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Space-division multiplexing for optical fiber communications

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Research on space-division multiplexing (SDM) came to prominence in early 2010 being primarily proposed as a means of multiplying the information-carrying capacity of optical fibers at the same time as increasing efficiency through resource sharing. Proposed SDM transmission systems range from parallel single-mode fibers with shared amplifier pump lasers to the full spatial integration of transceiver hardware, signal processing, and amplification around a fiber with over 100 spatial channels comprising multiple cores each carrying multiple modes. In this paper, we review progress in SDM research. We first outline the main classifications and features of novel SDM fibers such as multicore fibers (MCFs), multimode fibers, few-mode MCFs, and coupled-core MCFs. We review research achievements of each fiber type before discussing digital-signal processing, amplifier technology, and milestones of transmission and networking demonstrations. Finally, we draw comparisons between fiber types before discussing the current trends and speculate on future developments and applications beyond optical data transmission.

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1. INTRODUCTION

Optical transmission systems and networks are key elements of the worldwide communications infrastructure [1]. The ongoing provision of new services and larger data volumes to meet the needs of business, academia, governments, and citizens yields new challenges to optical network design, an issue exacerbated by recent changes in global working practices [2]. The exponential growth of data services in recent years [3] has led the photonics research community to explore a range of new optical fibers and related technologies to replace standard single-mode fibers (SMFs), the basis of most high-capacity, commercial fiber systems. Broadly termed as space-division multiplexing (SDM) [4,5], this research covers an assortment of technologies supporting transmission of individual data signals over multiple spatial paths of a common optical fiber channel. The motivation for adopting such systems is not only to multiply the information carrying capacity of optical fibers but also to reduce energy consumption and improve efficiency through integration, shared hardware, and joint digital-signal processing (DSP) [6].

Although, the idea of utilizing the spatial dimension of optical fiber cables for multiplexing dates back much further [7,8], SDM research became widespread in the last decade as SMF fiber systems using wavelength-division multiplexing (WDM) with coherent detection began to approach their theoretical capacity limits [9]. Improvements in fiber fabrication and processing technology fueled a quick advancement in SDM research leading to the realization of many new fibers and coupling techniques.

A generalized SDM transmission system is shown in the lower inset of Fig. 1, compared to a generalized WDM transmission system based on SMF in the upper inset. In addition to fibers and amplifiers, SDM systems require spatial multiplexers to direct optical signals in and out of spatial channels. SDM systems with more than 100 spatial channels, each carrying hundreds of WDM channels, have been demonstrated in a single fiber with a combined data rate exceeding 10 Pb/s [14,15]. These demonstrations illustrate both the challenges and opportunities for hardware and control integration arising from thousands of parallel data channels sharing a single fiber. Along with lower level component sharing techniques such as common light sources, amplifier pump lasers, or DSP, it is hoped that hardware integration inherent to SDM systems can both reduce the energy- and cost-per-bit across a wide range of optical transmission and network contexts.

Figure 1 also shows the evolution of published research demonstrations, setting new per-fiber data rate records in WDM systems using SMF from 1996 and SDM systems from 2011, when they first overtook WDM systems. Figure 1 shows that the data rates of WDM systems have been mostly limited to around 100 Tb/s until recently approaching 200 Tb/s through the adoption of new transmission bands [16,17]. In contrast, SDM systems supporting similar transmission bandwidths in each spatial channel have been shown to achieve data rates nearly 2 orders of magnitude greater. The potential for higher data rates, novel networking approaches, improved power efficiency, and integration possibilities has pushed SDM technology toward commercial deployment with numerous cabling and reliability studies, SDM multiplexers employed to

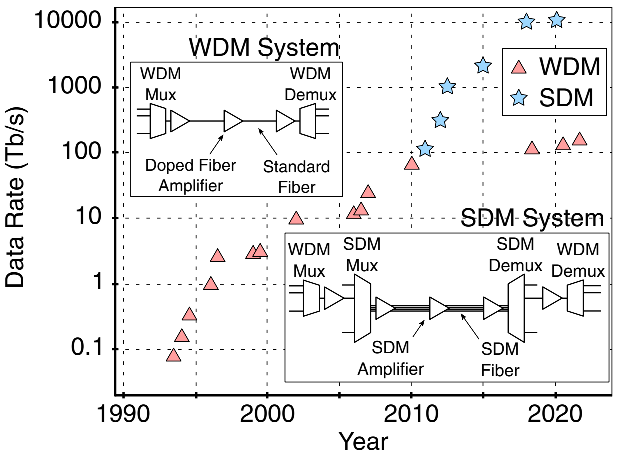

Fig. 1. Evolution of data rate records for WDM systems since 1996 and SDM systems [10–15] since 2011. Upper inset: generalized WDM system. Lower inset: generalized SDM transmission system.

upgrade installed multimode fibers (MMFs) [18], field deployment of an SDM fiber test bed [19], and a recently announced submarine transmission link using amplifier pump sharing [20].

In this paper, we summarize the achievements in the development of SDM fibers and technologies for the purpose of optical data transmission. Section 2 outlines the technologies needed to support SDM optical transmission and the development of new fibers, multiplexing technologies, amplification, and how DSP can be adapted for SDM systems. We then focus on SDM transmission systems in Section 3, reviewing modeling work before outlining progress benchmarked by transmission demonstrations. Section 4 summarizes current trends in SDM research and speculates on its future directions.

2. SDM TECHNOLOGIES

In this section, we describe key SDM technologies relating to the most widely studied SDM fiber types, shown schematically in Fig. 2. Although SMF bundles, ribbon fibers, and multielement fibers [21] are options for SDM systems, they do not require distinct associated technologies and are not described in detail. Instead, we focus on variants of multicore fibers (MCFs) and few-mode fibers (FMFs) or MMFs. In MCFs, multiple cores share a common cladding with the major distinction being the level of intercore coupling. We distinguish between MCFs generally referred to as weakly coupled (WC)-MCFs, where signal interactions between cores are typically undesirable and coupled-core (CC)-MCFs where a smaller core-pitch leads to stronger, intentional random coupling of signals in different cores. In FMFs and MMFs, an enlarged core or modified fiber profile supports multiple fiber modes. Finally, we describe work on the hybrid combination of FMFs and MCFs: FM-MCFs, where each MCF core is able to support more than one mode. In Section 2.A we describe the features and development of each fiber type; in Section 2.B we consider the impact of SDM fiber types on DSP; and in Section 2.C we discuss amplifier technologies.

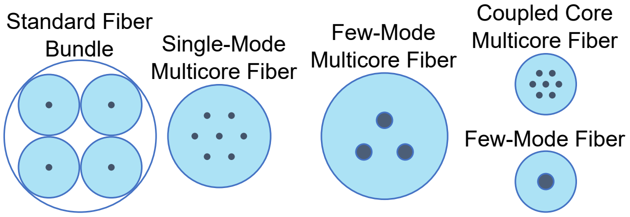

Fig. 2. Five classes of SDM fibers for optical data transmission.

A. SDM Fibers and Spatial Multiplexers

1. Single-Mode, Weakly Coupled Multicore Fibers

MCFs were proposed as early as 1979 [22] with single-mode WC-MCFs proposed later in 1994 [23], becoming a topic of widespread research in the last decade as a means of multiplying the transmission capacity of a single optical fiber. In WC-MCFs, the total capacity is proportional to the core count, assuming negligible field coupling between cores. Any residual field coupling leads to intercore crosstalk (IC-XT) [24], which may limit the transmission capacity. IC-XT is wavelength dependent, with a slope between 0.1 and 0.15 dB/nm, governed mainly by the wavelength dependence of the mode overlap of the interfering cores [25–27]. Figure 3 illustrates the accumulation of IC-XT along a WC-MCF. Residual coupling between an interfering and interfered core leads to IC-XT contributions produced at multiple points along the fiber. These contributions accumulate at the fiber output with arbitrary phases arising from variations in group velocity and polarization coupling within cores [27–29]. This leads to random time-varying IC-XT fluctuations at the fiber output [28], as exemplified in Fig. 3, which shows the time evolution of IC-XT produced within a 31.4 km 22-core WC-MCF with an average IC-XT of −45 dB [13] by a CW lightwave during a 60 min period. In contrast, the use of incoherent light sources reduces the IC-XT fluctuations, as shown in Fig. 3 when using filtered amplified spontaneous emission (ASE) noise with a 1 nm bandwidth. It has been shown that the IC-XT variance decreases with the product of the signal bandwidth and the difference between group velocities of the interfering cores, referred to here as intercore skew (ICS) [30]. Hence, IC-XT originating from carrier-supported modulation formats such as intensity modulated on–off keying (OOK) or pulse-amplitude modulation (PAM) can vary strongly in power and limit the performance of such links [31], while carrier-less signals, such as quadrature-amplitude modulation (QAM), typical in coherent systems, induces nearly constant power IC-XT, even with low ICS [32].

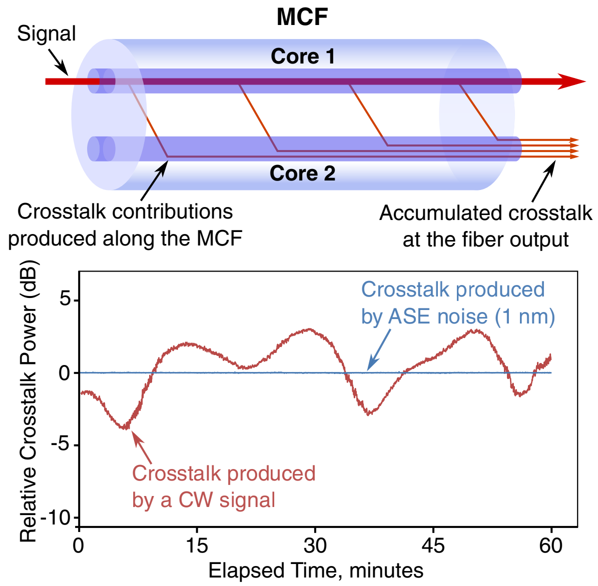

Fig. 3. Distributed crosstalk in single-mode multi-core fibers.

WC-MCFs may be classified as homogeneous [23] or heterogeneous [33], when the cores are designed to have similar or distinct propagation characteristics, respectively. In heterogeneous WC-MCFs, neighboring cores have different core properties to reduce core coupling [34] but can be more sensitive to macrobending, microbending, and fabrication imperfections, as shown in [35,36]. Homogeneous WC-MCFs have near identical cores, which can give slightly elevated IC-XT for the same core pitch but may allow simpler fabrication. In both cases, the design of the cores must also consider aspects such as effective area and cutoff wavelength, to ensure an acceptable level of fiber nonlinearities and single-mode operation [37,38]. Furthermore, the core positioning and cladding dimensions may be adjusted to manage the overall IC-XT and ensure attenuation comparable to SMFs [37,39].

Numerous WC-MCF designs have been proposed, with various cladding diameters and core structures. Figure 4 shows a selection of those designed for medium to long-haul transmission [12,13,24,40–53]. In these demonstrations, the coupling between SMF and WC-MCF cores was achieved in a range of devices including free-space optics [54], laser-inscribed waveguides [55], fused-fiber multiplexers [34,56], or bundled fiber devices [57]. Early proposals focused on seven-core fibers with a hexagonal layout of step-index cores resulting in high IC-XT of approximately −14 dB/km [40]. Larger cladding diameters up to 200 µm were then adopted [58] to reduce IC-XT to −37 dB/km. The introduction of trench-assisted cores further reduced IC-XT [41], enabling fibers with up to 19 cores in a hexagonal arrangement [48]. Later, moving to a circular layout allowed a larger core pitch in the same cladding area [59]. Such techniques lead to fabrication of a 37-core heterogeneous WC-MCF with a 248 µm cladding [53], corresponding to a spatial channel density (in this case, core count per unit of facet area) 9 times larger than that of SMF. It should be noted here that increasing the fiber cladding diameter has been related to both an increase in the fiber failure probability and a reduction of achievable splicing accuracy [39,58,60]. Indeed, concerns over the mechanical reliability of larger fibers as well as to aid compatibility with conventional cabling technology has also led to the exploration of WC-MCFs with the same 125 µm cladding diameter as SMFs [19,51,52]. These small WC-MCFs typically support four trench-assisted cores, achieving IC-XT values around −60 dB/km. Notable examples include the fabrication of compatible four-core WC-MCFs by four different vendors in a standardization effort [51], and the first field deployment of WC-MCFs as part of the INCIPICT project in the Italian city of L'Aquila [19].

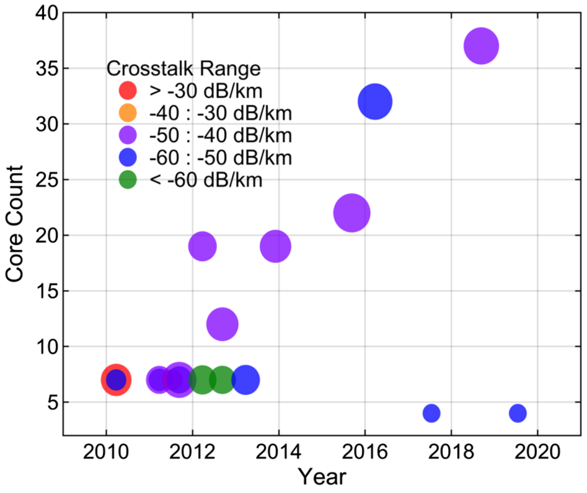

Fig. 4. Evolution of WC-MCFs. The bobble sizes illustrate the relative cladding diameter [12,13,24,40–53].

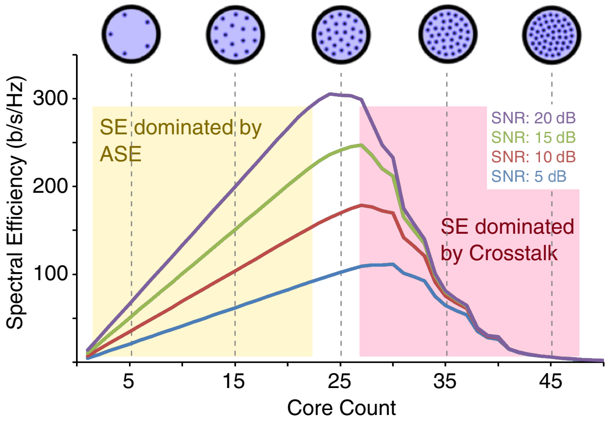

Fig. 5. Dependency of spectral efficiency on the core count of WC-MCFs.

We note that a universal WC-MCF is yet to be proposed with designs typically informed by the target application, depending on a number of parameters such as operating wavelength, target throughput, transmission reach, or DSP architecture [37,38,61–64]. These studies, among others, have addressed fiber design parameters such as core count, refractive index structure and pitch, cladding dimensions, and the transmitted signals to balance the interplay between the impacts of IC-XT, ASE noise, and fiber nonlinearities. This interplay is illustrated in Fig. 5, which shows the theoretical aggregate spectral efficiency (SE) of a linear link computed as a function of the core count for a fixed cladding diameter of 260 µm and multiple operational signal-to-noise ratios (SNRs). As the core count grows, the SE increases linearly, with the performance dominated by ASE. After an optimum core count, the IC-XT impact dominates performance, decreasing the SE. The optimum core count varies only mildly with the operational SNR [63] and has been shown to be fairly independent of the transmission distance [32,38,62]. Furthermore, a target IC-XT requirement for WC-MCFs of −60 dB/km was shown sufficient to support most applications of interest for coherent systems [32,38,62]. However, as optical transmission systems begin to use wider transmission windows including the S-, C-, and L-bands [16,17,65,66], the wavelength dependence of IC-XT [25,26] may limit the applicability of the aforementioned target crosstalk values [67]. Alternatively, advanced DSP techniques, discussed in Section 2.B, may be used to undo or minimize the impact of IC-XT.

Besides IC-XT and loss, the design of WC-MCFs must also take into account the ICS and its dependency on fiber bending and twisting. In comparison to parallel SMFs, a WC-MCF with low ICS enables better synchronization of data transmission in multiple cores [68,69], which is an essential property of SDM networks, enabling the use of spatial super channels, shared DSP resources, and spatial modulation and coding techniques, also discussed in Section 2.B [68,70,71].

WC-MCFs have also been proposed for short-reach applications, such as passive optical networks [23,72–74] and intradatacenter networks [69,75–79]. The use of WC-MCFs is particularly promising for the latter as an evolution of the existing multilane optical interconnect systems due to their potential for high core density [60,79]. WC-MCFs can be used to reduce the required front-panel space for optical connectors in high-density switches, with up to 256 cores in a single MPO-type MCF connector as reported in [80]. Furthermore, typically operating in the low IC-XT O-band region, the core count of such systems can be increased without increasing the cladding diameter. Indeed, an eight-core homogeneous WC-MCF with a 125 µm diameter has been shown to support O-band operation with an average crosstalk below −60 dB/km at 1310 nm [60]. A similar fiber was also demonstrated in the field, as reported in [19]. Alternative architectures for WC-MCFs designed for optical interconnects include cores in linear or rectangular arrangements [76,79], which aim at simplifying the fiber connectorization or coupling onto photodetector or laser arrays.

2. Few-Mode/Multimode Fibers

FMFs/MMFs are designed to guide multiple, orthogonal transverse fiber modes in a single fiber core and are typically designed with a standard cladding diameter of 125 µm. Standard MMFs with a 50 µm core diameter guide around 50 modes at a wavelength of 1550 nm [81]. Such fibers have been used in commercial short-reach links with intensity modulation for many years [82] with the large core diameter relaxing alignment tolerances for splicing and connectorization. Later, although still focused on the transmission of single data channels, MMF guiding only a few fiber modes were investigated as an intermediate fiber type between SMFs and large MMFs, becoming widely known as FMFs [83]. In the context of SDM, FMFs for the purpose of transmitting independent data signals on multiple modes at the same wavelength have been reported with 3–15 fiber modes. However, no consistent definition for the number of guided modes in FMFs and MMFs has been adopted in the literature. As most SDM research works have used FMFs rather than high mode-count MMFs, we refer to any MMF in the following as FMF. To transmit independent data streams over fiber modes, it is necessary to transform modes guided by multiple SMFs into mode patterns that can be guided by the FMF in mode multiplexers (MUXs). Those have largely been designed to be mode-selective and produce a one-to-one match between an input SMF and an individual fiber mode. Early MUX designs, based on free-space optics and phase plates, suffered from large loss of up to 20 dB [84]. Subsequently, various low-loss approaches including fiber-fused photonic lanterns [85], laser-inscribed 3D waveguides [86], and integrated silicon-photonic MUXs [87–90] have been reported. The scalability of mode MUXs to a large mode-count was addressed using fused-fiber photonic lanterns [91,92], while more recently the already commercially available technique of multiplane light conversion (MPLC) [93] has succeeded in producing MUXs with 45 modes [94], 210 modes [95], and 1035 modes [96]. Non-mode-selective MUXs, where linear combinations of fiber modes are excited, have also been reported based on free-space optics [97] and laser-inscribed 3D waveguides [98].

A crucial parameter determining a FMF's transmission properties is the range of propagation delays between fiber modes (differential-mode delay or differential mode-group delay, DMD or DMGD), which determines the memory length of the transmission system and subsequently the computational complexity of the system's DSP. The modal properties of a FMF strongly depend on the refractive-index profile, the two most common examples of which are shown in Fig. 6. The modes in fibers with a step-index, Fig. 6(a), group in mode groups of one or two spatial modes (each guided in two polarizations) that propagate with equal effective indices, while the effective index spacing between mode groups is unequal. Figure 6(b) shows the refractive index profile of a graded-index FMF with a parabolic index profile. The modes in such fibers form mode groups where each added mode group has one additional member. Furthermore, the effective indices of the mode groups are equidistant. An important feature of graded-index core designs is the reduced DMD by up to 2 orders of magnitude compared to step-index designs [82]. While minimizing a fiber's DMD was studied in the early days of optical fiber research for 850 nm systems [82], more recent optimizations of FMFs for SDM focused on minimizing the DMD in the low-loss 1550 nm wavelength region for fibers with various numbers of guided modes [81,99,100] and with the focus on wideband operation [101]. Hollow-core fibers, attractive for their reduced latency and high power tolerance, have also been designed to guide multiple modes [102]. Weakly coupled FMFs, optimized for operation with reduced or no requirement for multiple-input multiple-output (MIMO) DSP (Section 2.B.2), have included step-index [103–105] and elliptical core designs [106] with applications including passive optical networks. Another subcategory of FMFs is ring-core fibers [107] that have been predominantly demonstrated in the context of orbital angular momentum (OAM) mode transmission.

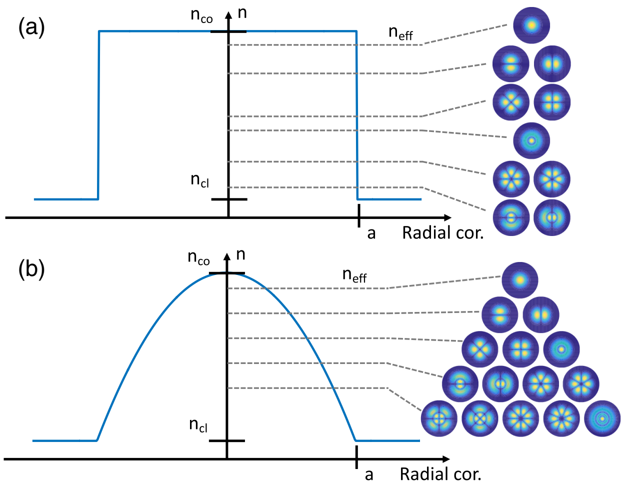

Fig. 6. Refractive index profile, effective indices and intensity patterns of (a) the first 10 modes in a step-index fiber and (b) the first 15 modes in a parabolic-index, graded-index fiber.

3. Coupled Multicore Fibers

Analogously to the mitigation strategies of polarization-mode dispersion in SMFs, strong coupling between spatial channels can beneficially reduce the spatial-mode dispersion (SMD) and, consequently, the transmission system memory length [108,109]. It can also reduce the impact of mode-dependent loss (MDL) [110,111] and Kerr-effect-based nonlinear signal distortions [112–114]. As the core pitch of a MCF reduces, the coupling level increases until a maximum coupling strength is reached. Further reducing the core pitch causes the propagating spatial channels to form super-modes and subsequently mode groups, similar to FMFs, increasing the total delay spread [115]. Intentional twisting and bending may also be used to reduce the SMD [116,117]. MCFs with intentionally enhanced coupling are referred to as randomly coupled or

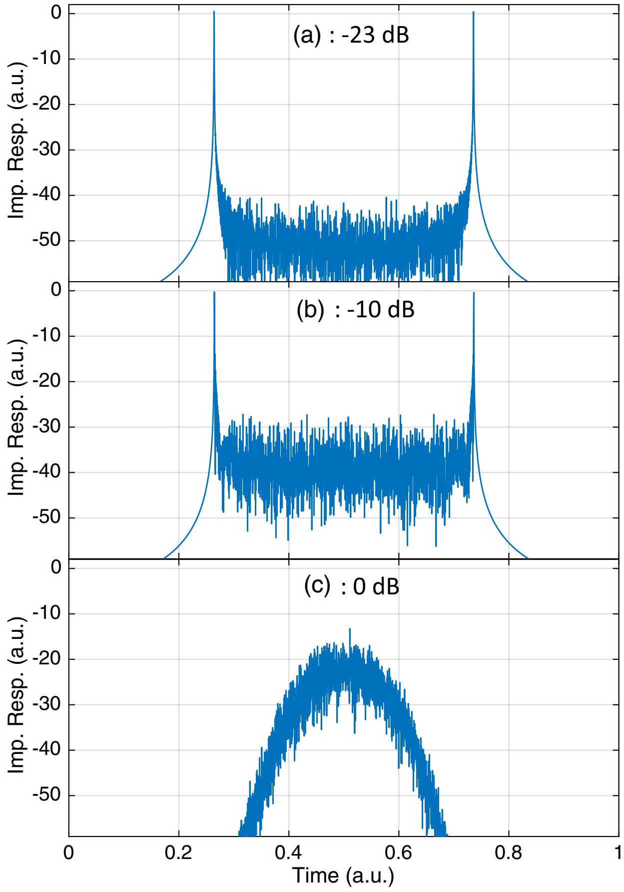

Fig. 7. Intensity impulse response for three different coupling strength levels in a two-core fiber.

coupled-core (CC-) MCFs. Figure 7 demonstrates the delay spread reduction due to strong coupling, represented by the intensity impulse response. The simplified simulation assumed two cores where signals propagate with a small delay difference and mix at varying total coupling strengths. The upper graph has low crosstalk of −23 dB, similar to two cores of a WC-MCF after long-distance propagation. The middle figure has a total crosstalk of −10 dB, as it would be reached after a few spans of the FMF. In both cases, the impulse response time spreads are equal. In contrast, the impulse response in the strongly coupled case takes a Gaussian shape, and the temporal spread is reduced. The consequence of this change in shape of the impulse response is that the total delay spread increases with the square root of the total transmission distance [108], compared to linearly in the weak coupling case. CC-MCFs with standard cladding diameters have been demonstrated with 2–12 cores [118–121], and an SMD of 1.5 $\mathrm{ps}/\sqrt{\mathrm{km}}$ has been reported in a two-core fiber cable [122], while 2.5 $\mathrm{ps}/\sqrt{\mathrm{km}}$ was reported in the first field-deployed four-core CC-MCF [19]. Spatial multiplexing for CC-MCF can be achieved with similar devices as for WC-MCF with fused-fiber multiplexers [123] being most common.

4. Few-Mode Multicore Fibers

FM-MCFs are a combination of FMF and WC-MCF technology. Multiple few-mode cores are arranged in a common cladding to achieve high spatial channel density but allowing per-core DSP with lower-order MIMO subsystems. Increasing the mode count per core in WC-MCF increases intercore coupling as higher-order fiber modes generally extend further into the cladding area [124,125]. Hence, care to reduce intercore crosstalk, through refractive index trenches or a larger core-pitch, is often taken to prevent the cladding diameter of FM-MCFs becoming too large. As with large core-count WC-MCFs (Section 2.A.1), mechanical reliability aspects such as splice loss are expected to increase with cladding diameter and place a limit on the number of spatial channels [39,58,60]. Indeed, of the FM-MCFs reported to date, all had cladding diameters larger than SMFs with the largest exceeding 300 μm. Various core and modes-per-core combinations have been reported, including a 12-core three-mode fiber [126], a seven-core six-mode fiber [127], a 19-core six-mode fiber [128], a 36-core three-mode fiber [129], a 38-core three-mode fiber [130] and a 12-core 10-mode fiber [131], being the fiber with the largest number of spatial channels yet reported, and having a moderately large cladding diameter of 217 μm. Spatial multiplexing has been demonstrated using fiber-fused photonic lanterns [132], fiber bundle type MUXs [133], and 3D waveguides [134], as well as two-stage approaches, with core- and mode-multiplexing performed separately [130,135].

B. Digital-Signal Processing for SDM

DSP is a key function of many optical transmission systems. Essential building-blocks of DSP in high-capacity, coherent SMF transmission include chromatic dispersion compensation, channel equalization, and carrier-phase recovery [136]. Standard DSP on each spatial channel is generally suitable in weakly coupled SDM fibers with consideration of interactions between spatial channels optional. In contrast, coupled SDM transmission requires an adaption of the entire DSP chain to account for interactions in the higher-dimensional signal space.

1. Joint and Shared DSP Among Weakly Coupled SDM Channels

In weakly coupled SDM systems such as WC-MCFs, signals in each core may be processed independently with standard SMF DSP chains and crosstalk considered as an additional noise source. However, if transmission impairments in different cores are sufficiently correlated, it is possible to use the information of the impairments in one core to equalize for the impairments in another core [137]. This was investigated in the case of joint-core carrier-phase estimation over multiple cores of a homogeneous WC-MCF [138] where the aim was to increase the overall quality of the carrier-phase estimation by minimizing estimation uncertainty. A resource-saving master-slave approach was also investigated where the carrier-phase estimate from one core was used to equalize signals in another core [137,139].

2. Multiple-Input/Multiple-Output DSP

In conventional SMF transmission, random coupling between polarization-multiplexed signals can be undone by applying channel equalizers with a two-by-two butterfly structure [136]. Analogously, mixing between signals in coupled spatial paths can be reversed using MIMO subsystems, first deployed in wireless communication systems [140]. MIMO subsystems usually contain equalizers often implemented as finite impulse response (FIR) filters, accounting for both the spatial coupling dimension and the temporal dimensions to include the delay spread between spatial channels. It is thus necessary to use filters with enough taps to account for the memory length of the SDM transmission link, e.g., linear delay accumulation of 10 ps/km over a 1000 km distance would require 500 half-symbol-duration spaced equalizer taps when operating at 25 GBaud. MIMO equalizers have been implemented either in the time domain for up to 15 spatial modes [141] or in the frequency domain with up to 45 spatial modes [142]. The computational complexity of MIMO equalizers typically increases with the number of coupled spatial channels and the total delay spread, while frequency domain equalizers are generally less computationally complex for long filter lengths [143,144].

Various update algorithms have been investigated for MIMO equalizers, including the least-mean squares (LMS) and the recursive least squares (RLS) algorithms [145], while advanced interference canceling schemes have also been proposed to reduce the signal distortions originating from mode-dependent loss [146,147]. It has also been shown that increasing the spatial channel count increases the rate of change of channel dynamics in both CC-MCFs [148] and FMFs [149]. MIMO DSP is mostly implemented at the receiver side but can also be implemented at the transmitter if the DSP can be updated at a rate sufficient to track the channel dynamics [150]. Real-time implementations of a 6 × 1 [151], a 4 × 4 [152], and an 8 × 8 MIMO subsystem [153] have demonstrated the practicality of higher-order MIMO at data rates compatible with current optical systems. An all-optical implementation of a 3 × 3 MIMO equalizer was demonstrated as a means to reduce power consumption [154] but has yet to include the temporal dimension. MIMO techniques have also been investigated in weakly coupled SDM transmission, where they can be used to undo crosstalk degradations that would otherwise be treated as additional noise [155]. Combining MIMO subsystems with digital back propagation (DBP) to mitigate nonlinear transmission impairments has been proposed for both strongly coupled SDM transmission, where it was shown that the DBP gain diminishes with increased coupling strength [156], and WC-MCFs to allow increased launch power [52,157].

3. Multidimensional Modulation and Coding

The multidimensional signal space of SDM systems also offers the possibility of implementing higher-dimensional coding and modulation across spatial channels [158–160]. This may be particularly interesting for systems using homogeneous WC-MCFs or coupled fibers with MIMO DSP where the temporal spread of spatial channels can be more easily managed. Experimental investigations have aimed at increasing the sensitivity and/or spectral efficiency, typically at the cost of a more complex receiver structure and have been based on multidimensional pulse positioning [161], single-parity-bit, core-coded QAM [162], high-dimensional sphere-packing algorithms [163], and lattice-coding [164], while other formats were designed to minimize nonlinear signal distortions [165] in a subset of the higher-dimensional signal space.

C. SDM Amplifiers

Optical amplifiers utilizing SDM are often envisaged as a key opportunity for both power saving and component integration that are attractive features of SDM, without necessarily needing SDM fibers for optical transmission. Indeed, a submarine system with pump sharing between single-core amplifiers of 12 fiber pairs has recently been cited as the first commercial implementation of an SDM system [20], and the power efficiency of similar systems has been analyzed [166]. In addition, erbium-doped fiber amplifier (EDFA) arrays of 60 μm cladding diameter EDF bundles [167] and multielement-fibers [21] have been reported with seven fibers, with performance in line with similar single-core EDFAs. More recently, hybrid micro-optic amplifier assemblies have been combined with a 12-core fiber for long-haul transmission with reduced pump power per path [168].

However, having the potential for the fullest integration of hardware and shared pumping, the majority of work on SDM amplification adopts SDM fibers as the gain medium and, as with transmission fibers, may be categorized depending on whether the active fiber supports multiple cores (MCs), multiple modes (MMs), or both. Of MC designs, the main distinction then becomes whether the pump light is directed into each core independently [169,170] or via a single high-power pump illuminating the cladding, typically from a low-cost, multimode laser [171–173]. In addition to a high gain, broad bandwidth, and low noise figure, properties desirable in conventional amplifiers, an ideal SDM amplifier should also offer negligible crosstalk between uncoupled channels, low cross-gain modulation between spatial channels, similar gain profiles, and similar delays between spatial channels. Further, they should allow per channel power monitoring and have favourable cost, complexity, and power consumption compared to the equivalent number of single-core amplifiers, with the primary metric for comparing power consumption being the pump conversion efficiency (PCE) [171]. In this section we focus on SDM amplifiers and related technologies with transmission demonstrations utilizing SDM amplifiers discussed further in Section 3 where Table 2 includes a list of notable transmission demonstrations utilizing SDM amplifiers.

1. MC-EDFAs

In core-pumped MC-EDFAs the pump light is typically combined in single-mode-WDM couplers before an MCF MUX [192]. Cladding-pumped schemes can input the pump light at the end of the EDF (end coupling), after combining with signal cores in a tapered fiber bundle [171] or dichroic mirror [172]. Alternatively, the pump light may be combined along a segment of the fiber with a side-coupling technique [192] where a tapered MMF is wrapped around a length of uncoated doped MCF. After pump coupling, cladding-pumped MC-EDFs typically use a double cladding structure [171,193], to contain pump light. Seven-core MC-EDFAs quickly demonstrated that control of individual pump lasers in each core can give comparable performance to single-core EDFAs [192] but without demonstrating significant hardware or power sharing. An attempt to improve sharing used free-space optics to split the pump laser power between core pairs in a 19-core C-band EDFA [59].

The cladding-to-core area ratio in MC-EDFs make competitive PCEs challenging although a study of equivalent L-band double cladding 7- and 19-core EDFs with 135 μm and 200 μm respective cladding diameters showed 2.5 dB improved pump efficiency in the larger fiber [194]. Pump efficiency is typically lower in the C-band due to the wavelength dependence of the emission and absorption cross-section [171], which leads to shorter EDF lengths and higher pump power required to achieve the same gain and NF, as observed in 19-core amplifiers [178,195]. It also becomes necessary to remove the unused pump light from the EDF after cladding pumping with the most common approach being a few centimeters of doped or passive MCF with the low-index coating removed and a system to dissipate heat [171]. Alternatively, the recycling of the pump light can be used to improve power efficiency. Pump collectors based on side-coupling to a MMF [196] were able to capture 75 percent of unused pump light in a seven-core EDFA, and 30 percent electrical power reduction was shown using cascaded collectors [197]. Alternatively, dichroic mirror based pump combiners have been used to recycle pump light, achieving 4 dB additional output power for the same pump power [198].

A further limitation of cladding pumping is the difficulty of reliable automatic-gain control often required in WDM networks. This has been addressed with the investigation of hybrid cladding + core-pumping designs. These use reduced power core pumps to provide core-by-core gain control to complement cladding pumping. Although reducing power efficiency, such amplifiers have shown good performance in a range of configurations [198,199] and similar transient response to conventional EDFAs [200]. Counter-propagating Raman pumps have also been used to add core-by-core gain optimisation in conjunction with cladding-pumping, and used in long-haul seven-core fiber transmission [201]. The issue of core-by-core gain control and spectrum equalization has been addressed in MC-EDFAs by integrating dynamic gain equalizers using LCoS [202] and spatial-light modulators [203].

2. *Coupled-Core and Few-Mode Amplifiers*

The reduced cladding diameter of FM and CC fibers may lead to less unused pump light under cladding pumping, allowing increased power efficiency. Indeed, the largest PCE to date was measured in a CC-EDFA covering the full C-band [204], albeit with a transmission distance limitation due to differential modal gain (DMG) and much lower PCE for L-band operation. Prior to that, a number of CC-EDFAs were reported. Recirculating transmission through 465 km of six-core CC-MCFA was achieved with a pair of cladding-pumped CC-EDFAs with bundled-fiber pump combiners [205], and strong coupling over both the signal and pump wavelengths in a short fiber was achieved in a four-core CC-EDFA [206]. Further, a CC-EDFA with six cores was shown to successfully amplify signals from a six-mode fiber directly spliced to the tapered six-core EDF [207], and a noise figure of 4.5 dB was measured across the C-band in a seven-core CC-EDFA [208].

Although information of the PCE of published amplifiers is rather sparse, the challenge in FM and FM-MC amplifiers is again power efficiency combined with minimizing DMG. Indeed early work proposed a technique for equalizing the modal gain [209]. FM-MC-EDFAs have the potential to amplify a large number of spatial channels with the largest to date being a seven-core six-mode L-band EDFA with separate mode and core multiplexers [210]. The L-band amplifier provided an average of 17 dB gain with less than 6 dB gain variation over spatial channels. A single-core six-mode amplifier with 5.6 dB modal gain variation across both C- and L-bands enabled transmission over 90 km and eight spans of a 19-core six-mode FM-MCF [211]. C-band coverage in a six-core, three-mode fiber was achieved using both forward and backward cladding pumping to amplify three-mode signals over 120 km in four spans [212]. This amplifier employed the concept of uniform cladding pumping previously employed in a FM-EDFA able to amplify 10–15 modes with 25 dBm output power and less than 2 dB DMG [213]. The amplifier used an intentionally oversized doped core to improve confinement of low-order mode groups and maximize the overlap with the bidirectional cladding-pumping gain. A shortened large-core EDF was also used to demonstrate under 0.5 dB DMG over 36 modes across the C-band [214].

3. SDM TRANSMISSION SYSTEMS

A. Modeling of SDM Transmission Systems

The wide parameter space makes accurate modeling of SDM transmission systems a demanding task, with each fiber and system approach posing unique modeling challenges. In this section, we outline the main achievements and outstanding challenges for SDM modeling in the key fiber types.

1. *Multicore Fiber Transmission Systems*

In WC-MCF transmission systems and particularly in coherent long-haul systems, intercore crosstalk (IC-XT) can be modeled as an additional noise source with constant power [30]. In strong contrast to this are transmission systems with carrier-supported, direct-detection modulation formats, such as OOK or PAM, where the power of IC-XT can vary substantially [30]. IC-XT models of varying levels of computational complexity have been developed to derive statistical properties of IC-XT-limited WC-MCF transmission systems, such as a system outage [215,216]. Numerical studies have further suggested that IC-XT power fluctuations in a WC-MCF with carrier-supported modulation formats require an additional OSNR margin to prevent system outage [217].

2. *Few-Mode and Multimode Fiber Transmission Systems*

Modeling the signal propagation in a MMF has been an active field in research long before applications in SDM [218]. However, combining FMFs with high channel count WDM signals requires the development of models that include more accurate estimates of the linear and nonlinear propagation effects. Of the linear propagation effects, modal coupling, propagation delay spread, and MDL are probably the most important for the system design [219]. Modal coupling decreases the total delay spread of the transmission channel, leading to a square-root dependence of the delay spread accumulation with propagation distance, while the slope of the square-root dependence relies on the coupling strength [108,109]. MDL statistics for varying numbers of coupled spatial channels were investigated [111] and the outage probability of MDL-limited systems estimated [110,220]. As with SMFs, nonlinear signal interactions can limit the capacity of FMFs. In addition to intramodal effects, such as cross-phase modulation or four-wave mixing, intermodal nonlinear signal distortions can impact the transmission performance, as different fiber modes can have a significant spatial overlap. A set of coupled Mankakov equations to describe the nonlinear signal propagation in FMFs has been developed [221], and various mode-group structures have been considered in the assessment of the total nonlinear signal distortion [221,222]. Analytical investigations of intermodal nonlinear signal distortions have been proposed [223,224]. Numerical studies have investigated the impact of various fiber or system parameters on the nonlinear signal distortions, including the number of fiber modes

Table 1. Notable Short-Reach SDM Demonstrations

Ref.	Layout	Data rate (Tb/s)	SSE (b/s/Hz/A_{SMF})	Clad. Diam. (μm)	Dist. (km)
			MCF		
[65]	4C	610	43.49	125	54
[228]	7C	109	7.57	150	16.8
[12]	12C	1010	28.08	225	52
[229]	14C	1050	36.53	216	3
[48]	19C	305	11.91	200	10.1
[13]	22C	2150	49.69	260	30
[230]	37C	1840	59.89	248	7.9
			FM-MCF		
[231]	4C3M	1200	79.61	160	3.4
[232]	7C3M	200	33.91	192	1
[135]	19C6M	10160	240.74	267	11.3
[15]	38C3M	10660	185.99	312	13
			FMF		
[233]	3M	29.6	6.73	125	50
[234]	3M	57.6	12	125	119
[235]	3M	284	29.82	125	30
[236]	6M	23	21.56	125	17
[237]	10M	115.2	28.8	125	87
[238]	10M	402.7	43.13	125	48
[141]	15M	1011	105.7	125	23
[142]	45M	101	151.5	125	27

Table 2. Notable Multispan SDM Transmission Experiments

Ref.	Layout	Data rate (Tb/s)	SSE (b/s/Hz/A_{SMF})	Clad. Diam. (μm)	Dist. (km)	SDM Amp. Type
			MCF			
[66]	4C	319.1	23.12	125	3001	–
[174]	7C	51.1	9.65	180	2520	Clad
[49]	7C	140.7	11.39	196	7326	Core
[175]	7C	110.9	9.11	196	6370	Core
[176]	12C	520	–	NA	8830	–
[177]	12C	105.1	–	NA	14350	–
[59]	19C	1.52	–	220	1200	Clad
[178]	19C	715	19.16	260	2009	Clad
[179]	32C	1001	58.06	242	205.6	–
[180]	32C	120	10.67	242	1850	Clad
			FM-MCF			
[146]	12C3M	34.56	81.66	230	2500	–
[181]	38C3M	6200	108.17	312	65	–
			FMF			
[182]	3M	0.1	–	125	1200	–
[183]	3M	33.3	9.12	125	500	Core
[184]	3M	18	9.00	125	1050	–
[185]	3M	9.9	12.00	125	3500	–
[186]	3M	159	18.28	125	1045	–
[187]	3M	2.88	23.04	125	6300	–
[188]	3M	40.2	9.03	125	3060	–
[147]	6M	2.25	18.03	125	3250	–
[189]	6M	138	34.50	125	650	–
			CC-MCF			
[118]	3CC	1.2	0.1	125	4200	–
[190]	3CC	172	19.16	125	2040	–
[191]	4CC	50.47	13.28	125	9150	–
[119]	6CC	18	1.4	125	1705	–
[120]	7CC	28	56.01	125	4400	–

[225], the strength of linear-mode coupling [226], and the impact of DMD management schemes [227].

B. SDM Transmission Demonstrations

In this section, we summarize the numerous transmission demonstrations across a range of fibers and systems that have shown the potential of SDM technologies to multiply the achievable data rates of SMFs, and we include a brief discussion of the achievements and specific challenges of each fiber type. To aid this purpose, Table 1 lists notable single-span SDM transmission demonstrations, while Table 2 focuses on recirculating or multi-span experiments for distances up to 14,000 km. In both tables, the layout column describes the number of modes (M) guided in each of (C) cores, together with the fiber's cladding diameter. Also shown is the achieved data rate, transmission distance, and spatial-spectral efficiency (SSE). SSE is defined as the spectral efficiency divided by the cladding area of the used fiber, relative to the cladding area of an SMF (A_{SMF}). Table 2 also shows the type of SDM amplifier utilized, where appropriate.

1. *Single-Mode Multicore Fiber Systems*

WC-MCF systems have the most straightforward migration path from SMF transmission systems and dominated early high data rate SDM transmission experiments, demonstrating as early as 2012 that such fibers were capable of Pb/s transmission with conventional transceiver hardware and no requirement for MIMO processing [12]. Shortly after, a seven-core fiber in connection with a core-pumped MC-EDFA enabled 140 Tb/s over oceanic distances [49]. Cladding-pumped MC-EDFAs have also been used for long-haul distances in 7 [174], 19 [178], and 32 cores [180]. The longest SDM transmission demonstration reached 14,350 km with a data rate of 105 Tb/s using a 12-core fiber with single-mode EDFAs. To date, the highest data rate achieved using WC-MCFs was 2.15 Pb/s using a 22-core fiber with a throughput per core of nearly 100 Tb/s [13]. The highest data rate per core was above 150 Tb/s, using S, C, and L transmission bands in a four-core fiber [65] with almost 80 Tb/s transmitted over 3001 km in a similar fiber [66].

2. *Few-Mode Fiber Systems*

FMF transmission supported by MIMO subsystems using all guided fiber modes to transmit independent data at the same wavelength was first demonstrated in 2011 over 10 km with a data rate of 336 Gb/s [239]. Since then, tremendous progress has been achieved in increasing the transmission distance, number of WDM channels, and fiber modes used for transmission. To date, the largest reported data rate in a FMF was 1.01 Pb/s over a 23 km 15-mode FMF [141], with the longest transmission distance being over 6000 km in three modes [187]. Raman amplification was demonstrated over 1000 km FMF transmission using bidirectional pumps in each of the LP_{11} modes to support the gain of conventional EDFAs [184] and in conjunction with three cores of a MC-EDFA and cyclic-mode permutation to reduce the temporal signal spread [240]. The largest number of modes used in a MIMO-based system was 45, where 20 WDM channels per

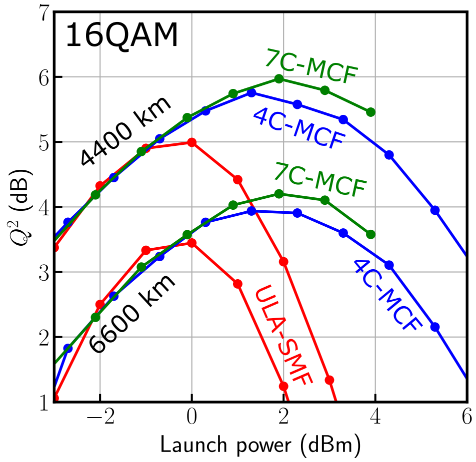

Fig. 8. Q-factor as a function of the launch power after 4400 km and 6600 km transmission in a SMF, four-core and seven-core CC-MCF where all fibers were manufactured with the same core parameters [120].

mode were transmitted over 26.5 km [142]. MIMO free transmission demonstrations in FMFs include a two-mode transmission over 150 km [241], four-mode transmission over 10 km [242], and mode-group multiplexed transmission over a 2.2 km MMF [243]. Weakly coupled 12-mode OAM transmission has been reported over a 1.2 km distance [244]. In addition to transmission demonstrations, FMF experiments have investigated novel system impairments specific to FMFs, such as intermodal nonlinear signal impairments [245] and detailed estimates of the impact of MDL on the transmission capacity [246].

3. *Coupled-Core Multicore Fiber Systems*

Tolerance to nonlinear signal distortions and a reduced temporal signal spread make CC-MCFs attractive for long-haul transmission. Seven-core CC-MCF transmission was shown to outperform both a four-core CC-MCF and SMF with matching core properties [120]. The main result of that experiment is shown in Fig. 8, for recirculating transmission up to a 6600 km distance. Similar performance between the fiber types was observed at low launch powers, but the CC-MCFs enabled greater signal quality and reach as the launch power was increased, with additional distance in the seven-core CC-MCF confirming that the nonlinear tolerance increases with the number of strongly coupled cores. Strong coupling was also shown to be maintained over a bandwidth exceeding 80 nm in a three-core CC-MCF experiment with a total data rate of 172 Tb/s at a distance of 2040 km [190]. Other notable demonstrations include a four-core CC-MCF at a distance of 9150 km at a data rate of 50.47 Tb/s [191], and in a 12-core CC-MCF, being the highest core-count CC-MCF reported to date [121].

4. *Few-Mode Multicore Fiber Systems*

To date FM-MCFs have enabled the largest number of spatial channels in a single optical fiber and the highest per-fiber data rates of more than 10 Pb/s in a 19-core, six-mode fiber [135] and later in a 38-core, three-mode fiber [15] albeit with cladding diameters of 267 μm and 312 μm, respectively. The latter fiber has also been used to demonstrate bidirectional transmission with 228 spatial channels [130] and in multispan transmission over 65 km distance [181]. The first transmission demonstration exceeding 1 Pb/s in a sub-200 μm cladding diameter fiber used a 160 μm diameter FM-MCF with 4 cores, each guiding 3 modes [231]. Most high core-count FM-MCFs have been of the order of 10 km in length, which makes recirculating transmission challenging. However, a 52.7 km span of 12-core, three-mode FM-MCF has enabled a transmission distance of 2500 km [146].

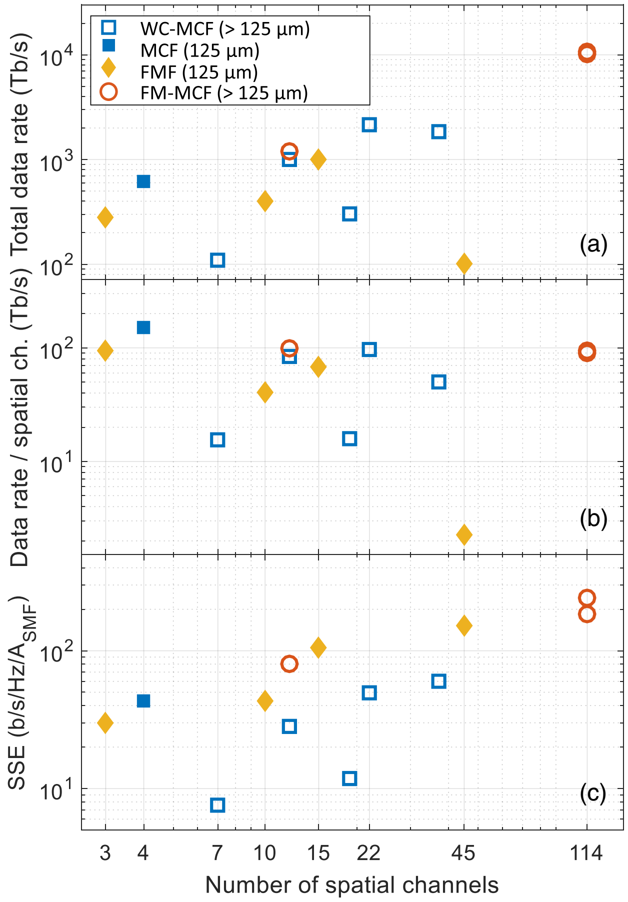

Fig. 9. Comparison of short reach, high-capacity SDM transmission experiments. References in Table 1.

C. Comparing SDM Transmission Systems

As discussed throughout this paper, SDM technologies may be focused on different application domains, and although the target of the transmission demonstrations is typically to maximize the achievable data rate and reach, the variety of fibers, systems, and approaches make comparisons challenging. In this section, we attempt to compare various SDM technologies using the published transmission demonstrations by considering standard metrics such as total data rates, number of spatial channels, and fiber geometry along with normalizing metrics such as throughput per spatial channel and the SSE.

1. *Single-Span Transmission Demonstrations*

Figure 9 compares various short-reach, high-throughput SDM transmission demonstrations. Each subplot includes the same experiments plotting a different transmission metric against the number of spatial channels. We further differentiate by marker type between fibers with a cladding diameter of a standard SMF (125 μm) and fibers with a larger cladding diameter. Figure 9(a)

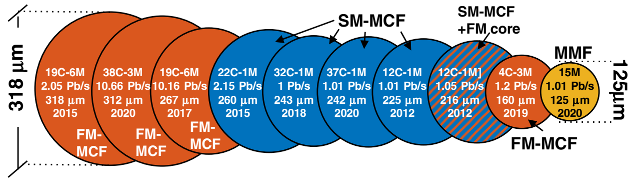

Fig. 10. Cladding diameters of fibers used in >1 Pb/s transmission experiments [12–15,141,179,229–231,247].

shows the total data rate confirming that the highest per fiber data rates have been achieved in FM-MCFs with over 10 Pb/s [15,135], compared to just over 2 Pbs [13] in WC-MCFs. Until recently, all transmission demonstration with data rates in excess of 1 Pb/s had used fibers with enlarged cladding diameter, as shown visually in Fig. 10; this also highlights a recent trend toward smaller cladding diameter fibers due to concerns over fiber fabrication, cabling, and reliability [39,58,60]. In order to compete with SMF arrays or ribbon fibers, it is important to demonstrate SDM transmission with per spatial channel data rates similar to those of SMFs. When using C- and L-bands, the maximum data rate in SMFs has been reported at approximately 100 Tb/s, while recently, adding the S-band enabled data rates approaching 200 Tb/s [17]. Figure 9(b) shows that all types of SDM technology have been demonstrated with data rates per spatial channel in the order of 100 Tb/s, suggesting linear scaling of data rates with the number of spatial channels is feasible. Not all SDM transmission experiments have used the same optical bandwidth, with many impressive demonstrations, focusing on high spectral efficiency rather than total data rate. To allow a comparison of these studies while also normalizing for fiber diameter, Fig. 9(c) shows the SSE. Figure 9(c) shows that the SSE generally increases when fibers support more spatial channels. It further emphasizes that FMF and FM-MCF generally have a higher SSE compared to WC-MCFs, which require a minimum spatial separation between cores to reduce crosstalk.

2. *Multispan Transmission Demonstrations*

Figure 11 summarizes notable medium-to-long-haul SDM transmission demonstrations. In contrast to the short-haul transmission demonstrations, Fig. 11(a) shows that all transmission demonstrations more than 1000 km with > 100 Tb/s data rate have used WC-MCFs. One factor explaining this is that the large FM-MCF fibers used in multi-Pb/s single span experiments have mostly been fabricated in shorter lengths, not conducive to recirculating transmission loops. Furthermore, WC-MCFs are not impacted by MDL that can limit the transmission distance of coupled SDM fibers. We note that MDL is not an inherent property of all coupled SDM fibers, and in laboratory experiments research-prototype devices also contribute significantly to MDL, giving hope that improved component engineering may enable coupled SDM solutions in line with WC-MCFs.

Figure 11(b) shows that FMF and CC-MCF transmission has demonstrated a high data rate per spatial channel over 1–2000 km with the highest data rates at longer distances being WC-MCFs. 11(c) again highlights the high SSE in coupled fibers with FM-MCFs having the highest SSE for more than 1000 km class transmission. CC-MCFs have demonstrated high SSE over transoceanic distances, and it is likely that high data rate transmission could also be achieved by adopting a wider optical bandwidth.

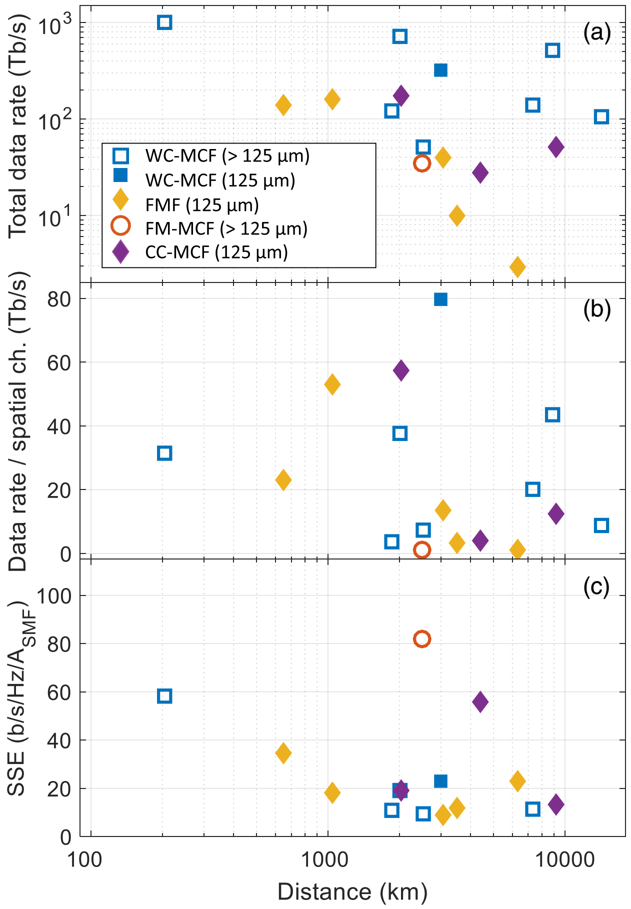

Fig. 11. Comparison of high-capacity medium/long-haul SDM transmission experiments. References in Table 2.

D. SDM Networking Demonstrations

The introduction of the spatial dimension allows for novel approaches for high-capacity optical networking [248,249], while providing the significant challenge of how to maintain the flexibility of current WDM networks without multiplying switching resources [250–252]. So far, combined switching in the spatial and wavelength dimensions has been difficult to achieve with single devices. Instead, combinations of spatial and wavelength switches have been proposed, introducing some form of switching restriction in either the space or frequency domain [253]. Spatial super channels [137] group the data for a given tributary within the same frequency band distributed across all spatial channels. Hence, traffic can be directed at SDM-ROADMs by jointly switching wavelength regions common to all spatial channels, as demonstrated using customized wavelength selective switches (WSS) [254,255]. The use of spatial super channels is particularly attractive for coupled spatial channel fibers as it avoids the need for spatial demultiplexing at network nodes. Alternatively, in spectral super channels [251] and in particular with full spectral switching [256], each tributary is assigned a spatial channel with ROADMs exclusively performing spatial switching, giving the advantage of using only spatial switches with substantially less loss than WSSs. This approach has been recently shown to allow low-loss ROADMs for long-distance transmission [257] as well as very high-capacity network nodes [258]. The former included the demonstration of core-selective switches, which are analogous to WSS for spatial switching and allow for the design of SDM-ROADMs using the same principles as those of conventional ROADMs. Nevertheless, the use of full spectral switching relies on the capability to optically demultiplex the transmitted spatial channels. As such it favors the use of WC-MCFs or fiber bundles.

4. OUTLOOK

In the preceding sections, we have described the most significant technologies and research achievements in the realm of SDM proposed for next-generation optical communications infrastructure. These include new optical fibers and associated devices, manufacturing techniques, transmission technology, and networking architectures. These developments have shown the potential of SDM systems to multiply the transmission capacity of conventional optical fiber systems by up to 2 orders of magnitude with single-mode MCFs in particular allowing per-spatial channel data rates matching those of SMFs. Nonetheless, the research effort is expected to continue at pace in years to come. Multi-core fibers and system still offer the simplest migration path from current systems but the research focus may swing further towards coupled SDM fibers and systems, where potential for disruption to conventional optical communications paradigms is greatest. Perhaps, this also occurs with a shift to more practical implementation and integration, such as recent demonstrations of high data rate transmission over coupled four-core MCF using real-time MIMO DSP [153] and on-chip mode-division multiplexing [259]. SDM amplifiers are also likely to be targets of deeper research with power efficiency and integration potential key to demonstrating advantages over conventional EDFAs. Finally, we would expect further research effort focused on hardware, such as switching, monitoring, and architectures to exploit SDM at the network level.

Commercial SDM deployments to date include the first submarine fiber cable with shared amplification of SMF bundles [20] and an upgrade solution for MMF cables [18]. In addition, a research test bed has shown cabled deployment of MCFs [19], a collaboration between four fiber vendors in Japan [51] has shown interoperability of a four-core MCF system, and ITU-T standardization efforts have begun [260]. However, whether this progress results in widespread commercial adoption of SDM systems is yet to be determined. Economic factors such as the high capital expenditure of new fiber rollouts and the undetermined manufacturing costs of SDM fibers are likely considerations. It can further be argued that no single SDM application is overwhelmingly superior over existing systems to justify the risk of investing in immature technology. Despite this, high-density SMF cables with several thousand fibers are currently being deployed, and the growth in capacity demand is still accelerating [6]. Hence, it seems likely that substantially higher-capacity network infrastructure will be unavoidable at some point, and SDM solutions may enter the market for space-efficiency reasons alone. The vast range of potential SDM solutions and optical communication systems in use globally, including greenfield applications such as data centers, suggest that it is only a question of when some of the technologies described here find their niche.

In addition to SDM research for optical data transmission, there exists a variety of cross-pollinating research utilizing SDM technologies with a strong interest in the development of new fibers and devices. Within the communications field, MCFs have been proposed for use in optical beam-forming for 5 G fronthaul networks [261] and microwave signal processing [262]. Further, they have found numerous uses in optical astronomy [263] and high-power fiber lasers [264]. A range of SDM fibers and spatial multiplexers have been utilized in quantum information processing [265], and MCFs have found uses both in the generation of entangled states [266] and in demonstrating the potential for coexistence of classical signals and quantum-key-distribution (QKD) signals in the same fiber [267]. FMFs and MMFs have been widely used in many imaging [268,269], spectroscopy [270], and beam shaping [271] research efforts, as well as being a component of holographic optical tweezers with numerous biomedical applications [272].

In conclusion, while SDM communications research continues worldwide, the focus is perhaps shifting away from escalating hero experiments of previous years to smaller, more practical fibers with the concern over the mechanical reliability and an eye toward standardization. Meanwhile, research on integration, coupled systems, amplifiers, and networks is expected to continue improving the outlook for SDM adoption. At the same time, SDM technologies have found their way into a range of optical fields with numerous, disparate potential applications.

Disclosures. The authors declare no conflict of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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