REVIEW ARTICLE
PUBLISHED ONLINE: 29 APRIL 2013 | DOI: 10.1038/NPHOTON.2013.94

nature photonics

Space-division multiplexing in optical fibres

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Optical communication technology has been advancing rapidly for several decades, supporting our increasingly information-driven society and economy. Much of this progress has been in finding innovative ways to increase the data-carrying capacity of a single optical fibre. To achieve this, researchers have explored and attempted to optimize multiplexing in time, wavelength, polarization and phase. Commercial systems now utilize all four dimensions to send more information through a single fibre than ever before. The spatial dimension has, however, remained untapped in single fibres, despite it being possible to manufacture fibres supporting hundreds of spatial modes or containing multiple cores, which could be exploited as parallel channels for independent signals.

The concept of using space-division multiplexing (SDM) to increase the capacity of an optical fibre is almost as old as optical fibre communications itself. The fabrication of fibres containing multiple cores — the first and most obvious approach for implementing SDM — was reported as far back as 1979[1]. Yet only recently has serious attention been given to building a complete network platform required to exploit this multicore fibre (MCF) approach. The alternative approach of using modes within a multimode fibre (MMF) to define spatially distinct channels also dates back to the same era[2].

The current rapid progress in SDM is occurring because of a convergence of enabling technological capabilities and a rapidly emerging need. In terms of technology, SDM development draws on recent progress in fibre research. This includes subtle improvements to conventional fibres[3] and the extremely high-precision fabrication methods developed to produce fibres with hollow cores and other complex microstructures[4–7]. Sophisticated mode control[8] and analysis[9] methods along with tapered devices[10] can be used; these were developed for high-power fibre lasers where better spatial mode control is critical for increasing power and brightness[11]. Photonic lanterns[12] and endoscopes[13], which have been developed for imaging applications, are also available. SDM research is also advancing at a time when coherent detection and digital compensation have become standard in high-performance systems for overcoming complex impairments. They are very important for SDM because SDM involves tightly packing spatial channels into a fibre, thus making crosstalk between channels an obvious potential problem. Significant crosstalk in a transmission line would have been particularly problematic a few years ago, before coherent detection systems offered the possibility of electronically removing crosstalk at the receiver.

These technologies have made SDM a viable strategy just as a severe need for innovation is emerging. Over the past 40 years, a series of technological breakthroughs have allowed the capacity per fibre to be increased around tenfold every four years (Fig. 1). Transmission technology has thus far been able to keep up with the relentless exponential growth in Internet protocol traffic. The cost of transmitting exponentially more data has also been manageable, mainly because more data has been transmitted over the same fibre by upgrading equipment at the fibre ends. However, over the next decade or so, an increasing number of fibres in real networks will reach their capacity limit[14]. Furthermore, this fibre capacity limit is not specific to a particular modulation format or transponder standard; rather it is fundamental, being derived from a straightforward extension of the Shannon capacity limit for a nonlinear fibre channel under quite broad assumptions[15]. The limit is that a standard single-mode fibre (SMF) can carry no more than about 100 Tbit s^{-1} of data, which corresponds to filling the C and L amplification bands of an erbium-doped fibre amplifier (EDFA) at a spectral efficiency of ~10 bits s^{-1} Hz^{-1}. Therefore, for all network operators, keeping up with increasing data traffic demands will mean lighting more fibres (operators that have access to a limited number of dark fibres will need to install new cables) — potentially also at an exponentially increasing rate. The forecasted upcoming ‘capacity crunch’ would occur in an era of unfavourable cost scaling. Without further innovation, deploying systems over parallel fibres will lead to costs and power consumption scaling linearly with capacity, which will constrain growth.

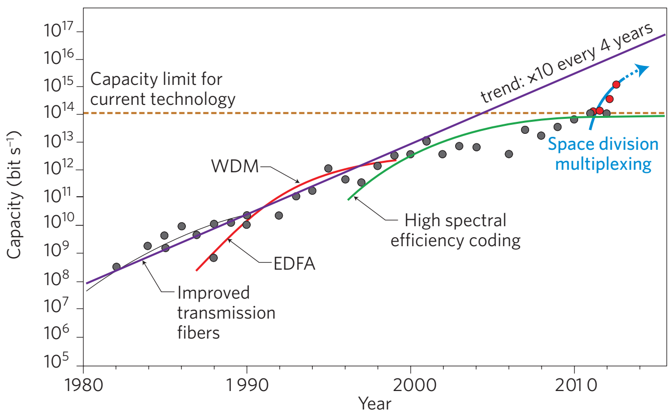

Figure 1 | The evolution of transmission capacity in optical fibres as evidenced by state-of-the-art laboratory transmission demonstrations. The data points represent the highest capacity transmission numbers (all transmission distances considered) reported at the postdeadline sessions of the annual Optical Fiber Communications Conference over the period 1982 to the present. The transmission capacity of a single fibre increases by a factor of approximately 10 every four years. Key previous technological breakthroughs include the development of low-loss SMFs, the EDFA, WDM and high-spectral-efficiency coding through DSP-enabled coherent transmission. The data points for SDM also include results from the postdeadline session of the annual European Conference on Optical Communications in 2011 and 2012. SDM seems poised to provide the next big jump in transmission capacity.

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Thus, to be beneficial to operators, SDM must not only increase the capacity per fibre (see Fig. 1), but also reduce the cost per bit and increase the energy efficiency[16]. As described later, capacity increase has readily been demonstrated, as some SDM fibres can easily support wavelength-division multiplexing (WDM) and advanced modulation formats in each spatial channel. However, reducing cost and reducing power consumption are formidable challenges. In this respect, SDM is very different from WDM, which inherently allows the sharing of key components; for example, an EDFA and a dispersion compensation module can easily be shared by many WDM channels with minimal added complexity. The benefits of SDM are more speculative and are based on the assumption that eventually many system components will be integrated and engineered to support this potentially disruptive new platform.

In response to this emerging need, a major research effort is being conducted around the world to assess the viability of SDM[17]. A wide array of new tools is now being using to probe the potential benefits of SDM, and progress is being made in overcoming the many engineering problems that exist.

Technical approaches for SDM

The term SDM now refers to multiplexing techniques that establish multiple spatially distinguishable data paths through a single fibre, although it has previously been applied to describe multiple, parallel fibres. This latter approach sets a benchmark cost per bit that must be bettered before any of the SDM approaches currently under investigation will be seriously considered for commercial deployment. Given the close proximity of the paths, the primary technical challenge of SDM is crosstalk management.

Multicore fibres. In the case of MCFs, in which the distinguishable paths are defined by an array of physically distinct single-mode cores (Fig. 2b), the simplest way of limiting crosstalk is to ensure that the fibre cores are well separated. Small variations in core properties, either deliberately imposed across the fibre cross-section[18] or resulting from the fabrication process and/or cabling[19], can also reduce cross-coupling along the fibre length. As discussed below, the highest capacities and longest transmission distances demonstrated so far in SDM systems have been realized using 'uncoupled' MCFs. A study of the tolerance of various advanced modulation format signals to in-band accumulated crosstalk (which includes contributions from signal multiplexing and demultiplexing, amplification, splicing and distributed coupling along the fibre length) showed that crosstalk levels of less than −25 dB are typically required to avoid significant transmission penalties[20]. By using fibre refractive-index profiles incorporating a trench around the core to better confine the mode, it has been possible to reduce core-to-core coupling to impressively low levels (<−90 dB km^{-1}) for a core spacing of around 40 μm, thus enabling transmission over several thousand kilometres[21]. However, fibre reliability problems (particularly susceptibility to fracture) mean that MCF diameters greater than ~200 μm are not considered practical, which imposes a fairly rigid limit on the number of cores that can be incorporated in MCFs for long-haul transmission. Most fibres to date have a hexagonal arrangement of seven cores; in this configuration, the central core has the highest level of crosstalk as it has six nearest neighbours, whereas the outer cores have only three nearest neighbours. More recent work[22] has used 12 cores arranged in a ring such that each core has just two nearest neighbours and experiences the same nominal level of crosstalk (−57 dB km^{-1} in this case). A 19-core fibre with a 200 μm outer diameter has also been reported; however, substantially higher crosstalk limited the effective transmission distance to ~10 km (ref. 23).

Multimode fibres. The situation is quite different for mode-division multiplexed (MDM) transmission in MMFs, for which distinguishable paths have significant spatial overlap, and consequently signals are susceptible to couple randomly among the modes during propagation. The modes will generally exhibit differential mode group delay (DMGD) and differential modal loss or gain. The energy of a given data symbol launched into a particular mode spreads out into adjacent symbol time slots as a result of mode coupling and DMGD, thus rapidly diminishing successful reception of the information it carries. Crosstalk occurs when light is coupled from one mode to another and remains in that mode on detection. Inter-symbol interference occurs when the crosstalk is coupled back to the original mode after propagating in a mode with a different group velocity. To mitigate these linear impairments, equalization by multiple-input multiple-output (MIMO) techniques[24] is required at the receiver, as in wireless systems in which multiple antennas at both the transmitter and receiver are used to improve link performance. In wireless communication, spatial multiplexing involves splitting a high-rate signal into multiple lower-rate streams that are transmitted from different antennas in the same frequency channel and arrive at the receiver antenna array, where MIMO digital signal processing (DSP) separates the streams into parallel channels. The lower out of the number of antennas at the transmitter and the number of antennas at the receiver limits the maximum number of spatial streams.

MIMO signal processing is already widely used in current coherent optical transmission systems with polarization-division multiplexing (PDM) over standard SMFs. A 2 × 2 matrix realization with four finite impulse response (FIR) filters recovers the signals on the two polarizations and compensates for polarization mode dispersion in the link[25]. For an MDM system with M modes, the respective algorithms would need to be scaled to $2M \times 2M$ MIMO, requiring $4M^2$ adaptive FIR filters. In comparison, the same capacity carried on M uncoupled SDM waveguides would require $4M$ adaptive FIR filters. Thus, assuming an equal number of taps per adaptive FIR filter and equal complexity of the adaptation algorithm, a $2M \times 2M$ MIMO system on M coupled waveguides will have a complexity scaling[26] as $4M^2/(4M) = M$ relative to M uncoupled SDM waveguides using PDM. To compensate for DMGD and mode crosstalk completely, the equalization filter length should be larger than the impulse response spread. The computational complexity of FIR filters implemented as time-domain equalizers increases linearly with the total DMGD of the link[25], which can make time-domain equalization unfeasible for long-haul MDM transmission. For commonly used equalizer algorithms, optical frequency-division multiplexing was found to offer the lowest complexity[27]. However, for orthogonal frequency-division multiplexing the DMGD to be compensated (and thus the reach) is limited by the length of the cyclic prefix. Another recent study[28] that sought to reduce the DSP complexity proposed single-carrier adaptive frequency-domain equalization for MDM transmission, where the complexity scales logarithmically with the total DMGD.

DSP complexity is an important consideration in the design of SDM fibres. Conventional MMFs with core/cladding diameters of 50/125 μm and 62.5/125 μm can support more than 100 modes and accumulate very large delays between modes in long links, despite being carefully engineered for small DMGDs. Unless there is a breakthrough in compensation electronics, these fibres will be unsuitable for long-haul transmission because the DSP complexity requirements will be very high. Recent advances have led to the development of fibres supporting a small number of modes, so-called 'few-mode fibres' (FMFs), that have a low DMGD (Fig. 2c). The most significant demonstrations have so far concentrated on the simplest FMF, which supports three modes (referred to as the three-mode fibre). The true modes of the fibre are the HE_{11}, TM_{01}, TE_{01} and HE_{21} vector modes, but the LP pseudo-mode basis (that is, the LP_{01} and degenerate LP_{11} modes constructed from linear combinations of the true vector modes) is used in practice because the modes forming this basis are more readily excited and detected than the true modes, thus providing a total of six polarization and spatial modes. (Some work has begun on using more complex modal basis sets, including modes that carry

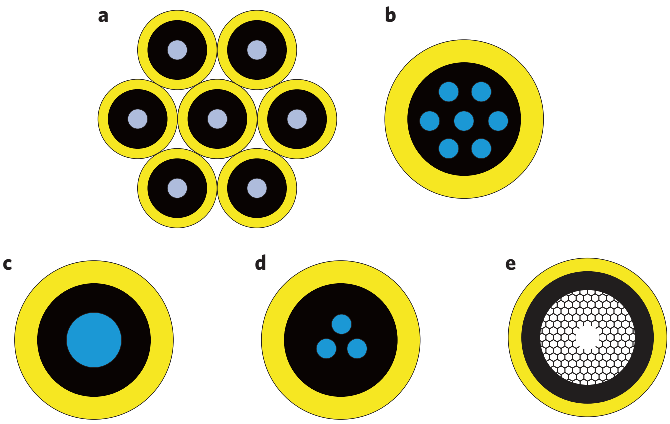

Figure 2 | Different approaches for realizing SDM. a, Fibre bundles composed of physically independent SMFs with reduced cladding thickness could provide increased core packing densities relative to current fibre cables. However, 'in-fibre' SDM is required to achieve the higher core densities and integration levels ultimately desired. **b,** MCF containing multiple independent cores with sufficiently large spacing to limit crosstalk. Fibres with up to 19 cores have been demonstrated for long-haul transmission — higher core counts are possible for short-haul applications (for example, data communications) for which higher levels of crosstalk per unit length can be tolerated. **c,** FMF with a core dimension/numerical aperture set to guide a restricted number of modes (typically 6–12 distinct modes, including all degeneracies and polarizations). **d,** Coupled-core fibres support supermodes that allow higher spatial mode densities than isolated-core fibres. MIMO processing is essential to address the inherent mode coupling. **e,** Photonic bandgap fibres guide light in an air core and thus offer ultralow optical nonlinearity and potentially lower losses than solid-core fibres. Work is currently being conducted to determine whether such fibres can support MDM[110].

orbital angular momentum. Such modes may reduce mode coupling. Both free space[29] and fibre[30] experiments have been reported.) The LP modes in step-index core designs (used in the first demonstrations of MDM in three-mode fibres) have a DMGD of a few nanoseconds per kilometre, meaning that the number of taps required for MIMO processing is impractically large for transmission distances much greater than 10 km. Consequently, core designs that offer substantially lower DMGDs are being developed. Using a graded-index core design[31], DMGDs as low as 50 ps km^{-1} have been achieved for three-mode fibres[32,33]. Moreover, DMGD cancellation has been demonstrated by combining fibres fabricated with DMGDs of opposite signs[31,33,34]. In this way, transmission lines with a net DMGD as low as ~5 ps km^{-1} (and with low levels of inherent mode coupling between mode groups) have been realized, enabling transmission over distances exceeding 1,000 km when incorporated with an appropriate amplification approach[35]. Although these results are technically impressive, it is unclear how scalable the basic approach will be. To assess this, experiments have been undertaken on six-[36] and five-mode[37] FMFs and the initial results have been encouraging. However, just as with the MCF approach, scaling MDM much beyond this is likely to prove very challenging, not least in terms of developing scalable, accurate and low-loss mode-launching schemes and ensuring that the required DSP remains manageable. In the future, MCF-based systems may also be designed to use MIMO equalization to deal with increased crosstalk arising from higher core densities and/or highly integrated transmitters/receivers, optical amplifiers and switching elements.

Although zero crosstalk and zero DMGD would be ideal for reducing the computational cost of compensation, these fibre parameters may ultimately be determined by the more fundamental impairments of nonlinearity and mode-dependent loss and gain. A developing school of thought contends that mode coupling is inevitable so that full $2M \times 2M$ MIMO is necessary, and that strong coupling should be actively exploited[38,39]. If mode coupling is weak then a data symbol carried by multiple modes with different group indices will spread linearly in time with fibre length. In contrast, if the coupling is strong, then the temporal spread will follow a random-walk process and will scale as the square root of the fibre length. Strong coupling can therefore potentially reduce the required number of MIMO taps and hence the DSP complexity. This is analogous to the spinning of current SMFs during fabrication to reduce polarization mode dispersion. Similarly, the impact of differential modal gain and loss can, in principle, be mitigated to some extent by strong mode coupling over a suitable length scale relative to the amplifier spacing[40,41]. Instead of reducing the DMGD to minimize linear impairments (which can be compensated), it has been shown that a larger DMGD can reduce the more problematic intermodal nonlinear impairment[42–44]. For example, simulations have revealed that two-mode transmission over 1,000 km has a significantly lower bit-error rate in a step-index fibre than in a delay-optimized parabolic fibre, assuming linear impairments are ideally compensated, due to the higher local values of DMGD[44]. More general models[45] and measurement techniques[46] are now being applied to better understand how to best mitigate nonlinear penalties in a MDM system; this is certain to become an important research topic in the coming years. Interestingly, almost all transmission comparisons to date have considered a small number of multiplexed modes, whereas intermodal nonlinear penalties are more interesting for many densely packed spatial channels. Researchers are also investigating the feasibility of using MDM in hollow-core photonic bandgap fibres (Fig. 2e), which offer ultralow nonlinearity (effectively making nonlinear effects negligible), low latency and potentially lower losses than solid-core fibres (albeit at longer transmission wavelengths of around 2 μm rather than 1.55 μm (refs 4,47,48)). Accommodating the high DMGD and mode-dependent loss associated with these fibres are key challenges for this approach.

Mode coupling can also be beneficial when applied to MCFs. By bringing the cores closer together to ensure strong linear mode coupling (Fig. 2d), it is possible to establish supermodes defined by the array of cores, which can then be used to provide spatial information channels for MDM to which MIMO can be applied[49,50]. This enables higher spatial channel densities for MCFs than can be obtained using isolated cores designs. Indeed, in this limit, one may argue that the MCF is essentially equivalent to a multimode fibre, albeit one in which the modal properties are defined and can be engineered by varying the geometric arrangement of cores. Nonlinearities may also be important in MCFs in this limit, where linear coupling between cores offers the benefit of mitigating the nonlinear cross-phase-modulation impairment[51].

SDM technology and integration

In addition to developing innovative fibres for SDM, researchers are also addressing component and connectivity challenges that are essential to build systems around SDM fibres. Recent component demonstrations give glimpses of what is possible, but they are based on varied and often conflicting assumptions about larger systems. Two visions for a total system are of particular interest: the 'grand vision' of an ultrahigh capacity, fully SDM system, and the 'upgrade path', where SDM components and links are gradually added to existing non-SDM infrastructure.

Researchers building components for fully SDM systems envision the future availability of high-performance MIMO and the need to increase the spatial multiplexing density well beyond low-crosstalk limits. Scalability is of primary importance, whereas low-crosstalk designs confer no benefit. These broad guidelines suggest the preferred component types: the constituent modulators or detectors in a transmitter or receiver should be coupled to an SDM fibre in a very scalable way without regard for one-to-one mapping of signals to modes (as the modes will quickly scramble). Such scalability is inherent in, for example, photonic-lantern multiplexers[12,52,53] (Fig. 3a) and spot-type transmitters[54] (Fig. 3b). Whenever possible, real systems should have passive multiplexers to reduce cost and power dissipation. Flexible devices for actively multiplexing a desired spatial channel, such as those based on spatial light modulators[55,56], may be important, but only in the small number of subsystems that require reconfigurable optical add/drop functions for spatial channels.

Amplifier design is somewhat less clear in this fully SDM regime. The potential cost and power savings of a cladding-pumped architecture are quite attractive[57]. On the other hand, demonstrations of few-mode core-pumped amplification with a low differential gain are interesting[58,59] and may be scalable to a larger number of modes. In both cases, further work is needed to develop gain fibres that can achieve a high efficiency and a low differential gain for many modes.

Today's flexible photonic mesh networks are based on reconfigurable add–drop multiplexers (ROADMs), which provide carriers the ability to establish light paths remotely and efficiently switch those light paths on demand. It is assumed that future fully SDM networks will have a similar routing flexibility, although there are many ways in which this could be implemented. Figure 3c shows a possible SDM network node that consists of an SDM-ROADM and associated SDM–WDM transmitters and receivers for the add and drop, along with SDM fibres and amplifiers for the three fibre directions addressed. The SDM ROADM itself can be quite complicated depending on the choices made regarding the type of superchannels (for example, frequency or spatial[60]) and the switching strategy (for example, wavelength by wavelength with all modes together; mode by mode with mode interchange; any wavelength/mode to any other wavelength/mode). The SDM-ROADM architecture will also depend on its support for colourless, nondirectional, contentionless and/or gridless operation.

The approach that mode coupling is inevitable and should be corrected only at the receiver implies that mode-independent routing elements will be a key technology. Such elements route wavelengths to different destinations while keeping all the spatial modes together. All modes are therefore present at the receiver, allowing MIMO processing to recover the transmitted signals. Chen *et al.*[61] reported the first demonstration of a few-mode-compatible optical add–drop multiplexer. Spatial superchannels and the plausibility of joint digital signal processing have also been considered[60]. Cvijetic *et al.*[62] gave a forward-looking view of SDM as a means of realizing maximum flexibility in routing. As it matures, SDM may offer benefits beyond high capacity and flexible routing in, for example, secure data transmission[63].

A very different vision of SDM involves incrementally incorporating upgrades to existing single-mode infrastructure. The upgrades must be reverse-compatible and offer short-term cost advantages. In this case, compatibility is more critical than scalability, making low-crosstalk solutions extremely important because they allow SDM fibres and components to be used as drop-in replacements for their non-SDM counterparts (leading to a 'hybrid SDM–SMF' network), and they can be used before real-time implementations of MIMO processing have been commercialized. This strategy is not incompatible with the above-mentioned 'grand vision', but it is focussed on much shorter-term goals. Initial steps along the SDM 'upgrade path' could be taken quite soon; for example, cables in a few ducts with unusually high congestion could be replaced without changing the surrounding network. Seamless connectivity will be a key requirement in early upgrades. Basic passive multiplexers have been demonstrated using free-space[64] and tapered[65] approaches, and both implementations are rapidly progressing towards more practical and compact solutions[22,66,67].

Upgrading a conventional SMF system by installing SDM amplifiers could provide considerable benefits if multicore amplifiers can achieve the efficiency improvements that are potentially realizable[57,68] using cladding pumping and pump sharing. This would give system companies a strong motivation for performing an incremental

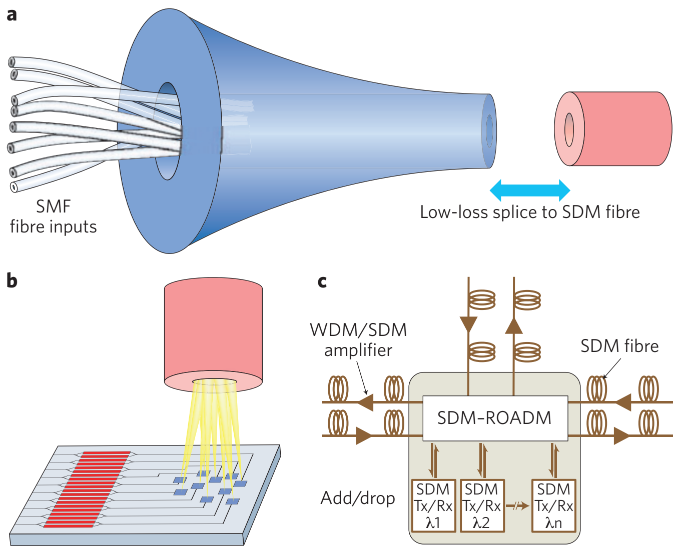

Figure 3 | The many components needed to fully exploit the advantages of high-density SDM. a, Elegantly scalable passive multiplexers. **b,** Integrated transmitter and receiver arrays providing low-loss coupling to many modes of an SDM fibre. **c,** Reconfigurable routing elements that can direct SDM traffic without the need for electronic MIMO in between transmitter and receiver. The strategy for switching wavelengths and modes, as well as any additional required functionality, will determine the complexity of the ROADM architecture.

upgrade, but it is technically challenging. Initial steps towards a cladding-pumped MCF-EDFA[69,70] are interesting, but are far from achieving high efficiency.

A key motivation for SDM is its potential to facilitate integration; this will be important both in incremental upgrades and later progress towards fully SDM systems. Synergistic development of integrated transmitter and receiver arrays along with compatible fibres and components is essential, as was first realized in short-reach data communications systems[71,72]. Matching of silicon integrated devices to fibres with seven[73] and eight[74] single-mode cores has been demonstrated. Devices that can produce complex orthogonal fields that match specific modes of a MMF have also been demonstrated[75–77]. Many other functions are needed in a real system. For example, a Raman pump-sharing circuit[78] illustrates how the number of components in transmission equipment can be greatly reduced by integration. The net benefit of integration will become clearer as the engineering of interconnects and multiplexers reduces the total loss to that of single-mode devices.

Progress in system demonstrations

Initial transmission experiments over MCFs were aimed at short-reach applications. Following a proposal to make high-density cables for fibre-to-the-home applications[79], Rosinski *et al.*[80] demonstrated simultaneous 850 nm, 1 Gbit s^{-1} transmission over two cores of a four-core MCF. More recently, 1.310 μm and 1.490 μm signals have been transmitted over an 11.3-km seven-core MCF for passive optical network applications, where a fibre-based tapered multicore connector was first utilized to couple signals into and out of the MCF[81]. For optical data link applications, seven-core multimode MCFs fabricated from graded-index core rods were demonstrated in 2010, with a transmission rate of 7 × 10 Gbit s^{-1} over 100 m using tapered multicore connectors and discrete 850-nm vertical-cavity surface-emitting lasers[82]. Lee *et al.*[71] used a hexagonal array of vertical-cavity surface-emitting lasers to couple directly to the six outer cores of a seven-core multimode MCF. They subsequently developed a vertically illuminated photodiode array matched to the

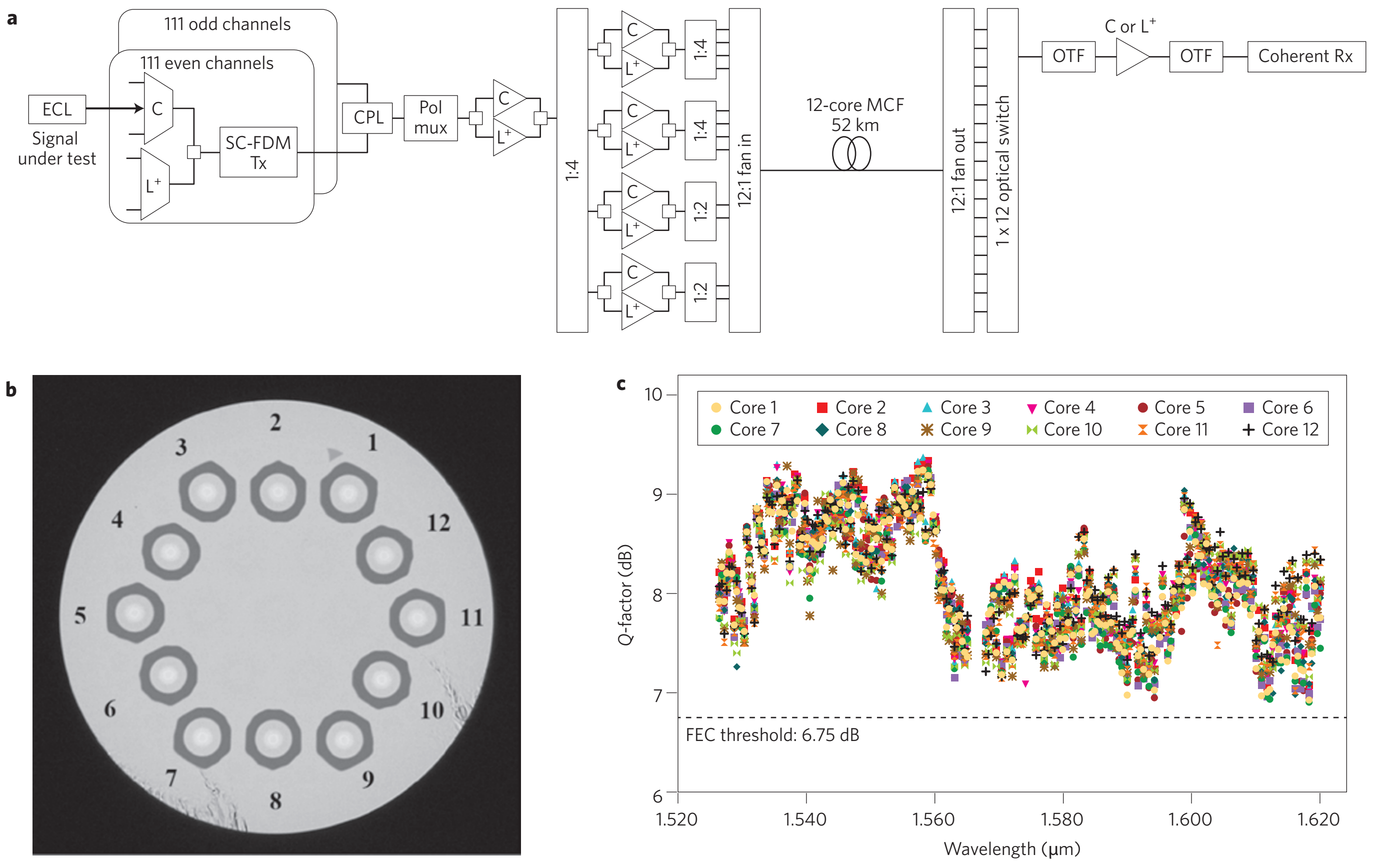

Figure 4 | 1.01 Pbit s^{-1} MCF WDM/SDM/PDM transmission experiment[22]. a, Schematic of the transmission system set-up showing (left to right) the modulation of the two sets of 111 channels, splitting and amplification for launching into a 12:1 fan-in device, transmission over a 52-km 12-core MCF, followed by a 1:12 fan-out device and a 1 × 12 optical switch to select one core for detection by the coherent receiver. ECL, external cavity laser; SC-FDM Tx, single-carrier frequency-division multiplexed transmitter; CPL, coupler; Pol mux, polarization multiplexer; OTF, optical tunable filter; Rx, receiver. **b,** Microscope image of cross section of the one-ring, 12-core fibre. **c,** Measured *Q*-factors of the 222 WDM channels in each of the 12 cores after 52-km transmission.

MCF[72], thus demonstrating a full 100-m MCF optical link at up to 120 Gbit s^{-1}.

Following significant advances in the design and fabrication of single-mode MCFs, demonstrations of SDM transmission over MCF for long-haul applications have shown impressive progress in terms of capacity, reach and spectral efficiency (Table 1). Two groups simultaneously reported the first WDM transmission experiments over MCFs using seven-core MCFs, with a 56 Tbit s^{-1} capacity over 76.8 km (ref. 83) and a 109 Tbit s^{-1} capacity over 16.8 km (ref. 84). In both experiments, the MCF crosstalk was sufficiently low that the signals on each core could be received independently (without MIMO processing), and optical amplification utilized conventional single-core EDFAs placed before and after the MCF. Over the past two years, a number of subsequent experiments over seven-core MCFs have been performed with spectral efficiencies of 14 bit s^{-1} Hz^{-1} or higher[85,86].

Several experiments have utilized coherent optical orthogonal frequency-division multiplexed superchannels to demonstrate ultra-high per-channel bit rates over MCF. Liu and co-workers[87] transmitted a single 1.12 Tbit s^{-1} superchannel consisting of 20 orthogonal frequency-division-multiplexing subchannels over a single 76.8-km span of an MCF. A later WDM experiment demonstrated transmission of eight 603 Gbit s^{-1} superchannels over 845 km at a spectral efficiency of 42.2 bit s^{-1} Hz^{-1} (ref. 88).

Takahashi and co-workers[89] recently transmitted 40 103-Gbit-s^{-1} channels over 6,160 km — the longest transmission distance over an MCF. Their experiment was the first to utilize a multicore EDFA for long-haul, WDM transmission over an MCF, and it achieved a record capacity–distance product of 177 Pbit s^{-1} km. A record capacity of 1.01 Pbit s^{-1} was transmitted over a 52-km MCF with 12 cores arranged in a single ring[22] (Fig. 4). This MCF and its fan-in and fan-out devices were specifically designed to give a crosstalk that was sufficiently low to allow high-order modulation formats[20] (in this case, 32 quadrature amplitude modulation at 400 Gbit s^{-1} per channel). In addition to supporting an aggregate spectral efficiency of 91.4 bit s^{-1} Hz^{-1}, the MCF had sufficiently low loss and crosstalk across the C- and extended L-bands (1.526–1.620 μm) to enable transmission of 222 channels and an aggregate capacity of 1.01 Pbit s^{-1} (Fig. 4c).

The MDM concept was first proposed in 1982 when Berdague and Facq used spatial filtering techniques to launch and detect two modes at the ends of a 10-m conventional graded-index MMF[2]. The analogy between wireless and optical channels was not recognized until 2000 when Stuart demonstrated the application of 2 × 2 MIMO for receiving two MDM channels after 1 km transmission[90]. Coherent optical 2 × 2 MIMO was demonstrated at 800 Mbit s^{-1} over 100 m and 2.8 km of 62.5-μm MMF[91]. Additional proof-of-principle demonstrations utilized direct detection and 2 × 2 MIMO[92], and modal diversity with direct detection using 2 × 4 MIMO[93]. As these early transmission experiments over conventional MMFs did not launch and receive all modes, they would not have been capable of achieving the low outage expected of optical communication links[94].

Recent FMF developments have enabled rapid progress in the capacity and reach of MDM system demonstrations, as shown in Table 1. In early 2011, three experiments over the simplest FMF supporting the LP_{01} and degenerate LP_{11} modes were reported at the same conference. Per-channel rates of 100 Gbit s^{-1} over two spatial modes were achieved over 4.5 km (ref. 95) and 40 km (ref. 96),

Table 1 | Summary of progress in SDM system experiments.

Year	Reference	Fibre type	Number of cores/spatial modes	Distance (km)	Span length (km)	Channel rate (Gbit s^{-1})	WDM channels in each core/mode	Net spectral efficiency (bit s^{-1} Hz^{-1})	Net total capacity (Tb s^{-1})	Capacity–distance product (Pb s^{-1} km^{-1})
2012	22	MCF	12	52	52	456	222	91.40	1,012.32	52.64
2012	89	MCF	7	6,160	55	128	40	14.44	28.88	177.87
2012	88	MCF	7	845	76.8	603	8	42.20	33.77	28.53
2012	23	MCF	19	10.1	10.1	172	100	30.50	305	3.08
2012	104	mstr-MCF	3	4,200	60	80	5	3.84	0.96	4.03
2011	86	MCF	7	2,688	76.8	128	10	15.02	7.51	20.19
2011	87	MCF	7	76.8	76.8	1,120	1		7.84	0.60
2011	50	mstr-MCF	3	1,200	60	80	1		0.22	0.27
2011	49	coupl MCF	3	24	24	56	1		0.15	0.004
2011	65	MCF	7	76.8	76.8	107	160	14.00	112.00	8.60
2011	83	MCF	7	76.8	76.8	107	80	14.00	56.00	4.30
2011	84	MCF	7	16.8	16.8	172	97	11.25	109.14	1.83
2012	107	MCF with SM and FM cores	12 SM cores, 2 FM cores	3	3	1050	385 in SM cores, 354 in FM cores	109.00	1,050.00	3.15
2013*	112	FMF	3	500	50	76	146	7.30	26.63	13.32
2013*	111	FMF	6	177	59	160	32	30.72	24.58	4.35
2013*	110	FM-PBGF	3	0.31	0.31	256	96	12.00	57.60	0.02
2012	36	FMF	6	130	65	80	8	7.68	3.07	0.40
2012	34	FMF	3	119	119	256	96	12.00	57.60	6.85
2012	101	FMF	3	209	209	80	5	4.42	1.10	0.23
2012	35	FMF	3	1,200	30	80	1		0.19	0.23
2012	100	FMF	3	85	85	112	1		0.31	0.03
2012	98	FMF	3	96	96	80	1		0.22	0.02
2011	37	FMF	5	40	40	112	1		0.52	0.02
2011	99	FMF	3	50	50	112	88	6.19	27.23	1.36
2011	35	FMF	3	33	33	112	6	6.19	1.86	0.06
2011	97	FMF	3	10	10	56	1		0.15	0.002
2011	96	FMF	2	40	40	112	1		0.21	0.01
2011	95	FMF	2	4.5	4.5	107	1	5.40	0.20	0.001

Upper rows show experiments utilizing MCFs. Centre row shows an MCF-FMF result. Lower rows show transmission results over FMFs. The channel rate includes polarization multiplexing; the net spectral efficiency and net total capacity exclude the overhead for forward error correction. SM, single-mode; FM, few-mode; coupl MCF, coupled-core MCF; mstr-MCF, microstructured coupled-core MCF; FM-PBGF, few-mode photonic-bandgap fibre. Most SDM transmission experiments have utilized either seven-core MCF or FMF supporting three spatial modes. The table shows the rapid progress in both reach and net capacity over two years. Recent experiments utilizing a 12-core MCF and a MCF with hybrid SM and FM cores have demonstrated record net capacities of more than 1 Pbit s^{-1}. *Latest results from the 2013 OFC conference.

whereas 56 Gbit s^{-1} signals in three modes were transmitted over 10 km (ref. 97) (both bit rates include polarization multiplexing). The three-mode experiment[97,98] first demonstrated full use of all degrees of freedom afforded by the FMF (six spatial and polarization modes), with signal recovery via full coherent 6 × 6 MIMO. Randel *et al.*[26] subsequently demonstrated WDM, MDM and PDM transmission of six wavelengths, three modes and two polarizations, achieving a 2.02 Tbit s^{-1} capacity (before subtracting the forward-error correction overhead).

In the first transmission experiment to include amplification in a MMF, a few-mode inline EDFA boosted the 88 WDM signals before the mode demultiplexer and reception[99]. To reduce the mode-dependent gain, the MM-EDFA was forward pumped in the LP_{21} mode and reverse pumped in the LP_{11} mode. In later work, the transmission distance was increased to 85 km (ref. 100). Distributed Raman amplification was employed to realize single-span MDM transmission over 209 km (ref. 101). In that experiment, the FMF supporting six spatial and polarization modes consisted of a first section with a large effective area (155 μm^2) depressed-cladding FMF (which is tolerant to nonlinear effects) followed by a graded-index FMF with a smaller effective area (<67 μm^2) for efficient Raman pumping. The DMGD was compensated by using fibre spools with a DMGD of the opposite sign to reduce the number of equalizer taps required for the MIMO processing.

To date, the longest transmission distance reported for MDM systems is 1,200 km, where a recirculating loop was utilized with a 30-km span consisting of two FMF sections having DMGDs of opposite sign[35]. Mode multiplexers and demultiplexers were placed before and after the FMF span in the loop so that single-mode EDFAs could be used. Recently, a net capacity of more than 57 Tbit s^{-1} (after subtracting the forward-error correction overhead) was demonstrated in a 119 km MDM system (Fig. 5a,b) consisting of 96 WDM channels each at 200 Gbit s^{-1} (refs 34,102). The FMF supported three spatial modes, and an inline multimode EDFA provided 18 dB gain per

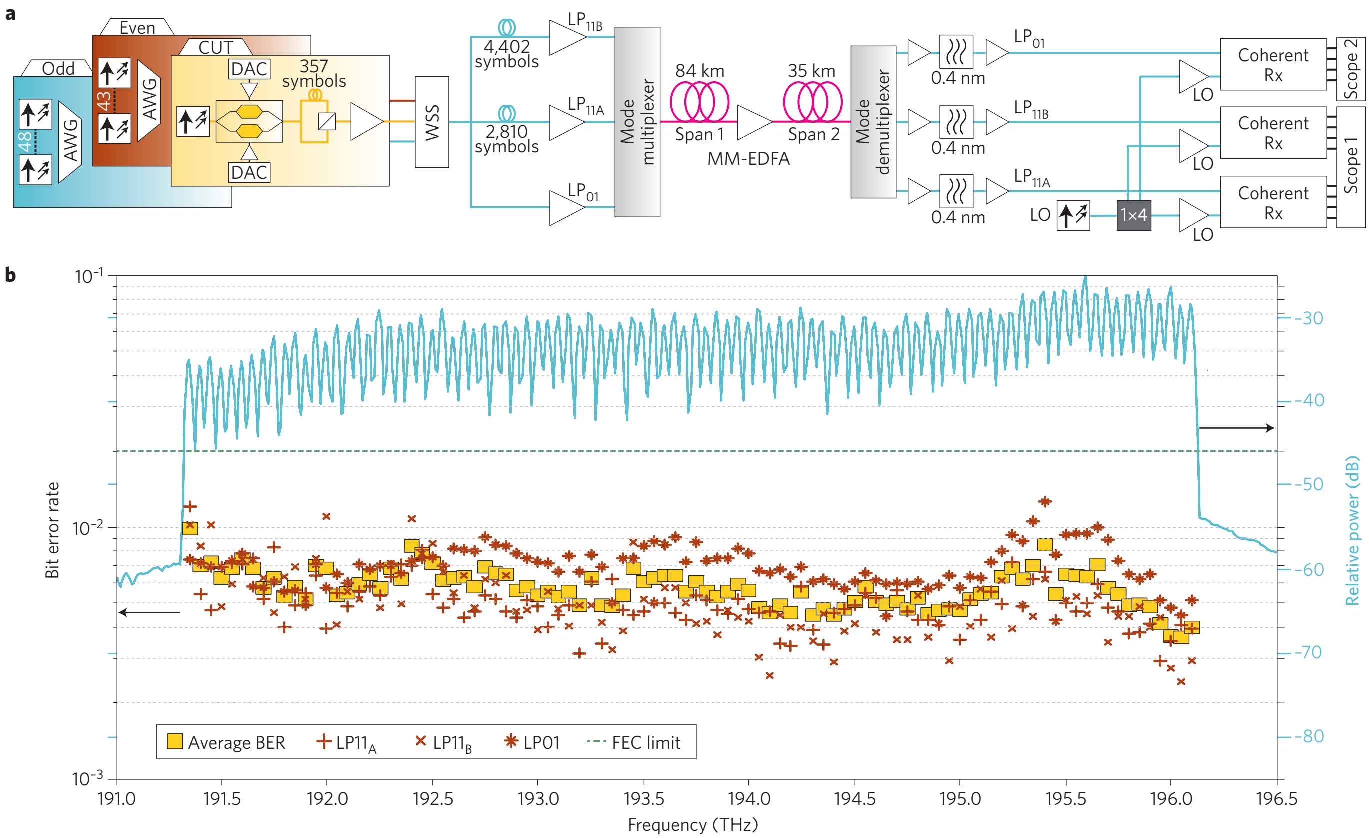

Figure 5 | 57.7 Tbit s^{-1} amplified WDM/MDM/PDM transmission experiment over a few-mode fibre[34,102]. a, Schematic of the experimental set-up showing (left to right) the three sets of transmitters for odd and even channels and the channel under test (CUT), splitting and amplification for launch into the mode multiplexer, transmission over the two few-mode-fibre spans with in-line MM-EDFA and mode demultiplexer and simultaneous reception of the channels transmitted in the three modes for MIMO processing. AWG, arrayed waveguide grating multiplexer; DAC, digital-to-analog converter; WSS, wavelength-selective switch; LO, local oscillator. **b,** Measured bit-error rates (markers) of all 96 channels in each of the three modes and optical spectrum (blue curve) after transmission over the 119 km of few-mode-fibre with a mid-span amplifier. BER, bit error rate; FEC, forward error correction.

mode, making it the first WDM FMF system to utilize a mid-span MMF amplifier. The 12 bits s^{-1} Hz^{-1} spectral efficiency and 57 Tbit s^{-1} capacity are the highest reported so far for MDM transmission. Ryf and co-workers[36] reported the highest number of spatial modes to be utilized as separate information channels; they used six spatial modes (LP_{01}, 2 × LP_{11}, 2 × LP_{21} and LP_{02}) and 12 × 12 MIMO.

Combining MCF and FMF concepts

As shown in Fig. 2d, multicore fibres with coupled cores[103] allow increased core density and/or larger core effective areas, where the latter minimizes nonlinear effects. As a result of the strong crosstalk between cores, the light propagation in the fibre can be described by the supermodes of the composite fibre structure. A single-channel transmission experiment with a 24-km homogenous three-core fibre with an effective area of 104 μm^2 has been reported[49], where all six (space and polarization) modes were launched and jointly detected. The large crosstalk of about −4 dB was almost completely suppressed by coherent 6 × 6 MIMO processing. In other work, an all-solid-glass microstructured fibre with three large (~129 μm^2) effective-area cores with a pitch of 29.4 μm was utilized in several experiments[50,103]. Using 6 × 6 MIMO processing, transmission over 1,200 km was achieved for a single 20-Gbaud quadrature-phase-shift keyed channel and over 4,200 km for five WDM channels[104] — a record distance at that time — thus demonstrating the feasibility of MIMO interference cancellation for long-haul transmission.

To further increase the capacity it is possible to combine the multicore and MDM approaches: indeed, the first experiments in this area are now beginning. For example, it is possible to produce an array of spatially isolated multimode cores rather than single-mode cores[105,106], thus enabling MDM to be overlaid directly onto the multicore approach. Fibres capable of supporting up to 21 different spatial modes (seven cores each supporting three modes) have been reported, although only relatively rudimentary system measurements have been performed so far[105]. In a related approach, a hybrid MCF with 12 single-mode cores and two few-mode cores supporting three spatial modes each has been utilized to demonstrate a transmission capacity of 1.05 Pbit s^{-1} (ref. 107). The transmission distance was only 3 km, but this experiment was the first to achieve a spectral efficiency of over 100 bit s^{-1} Hz^{-1}. Although these approaches are extremely challenging from a component perspective, they provide interesting opportunities both in terms of constraining DSP complexity and allowing very high spatial channel densities.

SDM networking and switching

Most SDM demonstrations to date have consisted of point-to-point transmission, but recent efforts have contemplated switching strategies and elements that can support flexible optical routing. There is a growing consensus that SDM networks should utilize spatial superchannels; that is, groups of same-wavelength subchannels transmitted on separate spatial modes but routed together, where the spatial modes could be the regular modes in a MMF or FMF, supermodes in a strongly coupled multicore fibre, or the fundamental modes of each individual single-mode core in an 'uncoupled' MCF[60,61]. Such a strategy could provide sufficient granularity for efficient routing and facilitate ROADM integration, help to simplify network design as the modes are routed as a single entity, improve transceiver integration (for example, share a single source laser in the transmitter and a single local oscillator in the receiver) and reduce the DSP load by exploiting information about common-mode impairments such as dispersion and phase fluctuations[60].

As a first-step towards an FMF-compatible ROADM, an optical add–drop multiplexer comprising two cascaded, free-space, thin-film filters has been demonstrated for the two orthogonal LP_{11} modes[61]. Recently, Amaya *et al.*[108] reported switching in the space, frequency and time dimensions in an elastic SDM and multigranular network that included two seven-core MCF links. Space switching was achieved via an optical backplane that interconnected MCF/SMF fibre inputs, functional modules and MCF/SMF fibre outputs; however, there was a high degree of complexity as a result of the required demultiplexing of the signals transmitted in the various MCF cores at each node. More recently, the first SDM ROADM supporting spatial superchannels (in six-core MCF) has been reported in a two-span system, where add, drop and express paths were measured[109]. Future work is needed to examine the trade-offs between the switching granularity and the resulting complexity of SDM networks.

Conclusions

Much exciting progress has been made in SDM transmission over the past two years. Various technological approaches are being developed, and record per-fibre capacities and long reaches have been demonstrated, some including SDM amplifiers. There have also been some initial demonstrations of switching/routing. However, this is just the beginning; much more work needs to be undertaken if per-channel reliability and performance competitive with those of existing single-mode links are to be achieved. Furthermore, most network operators will only consider deploying SDM if it lowers the cost-per-bit, provides the routing flexibility needed for efficient photonic mesh networks and allows a reasonable transitional strategy from systems based on standard SMF. Photonic integration, which is in its infancy, will be essential. Moreover, it remains to be seen whether any of the SDM fibre types proposed and demonstrated so far can be scaled to high-volume manufacturing and produced at a reasonable cost relative to SMFs. Whatever the ultimate outcome, the next few years promise to be a busy and exciting time in optical fibre communications research.

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Acknowledgements

D.J.R. thanks his colleagues and collaborators on the European Union Framework 7 funded MODEGAP project (258033) and the UK Engineering and Physical Sciences Research Council (EPSRC) funded Hyperhighway project (EP/I01196X/1) for discussions.

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Competing financial interests

The authors declare no competing financial interests.