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

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Abstract

Massive space-division multiplexing could enable multi-petabit fibre transmission, but its up-scaling is met with two major constraints, namely inter-modal coupling inside the fibre and multi-dimensional spatio-modal alignment at the fibre-transceiver interfaces. We show that by exploiting the natural physical properties of orbital-angular-momentum (OAM) modes in ring-core fibres, both constraints can be significantly relieved to construct block-diagonal end-to-end channel matrix. In the fibre, the OAM modes are partitioned into 4-fold near-degenerate spin-orbital mode groups by joint exploitation of their ring-confined modal field distribution, enlarged inter-group wave propagation-constant separation and azimuthal selection rules to suppress inter-group coupling, resulting in block-diagonal fiber transfer matrix with 4×4 sub-blocks. At the interfaces, the rotational invariance and high overlap between OAM modes allows cross-order transferable wavefront distortion correction, which is utilized to develop rapid adaptive optical alignment that suppresses inter-group crosstalk arising in the massive parallel mode launch and detection process. Leveraging the resulting block-diagonal end-to-end channel matrix, we realize a 10-km 19-core OAM fibre transmission system with only fixed-size 4×4 MIMO equalization modules and fully automated interface. The system supports 266 spatial channels each carrying 1,240 wavelength channels across the S, C and L bands, achieving the extreme multiplexing of 329,840 optical data streams with 25.24 Pb s⁻¹ aggregate capacity, reaching a spectral efficiency of 1935.6 bit s⁻¹ Hz⁻¹ and a spectral-efficiency density of 3.94 × 10⁻² bit s⁻¹ Hz⁻¹ μm⁻². To our knowledge, this is the first single-fibre system exceeding 100 usable SDM channels with low and constant MIMO complexity and no manual interface adjustment.

43 Introduction

44 Massive space-division multiplexed (SDM) with hundreds of spatial and mode
45 channels has been intensively investigated as a potential approach of scaling the
46 capacity of fiber-optic communications systems. Despite demonstrations of multi-Pbps
47 transmission^{1–10}, whether they offer practical advantages remain unclear, as in-fibre
48 modal crosstalk and fiber-transceiver interface complexity typically scale unfavourably
49 with channel count. Crosstalk originating from the distributed optical coupling between
50 the spatial channels-comprised of multiple cores and/or modes-in the fiber necessitates
51 high complexity MIMO signal processing whose hardware cost and energy
52 consumption overhead out-grow the capacity. At the fiber-transceiver interfaces, in
53 order to launch/detect hundreds of spatial and modal channels, the same number of
54 incoming/outgoing optical modes, typically with a Gaussian mode profile carried by
55 single mode fibres or waveguides, not only need to be simultaneously converted to/from
56 those of the transmitted fibre modes with high fidelity, they must also be precisely
57 aligned with the corresponding fibre cores and modes in order to avoid high insertion
58 loss and crosstalk, a daunting task whose complexity becomes prohibitive to any
59 manual or mechanical process.

60 Since 2013, structured light modes carrying orbital angular momentum (OAM) have
61 been introduced into space-division multiplexed (SDM) fiber-optic communications as
62 an orthogonal spatial basis to overcome the capacity limits of single-mode fibers¹¹.
63 Ensuing works^{12–14} demonstrated that OAM modes indeed support superior ability to
64 maintain orthogonality. The block-orthogonality between degenerate OAM mode
65 groups (MGs) of different topological charge values $|l|$ kept MIMO processing to a
66 fixed minimum scale in multi-OAM mode transmission up to 100 km over single core
67 OAM fibre¹⁵ and 1 Pbps transmission over a 7-core OAM fiber¹⁶. While these
68 experiments established OAM modes as a viable orthogonal basis over substantial fibre
69 lengths, scaling to more extreme spatial channel counts and densities exposes more
70 severe challenges.

71 Just as in multi-core few mode (MCFM) SDM fibers^{1,7,17–19} employing LP modes, to
72 significantly expand the OAM channel count requires both more cores and more OAM
73 modes per core. With more cores located further away from the principal axis of the
74 fibre, whether OAM-MG block-orthogonality could still be maintained is not
75 guaranteed, as the more complicated strain field introduced during fiber fabrication
76 could cause more refractive index profile anisotropy as well as geometric distortion of
77 the OAM-supporting cores in the off-axis cores.

78 Also similar to MCFM SDM schemes, low crosstalk multi-core multi-mode
79 launching heavily relied on time-consuming, experience-driven, painstaking manual
80 alignment. As spatial channel count scales towards the hundreds, this approach becomes
81 plainly impractical for managing the hyper-dimensional coupling parameter space.
82 More fundamentally, with more cores located farther away from the principal optical
83 axis, non-paraxial optical distortions can break the orthogonality of the launched modes.
84 Consequently, the block-diagonality of the OAM mode groups may be broken, resulting
85 in severe modal crosstalk that necessitates large-scale MIMO equalization.

86 In this work, guided by the fundamental physics of in-fibre OAM mode propagation,

we demonstrate that, by actively and fully harnessing the unique physical properties of OAM modes in ring-core fibers, including azimuthal angular momentum selection rules, rotational invariance, and ring-confined field structure, can be actively and fully harnessed to systematically regulate the end-to-end system transfer matrix $H = H_{Rx} H_{fiber} H_{Tx}$ through a progressive block-diagonalization process is enabled.

Specifically, **during fibre propagation**, the combined effects of ring-confined fields, enlarged propagation-constant separation between neighbouring mode groups, and azimuthal angular-momentum selection rules suppress inter-group coupling. Distributed mode mixing is therefore restricted to four-dimensional degenerate OAM subspaces, allowing the fibre transfer matrix H_{fiber} to retain a block-diagonal structure with fixed 4×4 sub-blocks. **At the transmitter and receiver interfaces**, the rotational invariance of OAM modes and the strong similarity of their intensity profiles across different topological orders enable cross-order transferability of distortion correction. This allows automated, algorithm-driven alignment to rapidly optimize the coupling matrices H_{Rx} and H_{Tx} , thereby suppressing off-diagonal crosstalk arising from interfacial misalignment and wavefront distortion.

Leveraging the thus block-diagonalized transfer matrix H , we realize an SDM transmission system over a 19-core OAM fiber of 10 km length. Through extreme multiplexing of 266 spatial channels each carrying 1240 wavelength channels spanning S, C and L bands, the system transmits 329840 parallel optical data streams and achieves an aggregate capacity of 25.24 Pb s⁻¹ over the full S+C+L bands, while reaching a spectral efficiency of 1935.6 bit s⁻¹ Hz⁻¹ and a spectral-efficiency density of 3.94×10^{-2} bit s⁻¹ Hz⁻¹ μm⁻² over the C+L bands, using only very modest 4×4 MIMO equalizers (as shown in Fig. 1; see Supplementary Note S1 for calculation details). To our knowledge, this represents the first single-fiber system exceeding 100 usable SDM channels while maintaining by far the lowest MIMO equalization complexity and without manual interface calibration.

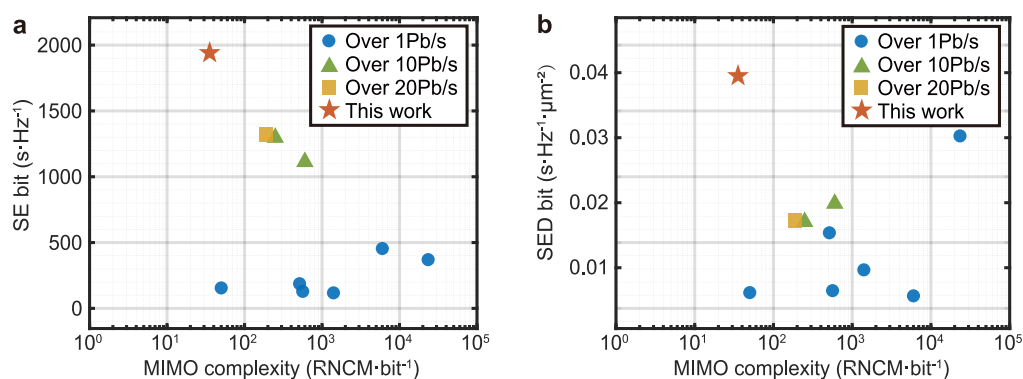


Fig 1. Comparison of spectral/spatial efficiency versus MIMO complexity^{1,7,8,10,16,20–23}. **a** Total SE in the C+L bands (GMI-estimated or before decoding); **b** SED of fiber in the C+L bands (GMI-estimated or before decoding)

Results

The major barrier to scaling space-division multiplexing is to effectively preserve modal orthogonality throughout transmission and interfacing²⁴. An SDM link is a linear MIMO channel, which can be expressed in the frequency domain as $\mathbf{y}(f) =$

$\mathbf{H}(f)\mathbf{x}(f) + \mathbf{n}(f)$ ²⁵. A scalable SDM architecture requires the end-to-end transfer matrix to be approximately block-diagonal with a bounded block size, preventing equalization complexity from exploding. We explicitly factorize the end-to-end transfer matrix as $\mathbf{H}(f) = \mathbf{H}_{\text{TX}}(f) \mathbf{H}_{\text{fiber}}(f) \mathbf{H}_{\text{RX}}(f)$ and enforce this block-diagonality by exploiting OAM physics across both the transmission medium ($\mathbf{H}_{\text{fiber}}(f)$) and the interfaces ($\mathbf{H}_{\text{TX}}(f)$, $\mathbf{H}_{\text{RX}}(f)$).

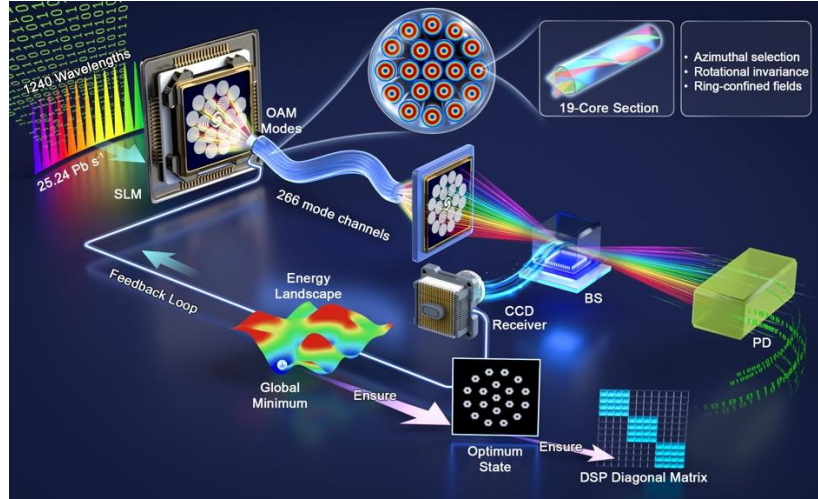


Fig 2. System architecture for 25-Pb/s space-division multiplexing via OAM-guided block diagonalization.

OAM-enforced sparse coupling in the 19-core ring-core fiber

To realize an effectively block-diagonal $\mathbf{H}_{\text{fiber}}(f)$, we simultaneously exploit the unique opportunities of regulating mode coupling in both the azimuthal and radial dimensions afforded by OAM modes in the ring core fiber (RCF).

The ring-shaped refractive index profile (RIP) provides radial confinement that results in well-defined OAM MGs containing near-degenerate modes with four spin-orbital momenta combinations $[\pm s, \pm l]$, where $s = 1$ is the spin angular momentum (SAM) quantum number and $\pm l$ is the orbital topological charge. By suppressing higher-order radial mode families, a large propagation-constant separation $\Delta\beta$ opens up between MGs of adjacent $|l|$, particularly at higher $|l|$, which renders common longitudinal perturbations (such as core-cladding boundary corrugations, micro-bends, etc) ineffective according to well-established mode coupling theories. In addition, a more nuanced avenue is also exploited in the fiber design, which is the coupling coefficient between a pair of modes strongly depends on the spatial overlap integral between their modal fields and the radial gradient of the RIP. Unique to OAM modes in RCFs, this integral can be significantly minimised due to the positive and negative gradients at the inner and out core-cladding boundaries that can cancel out each other's contribution to the integral.

Guided by the aforementioned principles, we designed the RCF with a two-layer ring-core index profile (Fig. 3c), which provides tight radial confinement for robust guidance of the first-radial-order OAM family and reduces the overlap between guided fields and common perturbations^[26]. The RCF core supports OAM MGs with $|l|$ up to 3 as shown in Fig. 3d. We intentionally retain the LP02 mode group to further enlarge

the $\Delta\beta$ between its adjacent $|l| = 2, 3$ OAM MGs (see Supplementary Note S2 for details). This non-OAM mode is not utilized for transmission and forms a ‘barrier’ to coupling between its two OAM neighbours. The RCF preform rods are synthesized by a plasma chemical vapour deposition (PCVD) process with precise inter-layer viscosity matching, vital for achieving the high contrast RIP design with low stress and very low micro-perturbations.

In the azimuthal dimension, the fact that OAM modes are eigenstates of the azimuthal angular-momentum operator imposes selection rules that prohibit many coupling pathways caused by circular-symmetry-breaking perturbations such as refractive index birefringence and core shape deformation^{27,28}. The resulting sparsity in the mode coupling matrix further reinforces the suppression of inter-group crosstalk over and above the coupling suppression measures in the radial dimension elaborated above (details can be found in Supplementary Note S3). Consequently, an effectively block-diagonal $\mathbf{H}_{\text{fiber}}(f)$ should be achievable, with mode coupling confined within the subspaces of the four near-degenerate $[\pm s, \pm l]$ OAM modes, provided that the circular symmetry of the core RIP and especially the geometric shape is well-maintained.

To ensure the above potential advantages are fully exploited in the practical implementation of a multi-core multi-mode fibre for massive OAM multiplexing, in addition to the optimized core design and fabrication, we further design a 19-core RCF with 1 central core, 6 inner layer cores, and 12 outer layer cores. The identical cores follow the equidistance triangular layout to main symmetry of the core with respect to their neighbours. Together with a carefully chosen distance between the outer layer cores and the fibre outer boundary, asymmetric strain and deformation are minimised in order to maintain the azimuthal coupling selection rules afforded by OAM modes. A core pitch of 44 μm is used with a low index trench of 17 μm radius to ensure low inter-core coupling with a fibre outer diameter of 250 μm .

The RCF preform rods are inserted into a viscosity-matched silica capillary with the 19 drilled holes precision-machined to ~ 0.5 μm inner-wall roughness. Careful vacuum melt-drawing of this integrated multi-core assembly effectively mitigates interfacial defects and structural distortions, faithfully replicating the targeted index profile and circular core shape, establishing the precise structural integrity required for robust modal transmission. A fibre specimen of 10 km length is produced, limited by the size of the preform assembly.

Optical time-domain reflectometry (OTDR) measurement confirms low attenuation averaging ~ 0.25 dB km^{-1} at 1550 nm alongside low in-core mode-dependent loss (MDL) of ≤ 0.06 dB km^{-1} (see Supplementary Note S4 for details). Swept-wavelength interferometry (SWI) is then used to measure the crucial mode coupling coefficient (Supplementary Note S5)²⁹. As illustrated in Fig. 3e, coupling between adjacent OAM MGs in the same core is maintained below -40 dB km^{-1} for most cores, while inter-core crosstalk is suppressed to approximately -50 dB km^{-1} . This low inter-group coupling reflects the OAM-enabled suppression mechanisms discussed above, stemming from radial confinement and azimuthal selection rules. The measured inter-group differential group delay (DGD), reaching $\sim 6, 7$ and 8 ns km^{-1}

between the $l = 0/1, 1/2$ and $2/3$ MGs, is also in line with the designed separation between OAM MGs (Supplementary Note S6). The combination of ultra-low coupling and large group-delay separation between OAM MGs provides direct experimental evidence of an effectively block-diagonal fibre channel with 4×4 sub-blocks. Consequently, provided that additional crosstalk at the fibre-transceiver interfaces is brought under control, a modular MIMO equalizer with fixed 4×4 complexity remains sufficient regardless of the total channel count.

Robust automated OAM interfacing and end-to-end crosstalk suppression

Beyond maintaining low-crosstalk propagation, scalable space-division multiplexing (SDM) requires highly diagonal multiplexing and demultiplexing matrices $\mathbf{H}_{\text{TX}}(f)$ and $\mathbf{H}_{\text{RX}}(f)$ to suppress interface-induced crosstalk. Due to misalignment and wavefront distortion as elaborated earlier, satisfying this requirement becomes very challenging for massive SDM as core and mode counts increase.

To make full use of the capacity afforded by the 19-core OAM fiber, it is necessary to launch a total of 266 mode channels consisting of 14 modes belonging to the $|l| = 0 - 3$ MGs (2 spin modes of $l = 0$, and 4 OAM modes in each MG of $|l| = 1 - 3$) in each of the 19 cores at the transmitter. The setup uses four pieces of 19-core single mode fibres (SMFs) whose core layout corresponds with that of the 19-core OAM fibre. As illustrated in Fig. 3a, the 19 Gaussian beams from one piece of 19-core SMF are converted into 19 OAM modes of a certain $|l|$ using a SLM encoded with 19 holograms and projected onto the end-facet of the 19-core OAM fibre (see Supplementary Note S7 for the optical coupling principle). Channels from all four pieces are polarization and spatially combined using waveplates and half-mirrors (Supplementary S7). Mode demultiplexing at the receiver was achieved using a phase plate bearing the conjugate topological charge of the mode to be detected.

To launch all 266 channels simultaneously with low loss and low crosstalk, and to maintain stable operation, we again exploit the intrinsic physical properties of OAM modes to build an automated system that achieves and dynamically maintains high fidelity mode conversion and precise alignment, significantly streamlining the alignment, calibration and stabilization processes that are practically impossible by conventional manual adjustment.

OAM modes are rotational invariant, as a rotation of $\phi \rightarrow \phi + \phi_0$ introduces only a global phase factor $\exp(il\phi_0)$ and leaves the spatial intensity profile, hence the end-launch coefficient, unchanged. This is experimentally verified with the $|l|=2$ and $|l|=3$ OAM modes that exhibit near-constant received power, with peak-to-peak fluctuations < 0.2 dB while rotating the demultiplexing waveplate full 360° (Fig. 3f; see Supplementary Note S8 for experimental details). Precise angular registration at the receiving interfaces is therefore eliminated. For comparison, under identical conditions, LP modes (LP₂₁ and LP₃₁) incur pronounced sinusoidal penalties exceeding 2 dB, therefore would have required dynamic angular tracking.

The mitigation of position-dependent aberration at the multi-core fibre facet is crucial for high-fidelity mode launch. Mode distortion typically originates from physical misalignment, local facet defects, refractive-index (RI) heterogeneities, and non-paraxial wavefront distortion in the coupling optics^{30,31}. Dynamic perturbations are also

caused by environmental disturbances such as vibration and air turbulence. Simultaneous and adaptive compensation must be implemented for all 266 modes for the system to operate stably.

We exploit the unique spatial degeneracy between the OAM modes in the ring-core fibre to achieve transferable wavefront correction. In each core, owing to the strong radial confinement engineered in our fibre design, higher-order OAM modes of different topological charge l exhibit highly uniform and overlapping radial intensity profiles, with calculated radial-profile overlap integrals exceeding 0.95 for adjacent orders and 0.85 for the most separated mode pair. These modes are therefore distinguished primarily by their different azimuthal helical phases. With the radial field distribution being virtually independent of l , a wavefront compensation profile calibrated for a single OAM topological charge $|l|$ can be directly transferred to others within the same core by simply changing the theoretical helical phase term. Such inter-mode transferability reduces calibration load to one mode per core (details can be found in Supplementary Note S8), circumvents exhaustive mode-by-mode recalibrations that are not only complicated but also potentially mutually conflicting.

The transferability is tested by implementing a phase correction profile on the SLM that compensates linear and quadratic aberrations optimized for the $|l|=3$ OAM mode in Core 1, so that the intensity of this mode after fibre transmission and demultiplexing at the receiver is maximised. The same profile is then transferred, without further optimization, to $|l|=2$ and $|l|=1$ within the same core. After the transfer, the received intensities remained within 0.5 dB of their independently optimized baselines (Fig. 3g). The reuse of aberration parameters effectively suppresses calibration complexity by a factor of at least 14. By comparison, transferring a correction profile optimized for LP_{31} directly to LP_{21} and LP_{11} causes a power penalty exceeding 4 dB (>60% intensity reduction).

Building on these intrinsic advantages, we implement an automated mode-field alignment scheme that avoids high-dimensional manual tuning in multi-core SDM. The rotational invariance and intra-core transferability significantly compress the effective parameter space and smooth the optimization landscape, compared to what would have been needed for other mode-bases. In a closed-loop configuration (Fig. 3a), we use the intensity of the demultiplexed Gaussian beam on the CCD as the target function and employ a simulated annealing (SA) routine to optimize the SLM phase profile (see Supplementary Note S9 for experimental details). A detailed description of the optimization workflow and algorithmic parameters is provided in Supplementary Note 10. For OAM modes, the algorithm converges reliably within ~ 100 iterations (Fig. 3h), whereas equivalent optimization on LP modes produced a markedly more rugged trajectory, requiring substantially more iterations and showing increased susceptibility to local minima. The convergence trace shown in Fig. 3h corresponds to the optimization of a single core. In practice, the objective functions of different cores are mutually independent, allowing the same optimization routine to be executed simultaneously across all 19 cores and all 266 modes.

Finally, we assess whether an effectively block-diagonal transfer matrix is realised over the full link including the multiplexer, 10-km transmission fibre, and the

demultiplexer (measurement details in Supplementary Note 12). While distributed inter-core crosstalk averaged -42 dB km^{-1} (Fig. 4b), the end-to-end crosstalk between adjacent non-degenerate OAM MGs averaged -25 dB km^{-1} (Fig. 4a). The experimentally retrieved transfer matrix indeed remains effectively block-diagonal, supporting low complexity 4×4 MIMO DSP that does not grow with total channel count. This performance is achieved across a broad $1480\text{--}1620 \text{ nm}$ span (Supplementary Note S12), with crosstalk variations of $<1.5 \text{ dB}$. An isolated deviation near 1490 nm in the S-band is consistent with the bandwidth limitation of passive spatial multiplexing components, rather than a breakdown of modal orthogonality.

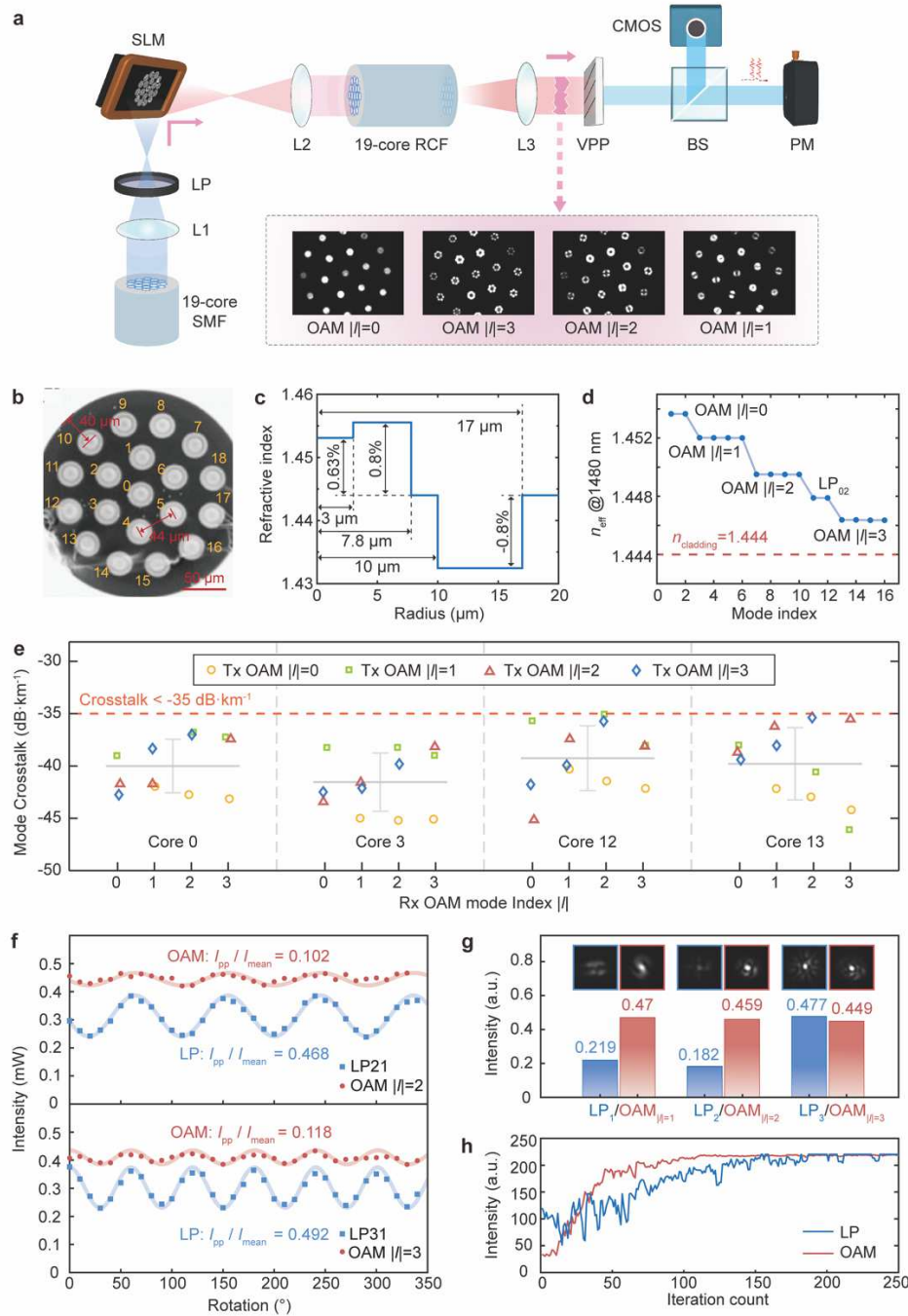


Fig 3. Characterization of the 19-core RCF and mode interface robustness. **a** Schematic of the experimental setup. **b** Cross-sectional micrograph of the fabricated 19-core RCF. **c** Refractive index profile of a single core. **d** Calculated effective refractive indices (n_{eff}) of the supported spatial modes. **e** Distributed intra-core mode crosstalk characterized via swept-wavelength interferometry (SWI). **f** Received intensity variations under rotational misalignment, demonstrating the intrinsic rotational invariance of OAM modes compared to linearly polarized (LP) modes. **g** Coupling efficiency comparison illustrating the cross-order wavefront calibration transferability of OAM modes versus LP modes. **h** Convergence curves of the simulated-annealing-based auto-alignment process.

25 Pb s⁻¹ Ultra-High-Capacity SDM-WDM Transmission

Enabled by the block-diagonal channel transfer matrix and the adaptive wavefront stabilization, we implement an ultra-high-capacity space- and wavelength-division multiplexed (SDM-WDM) transmission system over the 10-km 19-core RCF. The massive spectral-spatial channel parallelism is implemented by ultra-wideband 1240- λ DWDM spanning the S, C and L bands carried over all 266 modes, supporting a total of 329840 parallel spectral-spatial channels. Despite this unprecedented channel scale, the entire link can operate within a modular 4×4 MIMO signal-processing framework.

In the wavelength domain, 1240 wavelength carriers on a 12.5-GHz grid are multiplexed. To emulate a fully loaded system and quantify performance under realistic inter-channel nonlinear impairments, we adopt a sliding-window methodology in which high optical signal-to-noise ratio (OSNR) test channels are swept across the spectrum, whereas the remaining optical channels are filled with ASE-derived dummy channels to preserve representative loading conditions. Modulation formats are selected according to band-specific link budgets. Specifically, 12-GBaud probabilistically shaped 16-QAM (PS-16QAM) is used in the C and L bands, while 12-GBaud QPSK is employed in the S band as the achievable OSNR in the S band is constrained by amplifier output power.

In the spatial domain, we deploy a bidirectional multiplexing architecture to maximize channel utilization. More importantly, it allows to test the robustness of adaptive wavefront compensation under the stringent alignment conditions imposed by the free-space coupling optics (transmitter-side schematic in Supplementary Note S11).

Dense bidirectional operation over the 10-km fibre could potentially be impaired by Rayleigh backscattering. However, our quantification prior to transmission validates that this backscattering impact is sufficiently low to maintain signal integrity (derivations and measurements in Supplementary Note S13). Subsequently, the full spatial-spectral grid of channels was simultaneously launched into the 10-km 19-core RCF from both ends (see Supplementary S11 for the detailed optical path design). During the setup and transmission experiment, the wavefronts of the launched multi-beam arrays are dynamically optimized using aforementioned adaptive control scheme which compensates system aberrations in situ and maintains high-quality optical outputs across all cores and mode orders.

At the receiver, the benefits of the physical-layer transfer matrix sparsity became explicit, as the signal recovery for all 266 spatial channels was performed block-by-

block using strictly independent 4×4 MIMO equalizers corresponding to the 4 mode channels of each OAM MG, avoiding the prohibitive computational cost associated with joint, system-wide massive MIMO, consistent with the suppressed inter-group coupling. Irrespective of the large group-delay separation between the MGs, the required time-domain equalization (TDE) memory for each block is limited to 35 taps (Fig. 4d) which is decided by the small modal group velocity dispersion (GVD) within each near-degenerate MG. Post-transmission performance is evaluated using generalized mutual information (GMI)-estimated data rates, which provide an accurate estimate of achievable throughput for probabilistically shaped constellations. As shown in Fig. 4c, robust data rates are recovered across all cores, OAM modes and multiplexed wavelengths. Accounting for dual polarization and bidirectional transmission, this system delivers a total GMI-estimated aggregate capacity of 25.24 Pb s^{-1} over the full S, C and L bands. The aggregate spectral efficiency and spectral-efficiency density, evaluated over the C+L bands, reach $1935.6 \text{ bit s}^{-1} \text{ Hz}^{-1}$ and $3.94 \times 10^{-3} \text{ bit s}^{-1} \text{ Hz}^{-1} \mu\text{m}^{-2}$, respectively. These results demonstrate that OAM-enabled adaptive wavefront control sustains stable operation in ultra-dense SDM–WDM systems with over 3×10^5 spectral–spatial channels, validating the extreme capacity and scalability of the OAM-multiplexed paradigm.

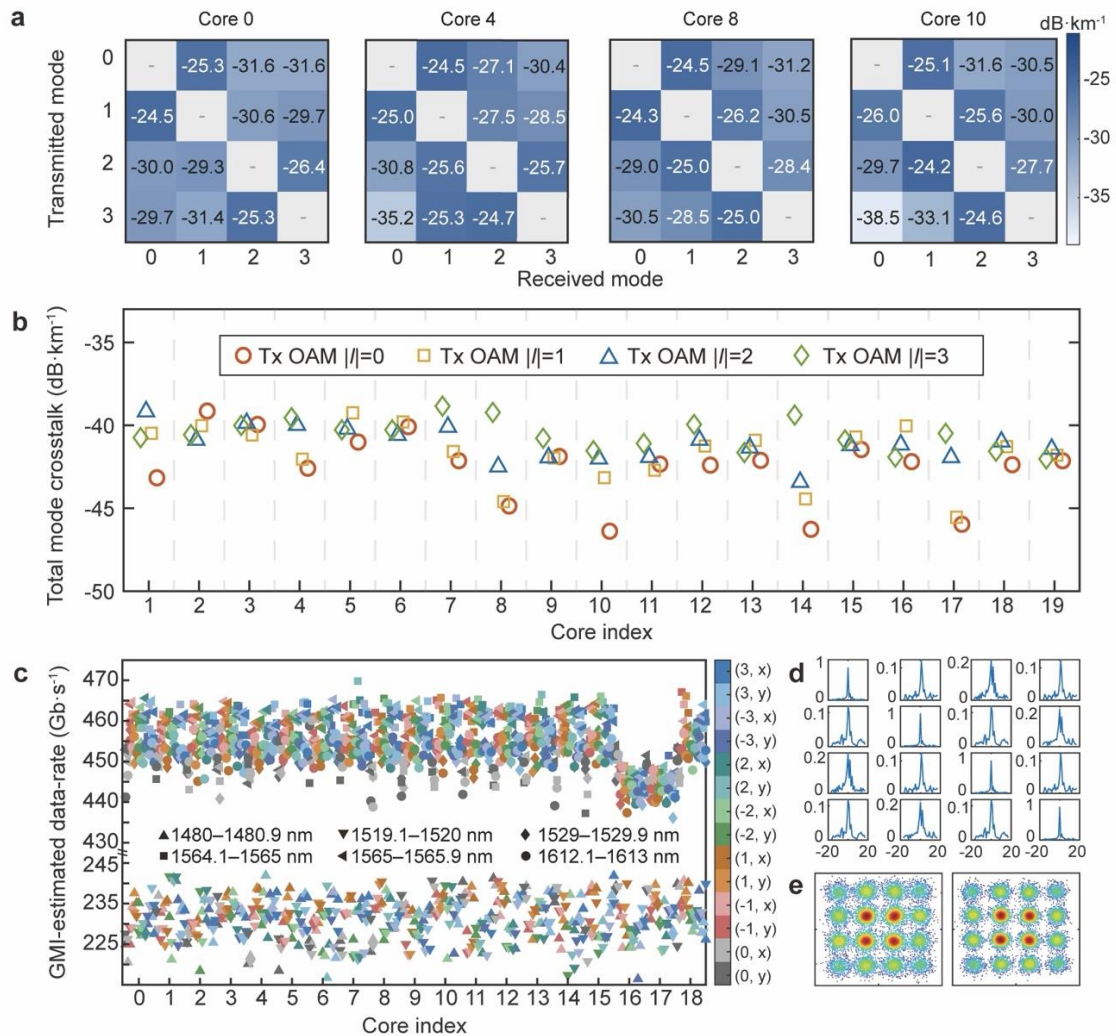


Fig. 4 End-to-end system crosstalk and ultra-high-capacity transmission performance. **a** Measured end-to-end intra-core mode crosstalk matrices for representative cores. **b** Total inter-core crosstalk (IC-XT) contributions from all other cores. **c** Generalized mutual information (GMI)-estimated data rates for all spatial channels across the S, C, and L bands. **d** Tap weights of the 4×4 MIMO time-domain equalizers for the OAM $|l|=2$ mode group. **e** Recovered signal constellation diagrams for the OAM $|l|=2$ channels.

Conclusions and discussions

In this work, we fully exploit the intrinsic physical properties of fiber-optic OAM modes to reshape the scalability problem in space-division multiplexing: from digitally compensating an increasingly dense multimode channel to physically structuring the channel before detection. The azimuthal properties - rotational symmetry and angular coupling selection rule - of ring-core OAM guidance suppresses distributed inter-group coupling during propagation, while the high similarity of transverse intensity profiles across OAM orders enable aberration corrections to be transferred across modes at the fibre–interface. Together, these properties confine residual mode coupling to small spin–orbit OAM subspaces and allow the adaptive alignment and multiplexing architecture to maintain an effectively block-diagonal MIMO transfer matrix. This physics-guided channel structuring enables 266 spatial channels and 1,240 wavelength channels in a 10-km 19-core ring-core fibre, achieving an aggregate capacity of 25.24 Pb s⁻¹ over the S, C and L bands and a C+L-band spectral-efficiency density of 3.94×10^{-2} bit s⁻¹ Hz⁻¹ μm⁻². Beyond setting a capacity benchmark, this work establishes a new paradigm for spatial crosstalk management based on modal physics rather than digital overcompensation.

Although the adaptive interface was implemented here with a programmable spatial light modulator to retain maximum experimental flexibility, the underlying principle is not tied to free-space wavefront control. In practical transceivers, the same function could be provided by integrated programmable photonic phase arrays with grating-coupler-based interfaces embedded at the fibre–chip interface. A key question is therefore whether the adaptive OAM-multiplexing scheme relies on densely sampled phase control, or whether it can operate with the much coarser spatial degrees of freedom available in compact photonic hardware.

The phase-front coarsening experiment in Fig. 5a addresses this question directly. By merging neighbouring SLM pixels into larger phase-control elements, the number of controllable degrees of freedom per fibre core is reduced from 54,119 active pixels to only ~135 elements under 20× coarsening, corresponding to a 400-fold reduction in spatial resolution. Despite this substantial reduction, the inter-channel crosstalk remains only weakly affected (Fig. 5b). This robustness indicates that the adaptive interface does not require pixel-level wavefront fidelity, but can instead exploit lower-dimensional correction hardware associated with the structured OAM mode profiles and their similar transverse intensity distributions.

This finding has two practical implications. First, it supports the transfer of the adaptive OAM interface from laboratory SLM optics to integrated photonic implementations with finite phase-control granularity, such as silicon-photonic or thin-film-lithium-niobate phase-array platforms. Second, it suggests that increasing the

number of fibre cores need not impose a prohibitive per-core control burden, because stable multiplexing can be maintained even when the spatial control resources assigned to each core are significantly reduced. The tolerance to coarse phase sampling therefore provides an important route towards compact, scalable OAM transceivers in which the complexity of the adaptive interface remains compatible with large-core-count SDM systems.

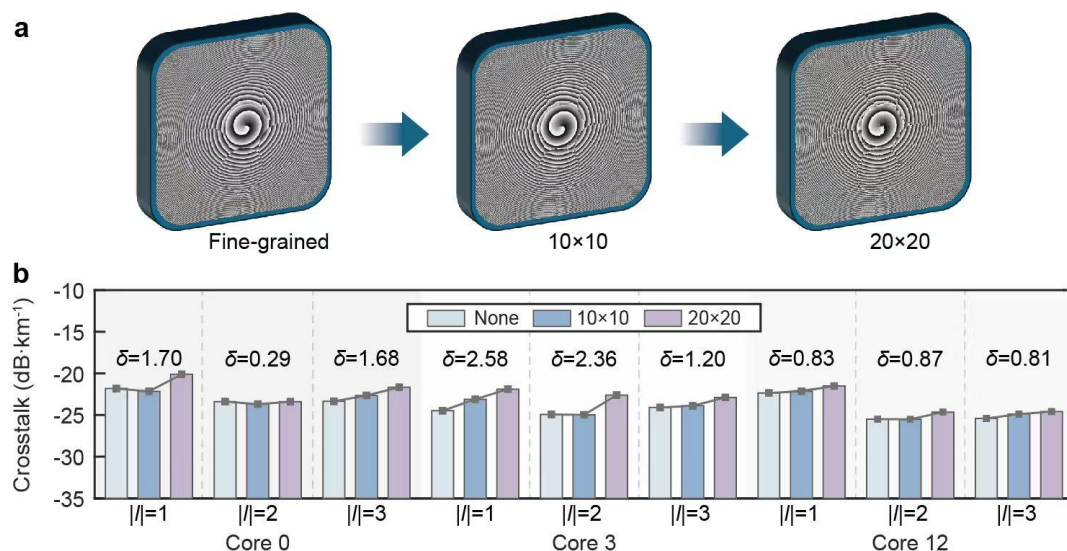


Fig 5. System tolerance to reduced spatial phase-sampling resolution. **a** Schematic illustrating the phase mask coarsening process (merging adjacent pixels) on the spatial light modulator. **b** End-to-end mode crosstalk characterization under varying degrees of spatial phase coarsening, demonstrating the robustness of large-scale OAM multiplexing to low-resolution phase control.

Taken together, these results indicate that OAM-based SDM offers a route to scale spatial capacity without allowing either interface control or receiver DSP complexity to grow in quadratic proportion to the total number of spatial channels. While demonstrated over a 10-km 19-core ring-core fibre, the architecture targets high-capacity interconnect and metro-scale transmission where aggregate throughput and spatial efficiency dominate system design. By managing 266 spatial channels with a fixed 4×4 MIMO complexity per mode group, we quantitatively show that OAM-based SDM overcomes the quadratic MIMO complexity scaling inherent to strongly coupled systems. With continued advances in fibre fabrication and distributed amplification, this physics-enforced orthogonality can extend to longer-reach networks, positioning OAM modes as a scalable foundation for next-generation high-capacity optical systems.

Materials and methods

Ultra-wideband WDM signal generation

The transmission testbed was configured to emulate a fully loaded SDM system (schematic in Supplementary Note S11). We employed a sliding-window technique where high-quality test channels generated by tunable external cavity lasers (ECLs) were swept across the S, C, and L bands, while the remaining spectrum was loaded with

spectrally shaped amplified spontaneous emission (ASE) to strictly enforce realistic inter-channel nonlinear impairments. The signals were 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. Both modulators are driven by a four-channel (AWG), generating signals of a $2^{18}-1$ pseudo-random binary sequence (PRBS).

Adaptive spatial multiplexing setup

OAM mode excitation was achieved using a free-space “19-to-19” conjugate imaging scheme designed to directly interface the transceiver array with the 19-core RCF, as detailed in Supplementary S7. In this architecture, 19 Gaussian beams emerging from a commercial 19-core single-mode fiber (SMF) fan-in device were collimated and projected onto a spatial light modulator (SLM). The SLM functioned as a common reference plane to bridge the geometric mismatch between the input 19-core SMF array (core pitch $\sim 65 \mu\text{m}$) and the target 19-core RCF array (core pitch $\sim 44 \mu\text{m}$).

We loaded the SLM with a composite phase mask that simultaneously applied (1) spiral phase profiles for OAM mode generation ($l = 0-3$) and (2) quadratic phase factors for wavefront curvature compensation. A telecentric imaging system was then employed to map the modulated beam array onto the RCF facet. To ensure optimal orthogonality for all 266 spatial modes, we implemented a physics-informed adaptive alignment algorithm. Unlike gradient-based methods prone to local minima, we employed a simulated annealing algorithm (SAA) incorporating a multi-step Markov chain mechanism. The algorithm stochastically perturbs the SLM parameters (including global phase, linear tilt) and utilizes the Metropolis acceptance criterion to iteratively optimize the coupling. By using the central intensity of the demultiplexed Gaussian spot as a scalar feedback metric, the system automatically converges to the global optimum, effectively compensating for system-induced aberrations without manual intervention (detailed flow in Supplementary S9).

Coherent detection and DSP

At the receiver side, OAM modes were demultiplexed utilizing an inverse-spiral transformation. The output beam array from the fiber was collimated and split into two paths, each passing through a specific vortex phase plate (VPP) with an inverse topological charge relative to the target mode. This operation converts the target OAM mode back into a fundamental Gaussian-like profile, which is then efficiently coupled into SMF connected to dual-polarization integrated coherent receivers (ICR). Due to hardware constraints, the spatial channels were captured in an asynchronous manner, where signals from different mode groups were sequentially evaluated.

The electrical signals were acquired by real-time oscilloscopes and processed offline. The digital signal processing (DSP) chain comprised resampling, chromatic dispersion compensation, frequency offset estimation, and carrier phase recovery. Crucially, to mitigate the residual intra-mode-group crosstalk, we employed modular 4×4 MIMO equalizers based on the blind constant modulus algorithm (CMA). Unlike full-matrix SDM equalizers, our scheme strictly processes only the four spin-orbit degenerate

modes $<\pm s, \pm l>$ within the same topological charge group, validating the block-diagonal nature of the channel. The computational complexity analysis confirming the efficiency of this architecture is provided in Supplementary S1.

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Author contributions

J.L. and J.Y.L. designed the system. J.Y.L. implemented the system setup and conducted the overall communication testing. H.Z. and S.Q.M. contributed to the optical path alignment and communication testing. L.S., L.Z., X.Z.L., R.C.W., and J. Luo contributed to the fibre fabrication. H.L.L., F.W., and R.G. contributed to the communication code design and digital signal processing. H.Z., H.L.L., J.K.D., and J.Q.L. contributed to the data processing. J.Y.L., J.L., Z.H.L., and S.Y.Y. wrote the manuscript. All authors reviewed the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

Supplement is available for this paper

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