \varphi_j^2 ds} \quad (26)$$

where φ_i and φ_j are the transverse mode fields distribution of mode i and j , respectively. They are calculated using a commercial finite element module (COMSOL Multiphysics) based on the refractive index profile of the selected fiber core within the seven-ring-core fiber. Meanwhile, n is the core refractive index in the fiber, and $k = 2\pi/\lambda$ is the wave vector of the light, where λ is the wavelength of the optical carrier.

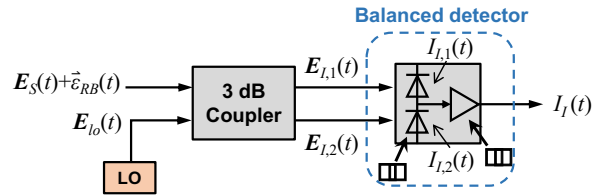


Fig. S17 Schematic setup of coherent detection using balanced detectors. LO: Local oscillating light; PD: photodetector; EA: electrical amplifier.

Given the utilization of coherent detections at the receivers in the transmission systems (refer to Fig. 6 in the main text), it is necessary to analyze the interactive effects among the local oscillating (LO) light, the received signal and the RB noise. Here noted that only RB noise is considered alongside the optical signal at the receiver for simplicity. As illustrated in Fig. S17. The electrical field at the two output ports of the 3 dB coupler can be expressed as:

$$E_{I,1}(t) = \frac{1}{\sqrt{2}} [E_s(t) + \varepsilon_{RB}(t) + jE_{lo}(t)] \quad (27)$$

$$E_{I,2}(t) = \frac{1}{\sqrt{2}} [jE_s(t) + j\varepsilon_{RB}(t) + E_{lo}(t)] \quad (28)$$

where $E_S(t)$ and $E_{lo}(t)$ are electrical field of the received signal and the LO carrier, respectively. $\vec{E}_{RB}$ is the received RB electrical field. Given the received optical signal, RB noise and LO light are with the same polarization, the expression for the detected photocurrents can be derived after passing through the two photodetectors (PDs) for balanced detection.

$$I_{I,1} = \frac{R}{2} |E_S(t)|^2 + \frac{R}{2} |E_{lo}(t)|^2 + \frac{R}{2} [-jE_S(t)E_{lo}^*(t) + jE_S^*(t)E_{lo}(t)] \\ + \frac{R}{2} [E_S(t)\epsilon_{RB}^*(t) + E_S^*(t)\epsilon_{RB}(t)] + \frac{R}{2} |\vec{E}_{RB}(t)|^2 \\ + \frac{R}{2} [jE_{lo}(t)\epsilon_{RB}^*(t) - jE_{lo}^*(t)\epsilon_{RB}(t)] \quad (29)$$

$$I_{I,2} = \frac{R}{2} |E_S(t)|^2 + \frac{R}{2} |E_{lo}(t)|^2 + \frac{R}{2} [jE_S(t)E_{lo}^*(t) - jE_S^*(t)E_{lo}(t)] \\ + \frac{R}{2} [E_S(t)\epsilon_{RB}^*(t) + E_S^*(t)\epsilon_{RB}(t)] + \frac{R}{2} |\vec{E}_{RB}(t)|^2 \\ + \frac{R}{2} [-jE_{lo}(t)\epsilon_{RB}^*(t) + jE_{lo}^*(t)\epsilon_{RB}(t)] \quad (30)$$

where R represents the responsivity of the PDs. After undergoing differential reception through the use of balanced detectors, the final output current can be express as:

$$I_I = I_{I,1} - I_{I,2} \\ = R[jE_S(t)E_{lo}^*(t) + jE_S^*(t)E_{lo}(t)] + R[jE_{lo}(t)\epsilon_{RB}^*(t) - jE_{lo}^*(t)\epsilon_{RB}(t)] \\ = I_{S-lo} + I_{RB-lo} \quad (31)$$

where P_{lo} represent the power of forward transmitting signal and the LO light. $\Delta\omega$ is the frequency difference between the optical carrier of the received optical signal and the LO light. Since the RB noise has the same spectral property with the received signal, they have similar frequency difference with the LO light. $A(t)$ and $A_{RB}(t)$ represent the variations of the amplitude of the received optical signal and the RB noise, respectively. $\Phi(t)$ and $\phi_{RB}(t)$ are the modulated phase of the received optical signal and the RB noise, respectively. $\varphi_n(t)$ and $\varphi_{nRB}(t)$ represent the phase noise of the LO laser relative to the received optical signal and the RB noise, respectively. φ_0 is the original phase of the LO laser. It can be seen from Eqs. (31) that the beating noise arising from the interaction between the received signal and the RB noise is alleviated after coherent detection. Only two terms remain to be preserved: the first term I_{S-lo} denotes the beating signal between the received signal and the LO light, while the second term I_{RB-lo} represents the beating noise between the RB noise and the LO light.

After frequency-offset compensation and carrier phase recovery based on the digital signal processing, the signal-LO beating term can be expressed as:

$$I_{S-lo} = 2R\sqrt{P_{lo}} \cdot A(t) \sin \varphi(t) \quad (32)$$

Therefore, the average power of I_{S-lo} can be simply express as:

$$\langle I_{S-lo} \rangle^2 = 4R^2 P_S P_{lo} \quad (33)$$

where P_S denotes the average power of the received signal. Similarly, the average power of RB-LO beating noise I_{RB-lo} can be expressed as:

$$\langle I_{RB-lo} \rangle^2 = 4R^2 P_{lo} \langle P_{RB,ij} \rangle \quad (34)$$

Here $\langle P_{RB,ij} \rangle$ is the term shown in Eqs. (25), theoretically equivalent to the integral of power spectral density with respect to the reception bandwidth, given the random nature of I_{RB-lo} .

Therefore, the power ratio of the beating signals to the RB-LO beating noise can be simply express as:

$$\langle I_{S-lo} \rangle^2 / \langle I_{RB-lo} \rangle^2 = P_S / \langle P_{RB,ij} \rangle \quad (35)$$

According to the above analysis, the theoretical power ratio $\langle I_{S-lo} \rangle^2 / \langle I_{RB-lo} \rangle^2$ for in-fiber orbital angular momentum (OAM) mode l_F of the forward transmission, under different power levels of OAM mode l_B of the backward transmission, is calculated and illustrated in Fig. S18. The detailed parameters utilized in the calculation are listed in Table S3 for reference. Here noted that, in the scenario of bidirectional transmission with two-mode multiplexing (OAM $l_F = 1 \& 2$, $l_B = 1 \& 2$), we assume there is no inter-mode crosstalk and only signal in forward mode channel $l_F = 1$ is evaluated in the calculation.

Table. S3 Calculation parameters of the theoretical power ratio

Parameter	Unit	Value
$\alpha_S, \bar{\alpha}$	1/km	0.0725
B_{11}, B_{12}	-	$7.23 \times 10^{-4}, 4.68 \times 10^{-4}$
L	km	10

(B_{33}, B_{34} : Recaptures factors from calculation using COMSOL Multiphysics based on the refractive index profile of the selected fiber core within the seven-ring-core fiber.)

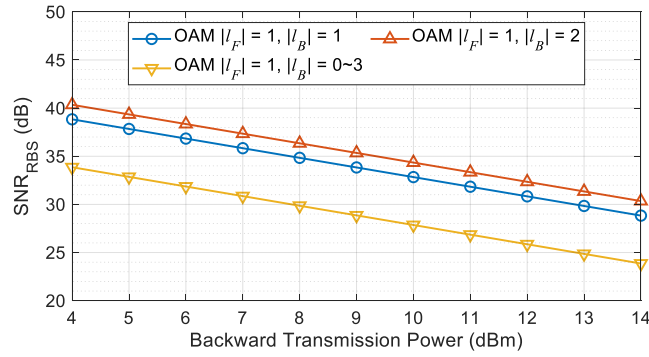


Fig. S18 $\langle I_{S-lo} \rangle^2 / \langle I_{RB-lo} \rangle^2$ of the forward transmission vs. backward transmission power; l_F : topological charge of the forward transmission OAM MG; l_B : topological charge of the backward transmission OAM modes.

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