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Ultra-high-density spatial division multiplexing with a few-mode multicore fibre

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Single-mode fibres with low loss and a large transmission bandwidth are a key enabler for long-haul high-speed optical communication and form the backbone of our information-driven society. However, we are on the verge of reaching the fundamental limit of single-mode fibre transmission capacity. Therefore, a new means to increase the transmission capacity of optical fibre is essential to avoid a capacity crunch. Here, by employing few-mode multicore fibre, compact three-dimensional waveguide multiplexers and energy-efficient frequency-domain multiple-input multiple-output equalization, we demonstrate the viability of spatial multiplexing to reach a data rate of 5.1 Tbit s^{-1} carrier^{-1} (net 4 Tbit s^{-1} carrier^{-1}) on a single wavelength over a single fibre. Furthermore, by combining this approach with wavelength division multiplexing with 50 wavelength carriers on a dense 50 GHz grid, a gross transmission throughput of 255 Tbit s^{-1} (net 200 Tbit s^{-1}) over a 1 km fibre link is achieved.

With the persistent exponential growth in Internet-driven traffic, the backbone of our information-driven society, based on single-mode fibre (SMF) transmission, is rapidly approaching its fundamental capacity limits[1]. In the past, capacity increases in SMF transmission systems have been achieved by exploiting various dimensions, including polarization and wavelength division multiplexing, in tandem with advanced modulation formats and coherent transmission techniques[2]. However, the impending capacity crunch implies that carriers are lighting up dark fibres at an exponentially increasing rate to support societal capacity demands[3]. To alleviate the corresponding costs and increased energy requirements associated with the linear capacity scaling from using additional SMFs, spatial division multiplexing (SDM) within a single fibre can provide a solution[4,5]. By introducing an additional orthogonal multiplexing dimension, the capacity, spectral and energy efficiency, and therefore the cost per bit, can be decreased, which is vital for sustaining the business model of major network stakeholders. To fulfil the SDM promise, a new paradigm is envisaged that allows up to two orders of magnitude capacity increase with respect to SMFs[6]. SDM is achieved through multiple-input multiple-output (MIMO) transmission, employing the spatial modes of a multimode fibre (MMF)[7], or multiple single-mode cores, as channels[8–13]. Recently, a distinct type of MMF, the few-mode fibre (FMF), has been developed to co-propagate three or six linear polarized (LP) modes[14–17]. Driven by rapid enhancements in high-speed electronics, digital signal processing (DSP) MIMO techniques can faithfully recover mixed transmission channels[18], allowing spectral efficiency increases as spatial channels occupy the same wavelength. State-of-the-art single-carrier FMF transmission experiments have demonstrated capacity increases in a single fibre by exploiting six spatial modes, achieving 32 bit s^{-1} Hz^{-1} spectral efficiency[17]. By using multicore transmission, a spectral efficiency of 109 bit s^{-1} Hz^{-1} has been demonstrated using 12 single-mode cores[19]. In this work, we demonstrate ultra-high-capacity transmission over a 1 km hole-assisted few-mode multi-core fibre (FM-MCF)[20,21], with seven few-mode cores, each allowing the LP_{01} and two degenerate LP_{11} modes to co-propagate in the X- and Y-polarization. A custom-designed butt-coupled integrated three-dimensional (3D) waveguide is key to multiplexing all 21 spatial LP modes per linear polarization being simultaneously transmitted. The fibre design minimizes intercore crosstalk and reduces the required MIMO equalizer complexity from 42×42 to $7 \times (6 \times 6)$, hence reducing energy consumption. In addition, an energy-efficient MIMO frequency-domain equalizer (FDE) is used for every core. A single-carrier spectral efficiency of 102 bit s^{-1} Hz^{-1} is achieved by encoding 24.3 GBaud 32 quadrature amplitude modulation (QAM), allowing for next-generation 5.103 Tbit s^{-1} carrier^{-1} gross (4 Tbit s^{-1} carrier^{-1} net) data rate spatial super channels. Combining the spatial dimension with 50 wavelength channels on a 50 GHz International Telecommunication Union (ITU) grid, a gross total capacity of 255 Tbit s^{-1} (200 Tbit s^{-1} net) is demonstrated, further indicating the viability of combining few-mode and multicore transmission techniques in a single fibre to achieve ultra-high capacity.

Hole-assisted few-mode multicore fibre

In this work, the key requirement for an ultra-high-density SDM system is a multicore fibre with high mode density and ultra-low crosstalk, provided by the few-mode multicore approach. In a conventional multicore fibre, crosstalk constitutes only intercore crosstalk. However, for FM-MCFs, both intracore (between LP modes) and intercore crosstalk are to be considered[20]. In relation to intracore crosstalk, it is inevitable that strong modal interactions occur due to perturbations, splice points and multi-mode components, along a realistic transmission link[22–25]. Accordingly, when designing and fabricating FM-MCFs, suppressing intercore crosstalk is critical. One method for minimizing intercore crosstalk is to fabricate a fibre with a large core-to-core pitch, but at the detriment of information density. In contrast to trench-assisted structures, the hole-assisted structure adopted for such a fibre has the

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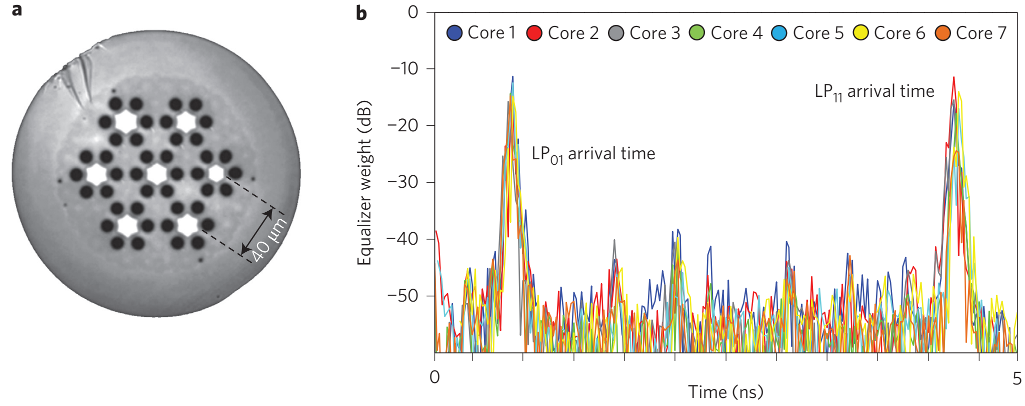

Figure 1 | Few-mode multicore fibre characteristics. a, FM-MCF cross-section, which is butt-coupled to the 3D waveguide. **b**, Measured MIMO equalizer response of all seven cores for the transmitted LP_{01} X-polarization to the received LP_{01} X-polarization at 1,555.75 nm, allowing differential mode delay estimation with an accuracy of ~20 ps, indicating a similar performance of all cores. As all LP modes are equally excited, the respective MIMO equalizer matrix elements are similar.

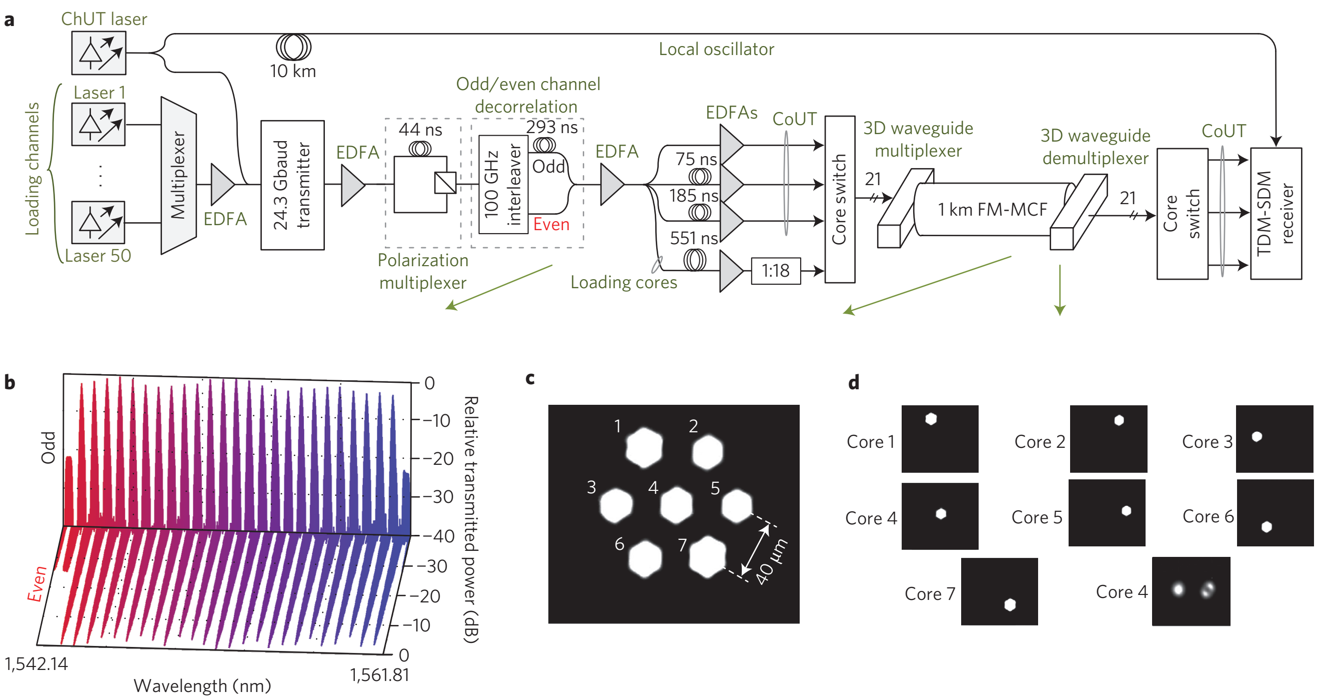

Figure 2 | FM-MCF WDM/SDM experimental transmission set-up. a, The loading channels and one CoUT are simultaneously modulated by a 24.3 GBaud 16 or 32 QAM constellation sequence. Consecutively, polarization, carriers, cores and modes are decorrelated. The 3D multiplexer guides the transmission channels into and out of the FM-MCF via butt-coupling, where the CoUT is varied through all cores consecutively. **b**, Decorrelated wavelength spectrum after being interleaved by a wavelength-selective switch. **c**, Saturated camera image taken at the receiver side, with all cores lit simultaneously. **d**, Independent cores are excited, indicating low crosstalk per core. Right bottom: selective launching of the LP_{01} and LP_{11} modes in the centre core (core 4), respectively, where the modal energy is confined to the centre of the hexagonal core structure.

benefit of improved mode-confinement and intercore crosstalk reduction, which is best minimized by tuning the air-hole diameter and air-hole pitch around each core. Accordingly, a 1 km step-index seven-core FM-MCF with an outer diameter of 192 μm (±0.5 μm) and a coated fibre diameter of 37 μm was successfully fabricated (Fig. 1a). For improved placement within future ducts for actual deployment, the fabricated fibre cladding diameter can be reduced to 150 μm without losing its transmission attributes. Individual cores with a diameter of 13.1 μm and a core refractive index difference of 0.36% were hexagonally arranged at a core-to-core distance of 40 μm. Air-holes with diameters of 8.2 μm were placed 13.3 μm apart, creating an air-hole to pitch (air-hole diameter d; air-hole pitch Λ) ratio of 0.62, corresponding to an intercore crosstalk of under −80 dB km^{-1}, which provides the potential to scale to longer transmission distances[10,11,20]. During measurements, the FM-MCF was wound on a conventional fibre drum with a mandrel radius of 15.9 cm. The LP_{01} mode average measured attenuation for all cores is 0.3 dB. The measured effective areas (A_{eff}) for the LP_{01} and LP_{11} modes are 112 and 166 μm^2, respectively. Depicted in Fig. 1b are the impulse response measurements for all cores, which indicate a differential mode group delay of 4.6 ps m^{-1} at 1,550 nm. The calculated chromatic dispersions at

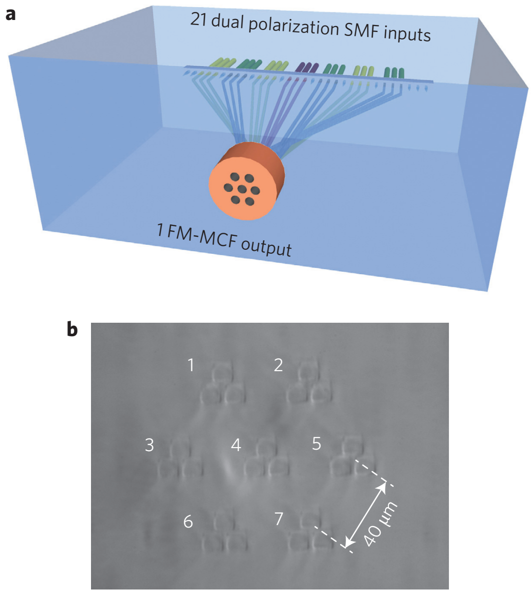

Figure 3 | Three-dimensional waveguide characteristics. a, Schematic of the 3D waveguide, where sets of three transparent waveguides are placed in a triangular arrangement to address respective few-mode cores. **b**, 3D waveguide FM-MCF facet microscope image.

1,550 nm for the LP_{01} and LP_{11} modes are 23 and 28 ps nm^{-1} km^{-1}, respectively, while the dispersion slopes for LP_{01} and LP_{11} are 0.06 and 0.07 ps nm^{-2} km^{-1}, respectively. The calculated cutoff wavelength is ~1,300 nm for the LP_{21} mode and ~2,100 nm for the LP_{11} mode, ensuring effective two-mode guidance for C- and L-band WDM transmission.

Experimental implementation

At the transmitter side (Fig. 2a), 50 conventional low-linewidth (<100 kHz) external cavity lasers (ECLs) on a dense 50 GHz ITU frequency grid spanning the telecom C-band wavelength region from 1,542.14 to 1,561.81 nm were used as loading channels. During the FM-MCF performance verification, all few-mode cores were investigated as the core under test (CoUT) was varied consecutively. By replacing each loading wavelength channel within the channel under test (ChUT) laser, quantitative performance measurements were performed via bit-error-rate (BER) estimation. To manage the complexity of the measurement process, the transmitter ChUT laser was split into two equal tributaries, with the second tributary acting as a remote local oscillator (LO) for all 700 measurements[26,27]. As the transmitter and receiver shared the same laser source, a 10 km SMF was inserted into the LO path to minimize the impact of laser phase coherence. All carriers were modulated by a lithium niobate ($LiNbO_3$) IQ-modulator, which was driven by two digital-to-analog converters (DACs), representing the in-phase and quadrature components, to generate a 24.3 GBaud 16 or 32 QAM signal. Higher-order modulation formats are particularly interesting for fibre performance investigation because of their susceptibility to impairments in the transmission channel. Before transmission, the modulated carriers were decorrelated consecutively for polarization, carriers, modes and cores. The relative powers of the decorrelated carriers are shown in Fig. 2b, showing a relatively equal power distribution over the entire transmitted wavelength band. In addition, due to the excellent autocorrelation properties of the transmitted sequences from the DACs, all transmitted channels guided into the mode-multiplexer can be considered to be independent and distinct. Several mode-multiplexing techniques have been developed that selectively excite a set of modes in few-mode fibres, such as phase plates[28–30], spot launchers[31–34] and adiabatically tapered photonic lanterns[35–37]. In contrast to the bulky optics associated with phase plates, the latter two techniques potentially have the compactness necessary for integration into a future transponder. Hence, a customized and compact 3D waveguide multiplexer was designed to simultaneously spot-launch all spatial channels into the FM-MCF. Accordingly, the waveguides in the mode multiplexers were formed in a 5.3 mm × 10 mm borosilicate glass substrate by direct laser writing using focused ultrafast femtosecond laser pulses. Borosilicate glass supports an extensive wavelength band, covering all key telecom bands ranging from visible light up to 2.2 μm. The inscription technique produces controllable subsurface refractive index modification and allows the required 3D pattern of transparent waveguides to be carefully controlled to ±50 nm. As shown in Fig. 3a, the 21 SMF inputs (with a 127 μm pitch V-groove) were attached to waveguides (assigned in seven sets of three waveguides) and inscribed in a hexagonal arrangement with a diameter of 80 μm to match the core arrangement and structure of the FM-MCF. The individual square waveguides have a cross-sectional effective area of 36 μm^2 (Fig. 3b), and each set of three waveguides was placed in a triangular arrangement[38]. This arrangement minimizes insertion losses, while equally exciting the LP_{01} and LP_{11} degenerate modes in

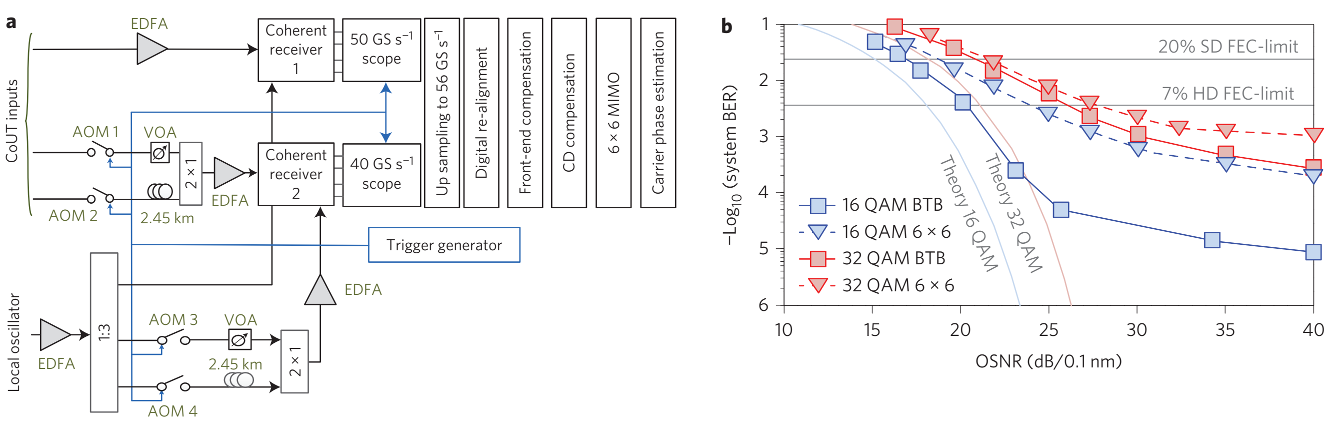

Figure 4 | TDM-SDM receiver characterization. a, TDM-SDM receiver, where one dual polarization mode is received by coherent receiver 1 and two modes are serially received by coherent receiver 2. The AOMs act as signal gates, with a closing time corresponding to the propagation time of the delay fibre, enabled by the trigger generator. The variable optical attenuator (VOA) ensures equal power reception of both modes. In the digital domain, the serialized signals are parallelized to construct three received dual-polarization modes. **b**, Performance of single-channel transmission received by the TDM-SDM receiver with respect to back-to-back (BTB) performance, indicating an error floor of 2×10^{-4} for 16 QAM and 1×10^{-3} for 32 QAM.

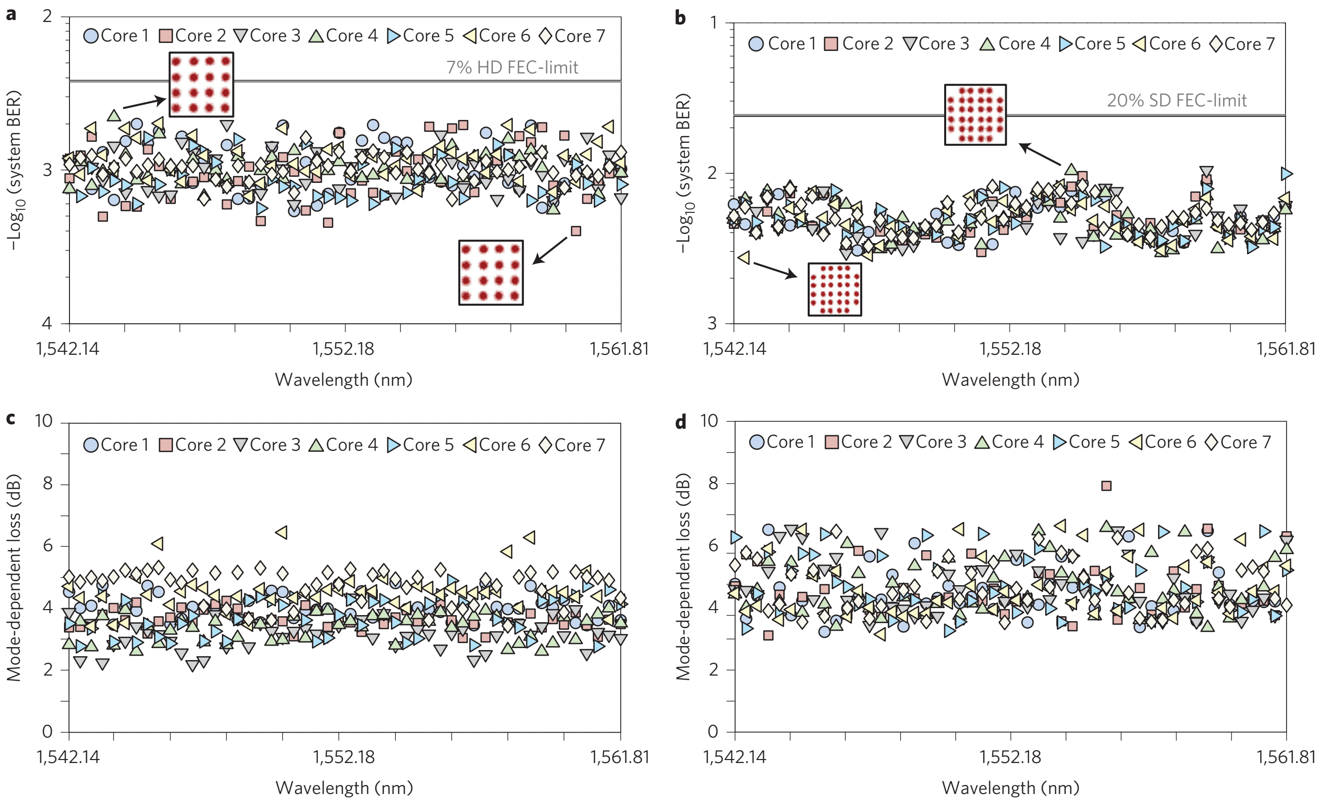

Figure 5 | Transmission results. a, 16 QAM transmission performance. All channels perform well below the 7% hard decision FEC limit required to ensure error-free transmission for a 81.6 bit s^{-1} Hz^{-1} gross spectral efficiency. **b**, 32 QAM transmission performance is well below the 20% soft decision FEC limit, providing a 102 bit s^{-1} Hz^{-1} gross spectral efficiency. **c**, 16 QAM transmission measured MDL figures for all transmitted channels, averaging at 3.9 dB. **d**, 32 QAM measured MDL figures, averaging at 4.4 dB.

each core to minimize mode-dependent loss (MDL)[34]. The MDL was approximated at 1.5–2 dB and the insertion loss on average was 1.1 dB across all 21 waveguides (excluding fibre) at 1,550 nm. The waveguides were designed to minimize polarization-dependent loss (measured to be <0.2 dB), which was incorporated into the MDL approximation. The compact nature of the 3D waveguide allows a highly stable butt-coupled interface to the FM-MCF end-facets, without requiring additional bulky imaging optics. A 3D waveguide was used as both the spatial multiplexer and demultiplexer in this experimental set-up. The total end-to-end loss measured after transmission was 12 dB (including multiplexer and demultiplexer 3D waveguide), which is in line with single-core few-mode results[34]. Crosstalk was measured by individually exciting the different cores. The measured crosstalk value was below −70 dB km^{-1}, which was limited by the dynamic range of the Newport 2832-C power monitor used for the measurement. Figure 2c presents a 1,550 nm near-field image captured at the demultiplexer side, where the camera input power was saturated per core. Figure 2d demonstrates the saturated power per core for each individually excited core, showing the low crosstalk provided by the air-hole-assisted design. For the near-field image, the observed crosstalk was also less than −70 dB km^{-1}, limited by the dynamic range of the near-infrared camera used. The right bottom figure in Fig. 2d (core 4) shows the individual excitation of the two LP modes of the centre core.

To enable mode measurement after FM-MCF propagation, we first proposed and devised an elegant few-mode measurement technique. The essence of the technique is shown in Fig. 4a, where the novel time-domain multiplexed (TDM) SDM receiver with two dual-polarization coherent receivers is used for simultaneous reception of the three transmitted modes per core. The first coherent receiver receives the first mode and a second coherent receiver receives the remaining two modes, demonstrating the potential scaling of received modes in both time and number of dual-polarization coherent receivers. A key requirement of this receiver subsystem is to have switches with short rise/fall times (<1 ns). Micro-electro-mechanical systems (MEMS) and piezoelectric switches were initially considered, but these cannot support the required high-speed switching, hence leaving only acoustic optical modulator (AOM) and semiconductor optical amplifier (SOA) switches as potential solutions. Unfortunately, a major drawback of SOA switches is the addition of parasitic amplitude stimulated emission (ASE) noise to the received signals. In this work, low-insertion-loss AOM switches were therefore chosen that comply with the rise/fall time of <1 ns, providing an excellent choice for acting as high-speed signal gates with a close time of 11 μs. This equates to the propagation time provided by the inserted single-mode delay fibre. The open and close times of the switches were controlled by a trigger generator and, by combining the gated signals, optical alignment of two dual-polarization modes for serialized reception by a single coherent receiver was achieved. In MIMO coherent transmission, received modes have to beat with the same LO. Therefore, the signal TDM-SDM scheme was replicated in the LO path. After analog-to-digital conversion by real-time oscilloscopes, the modes were parallelized for offline processing. Successively, in the digital domain, front-end impairments, chromatic dispersion, MIMO equalization and carrier phase estimation were performed[39–41]. Key to unravelling the mixed modes is a low-complexity, and hence an energy-efficient, frequency-domain MIMO equalizer with adaptive step size for high tracking capabilities[18,42]. The equalizer uses the 50% overlap–save scheme, combined with a radix-4 fast-Fourier transform (FFT) to minimize the required complex computations[43], resulting in 5.76 and 4.61 complex multiplications per bit for 16 and 32 QAM transmission, respectively, further highlighting the low energy consumption achieved for DSP. In addition, this scheme allows residual receiver impairments to be reduced after front-end impairment compensation has been performed, resulting in optimum BER performance.

Results

To demonstrate the FM-MCF transmission capabilities, we first characterized the transmitter and receiver performance by noise loading at the transmitter side for optical signal-to-noise ratio (OSNR) measurements as depicted in Fig. 4b. At the 40 dB OSNR level, with respect to back-to-back measurements, the 6×6 single-channel MIMO measurements for 16 and 32 QAM indicate a modest error floor increase of 2×10^{-4} and 8×10^{-4} for single wavelength transmission, respectively. This BER increase is mainly attributed to residual channel interference after the frequency-domain MIMO equalizer unravels the channels.

With every wavelength channel in all cores enabled simultaneously, Fig. 5a,b demonstrates the successful transmission of 16 and 32 QAM, respectively, where the forward error correcting (FEC) overhead is assumed to ensure error-free transmission. The average values of BER after WDM transmission (Fig. 5a,b) are approximately 1×10^{-3} and 5×10^{-3}, corresponding to respective BER penalties of 8×10^{-4} and 4×10^{-3} for 16 and 32 QAM transmission in comparison with single-channel performances at 40 dB OSNR. The insets in Fig. 5a,b represent the best- and worst-performing channel constellations of the respective constellation types, and the gross aggregate transmission capacity of 255.15 Tbit s^{-1} signifies the potential high-density space-division-multiplexing capabilities of the hole-assisted FM-MCF. This successful use of the butt-coupled 3D waveguide multiplexer and demultiplexer demonstrates the high integration capabilities obtained by combining multicore and multimode SDM techniques. However, inherent to space-division-multiplexed transmission is a received power difference between transmitted channels, denoted by the MDL. Obtained from mutual information estimation, MDL is a figure of merit for establishing the theoretical transmission capacity[44], which is computed through singular value decomposition of the transmission channel matrix, obtained by least-squares channel estimation[45,46]. The MDL figures of all wavelength carriers are presented in Fig. 5c,d, with average estimated MDLs of 3.9 dB and 4.4 dB for 16 and 32 QAM, respectively. The small MDL differences are attributed to slight misalignment between the cores and (de)multiplexer, as well as wavelength-dependent mode field excitation during the experiment. The observed MDL differences are similar to those reported in a previous work for single-core few-mode transmission[34], further demonstrating that multicore and multimode SDM can be combined to enable ultra-high-density transmission capacity. Current activities focus on increasing the number of modes per core[14,15] and increasing the number of cores[12] to further increasing the spectral efficiency in a single fibre. By combining both technologies, as demonstrated in this work, a platform for two-dimensional scaling is provided. The system's linear and nonlinear transmission properties[47–50], emerging optical components and DSP complexity will decide the optimum combination of the two dimensions[6].

Conclusion

We have demonstrated a robust 50-channel WDM transmission of 21 spatial LP modes in both polarizations, enabled by a hole-assisted FM-MCF. The signal is coupled into and out of the FM-MCF using custom-designed low-loss (<1.5 dB) 3D waveguide (de)multiplexers, demonstrating the high potential for integration into emerging core network transponders. Furthermore, low-computational-complexity MIMO DSP was used to enable an aggregate transmission capacity of 255 Tbit s^{-1} (200 Tbit s^{-1} net), consisting of 50 spatial super channels transmitting 5.103 Tbit s^{-1} $carrier^{-1}$ (4 Tbit s^{-1} $carrier^{-1}$ net) on a dense 50 GHz wavelength ITU grid with a spectral efficiency of 102 bits s^{-1} Hz^{-1} for fully mixed MIMO transmission per core. While readily enabling beyond next-generation capacity per wavelength, the demonstrated transmission system also has the potential to combine 21 legacy SMFs operating on an ITU standardized 50 GHz spaced wavelength grid into a single fibre. In view of the emerging amplifier multimode and multicore technologies, this work shows that a new class of fibres combining few modes and multiple cores will pave the way towards future high-density SDM transmission systems.

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Author contributions
R.G.H.v.U. and C.M.O. developed the concept and conducted the transmission experiments. R.A.C., A.S. and G.L. conceived the FM-MCF concept. R.A.C., E.A.L. and A.S. designed and fabricated the hole-assisted FM-MCF. C.X. modelled the fibre. R.G.H.v.U., C. M.O. and F.M.H. designed and characterized the 3D (de)multiplexer. R.G.H.v.U. developed the DSP algorithms. R.G.H.v.U. and C.M.O. designed and verified the TDM-SDM receiver concept. C.M.O., H.d.W. and A.M.J.K. provided overall leadership across all aspects of the work. C.M.O., R.G.H.v.U. and R.A.C. wrote the manuscript.

Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to R.G.H.v.U., R.A.C. and C.M.O.

Competing financial interests
The authors declare no competing financial interests.