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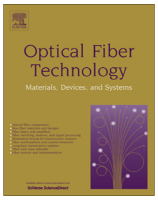

High-capacity dense space division multiplexing transmission

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ABSTRACT

In this paper, we review space division multiplexing (SDM) transmission experimental demonstrations and associated technologies. In past years, SDM achieved high capacity transmission through increased spatial multiplicity, and long-haul transmission through improved transmission performance. More recently, dense SDM (DSDM) with a large spatial multiplicity exceeding 30 was demonstrated with multicore technology. Various types of multicore and multimode SDM fibers, amplification, and spatial multi/demultiplexers have helped achieve high-capacity DSDM transmission.

1. Introduction

The transmission capacity in commercial optical fiber communication systems has been increasing at an annual rate of 140%, and the trend is likely to continue because of the expected demand triggered by the introduction of new data communications and high definition video services. The capacity per fiber demonstrated in research and the system capacity per fiber deployed in commercial transport systems are shown in Fig. 1. The maximum transmissible capacity through a single-mode fiber (SMF) has increased approximately 1000, 100, and 10 times through the use of various multiplexing technologies, namely time division multiplexing (TDM), wavelength division multiplexing (WDM), and digital coherent technologies.

As a result of 30 years of systems research, the experimental capacity has reached more than a hundred terabits per second [1,2]. This is considered to be almost the capacity for an SMF because of the maximum input power and the nonlinear Shannon limits [3]. The transmission capacity of commercial transport systems has also continued to increase, and is introduced about 5–10 years after the corresponding research. If the current growth rate is to continue, the commercial capacity may reach its upper limit within the next decade. To meet the demand for higher capacity, new multiplexing technologies are needed that can offer an additional multiplicity of around ten to a hundred times and full compatibility with current TDM, WDM, and digital coherent transmission technologies.

The use of space division multiplexing (SDM) with multicore fiber (MCF) or multimode fiber (MMF) has been proposed as the potential next generation multiplexing technology for optical fiber communications [4]. Over a period of a few years, many transmission studies have been presented that use a variety of SDM fibers possessing multiple cores or supporting multiple modes. Studies on SDM have accelerated and have realized high capacity transmission exceeding petabit/s [5–8], and a high capacity distance product of over 1 Exabit/s × km [9,10]. Moreover, as a further advancement in spatial multiplexing technology, we have presented dense space division multiplexing (DSDM) [11] with more than 30 spatial channels [11–16]. Recent progress in DSDM transmission systems using multicore and multimode fiber have been reviewed in [17].

In this paper, we expand and update recent studies of high capacity and dense SDM transmission over multicore and/or multimode SDM fibers [17]. Section 2 introduces the progress made on SDM research from the early studies to the current high capacity and dense SDM transmission. Section 3 describes spatial multiplexing technologies in optical fibers, as well as other functional elements in an SDM system. Section 4 presents an overview of SDM transmission experiments and Section 5 concludes the paper with a brief summary.

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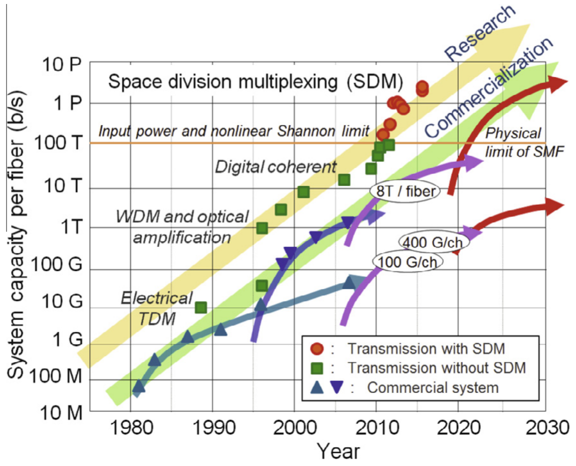

Fig. 1. System capacity per fiber in optical communication systems.

2. High capacity and dense SDM transmission

In this section, we review SDM transmission studies over the past five years, from the early stages in around 2011 to the present high capacity dense SDM transmission.

2.1. Beginning of SDM studies

SDM transmission experiments started with a small number of cores or modes in SDM fibers. Fig. 2 shows the spatial multiplicity in SDM-WDM transmission experiments. Since around 2011, various types of SDM fibers and spatial multi/demultiplexers (MUX/DEMUXs) have been proposed and tested experimentally.

Uncoupled seven-core [18,19] and coupled three-core [20] transmission experiments were performed using free-space optics or fiber bundle fan-in/fan-out (FI/FO) spatial multi/demultiplexing devices. Capacity exceeding 100 Tb/s was demonstrated in seven-core WDM-SDM experiments using polarization division multiplexed (PDM) quadrature phase shift keying (QPSK) modulation with several hundred wavelength channels [18,19]. Long-distance WDM-SDM transmission experiments were also conducted over uncoupled and coupled MCFs.

In early multimode transmissions, few-mode fiber (FMF) was used, which restricts the modes transmissible in a fiber to several low-order modes. Depressed cladding FMF, and then graded index (GI) FMF were used along with differential mode delay (DMD) management, which combines multiple FMFs with opposite DMD characteristics. Phase plate-based mode converters were commonly used for mode multi/demultiplexing, while there are currently various low-loss mode MUX/DEMUXs. Most of the few-mode experiments transmitted a single wavelength or few wavelength channels over a single span of FMF, or multiple FMF spans assisted with conventional single-mode amplifiers [21] or Raman amplification technology [22]. The fundamental multicore and multimode transmission studies undertaken at this stage eventually led to high-capacity and long distance transmission experiments.

2.2. High-capacity transmission in SDM fibers

High-capacity transmission experiments over SDM fibers were realized accompanied by an increase in spatial multiplicity. Fig. 3 shows the capacity and distance of SDM-WDM transmission experiments. A high-capacity 305-Tb/s transmission was realized with a 10.1-km 19-core MCF [23]. We then demonstrated the first petabit/s transmission utilizing a spatial multiplicity of 12 in a low crosstalk 12-core fiber, DWDM with over two hundred wavelength channels, and high spectral efficiency (SE) PDM 32 quadrature amplitude modulation (QAM), yielding a transmission capacity of 1.01 Pb/s [5]. Another transmission was reported with 1.05 Pb/s capacity over a 3-km hybrid MCF containing 12 single-mode cores and two 3-mode cores [6]. These experiments remained the highest capacity per fiber for several years. With a further increase in the number of cores to 22, the capacity was increased to 2.15 Pb/s over 31 km of 22-core MCF [8]. The capacity per core in a multimode transmission also increased from the previous maximum of 57.6 Tb/s over a 119 km span of 3-mode FMF [24] to the current 115.2 Tb/s using 10-mode multiplexing over an 87 km span of MMF [25].

2.3. Long-haul transmission over SDM fibers

The extension of the transmission distance was made possible by improvements in the SDM fiber design and fabrication technique, the development of SDM amplifiers and low-loss spatial MUX/DEMUXs, and the technique for mitigating transmission impairments including crosstalk, DMD, and mode dependent loss (MDL) [26]. A transmission distance of over 100 km was realized by connecting multiple SDM fiber spools or by constructing parallel single-mode or multimode recirculating loop systems. A number of multicore and/or multimode erbium-doped fiber amplifiers (EDFAs) are now available and are being used more extensively in SDM transmission experiments [27–30]. Raman amplification can also be used with SDM fibers or can be jointly used in combination with multimode and/or multicore EDFAs [31].

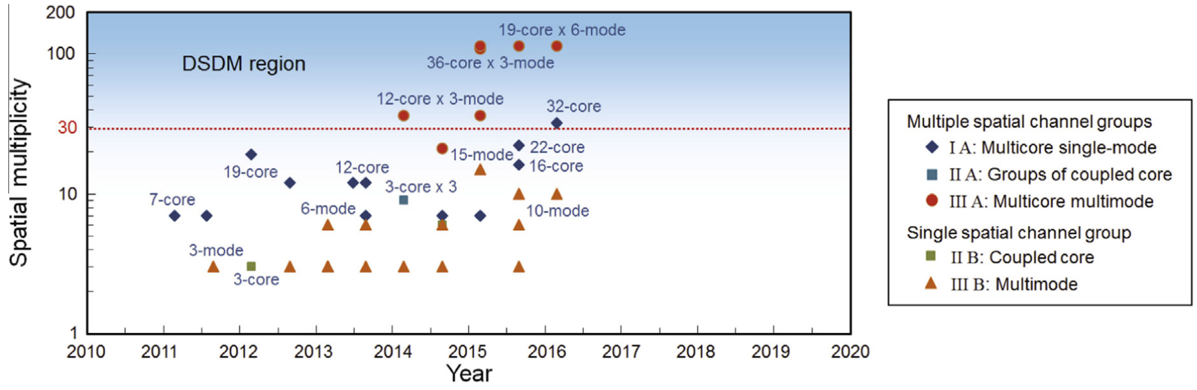

Fig. 2. Spatial multiplicity in SDM-WDM transmission experiments.

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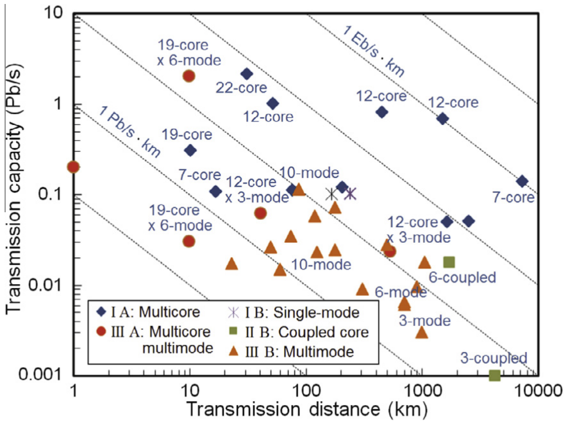

Fig. 3. Capacity and distance over SDM fibers.

Transmission in an uncoupled single-mode MCF is equivalent to parallel single mode transmission as long as the inter-core crosstalk is maintained at a low value. Thus, the requirements for MCF are a low inter-core crosstalk, fiber characteristics equivalent to those of a conventional SMF, and a design that offers the efficient use of the fiber cross-sectional area. A long-distance 7326 km transmission over 7-core MCF [9], and a 1500 km bidirectional transmission over 12-core MCF [10] were demonstrated with capacity distance products of 1.031 and 1.032 Eb/s × km, respectively.

With transmission over an MMF, MDL is a major impairment that limits the maximum transmission reach [32,33]. DMD reduction is also important since the complexity of multiple-input and multiple-output (MIMO) digital signal processing increases with DMD, which increases linearly with distance in a weakly coupling regime. A long-distance 3-mode transmission of 16-WDM PDM-QPSK signals over 1000 km was reported using a low DMD 3-mode GI-FMF and a 3-mode EDFA in a multimode recirculating loop system [34]. More recently, a 1050 km transmission was demonstrated over Raman-amplified three-mode fiber [35]. With six and ten modes, WDM PDM-QPSK signals were transmitted over 708 and 125 km, respectively [36,25]. A strongly coupled transmission [37] is known to alleviate the impairments caused by DMD and MDL because of the averaging effect of the characteristics between multiple spatial channels, and thus increase the distance compared with a weakly coupled transmission. A coupled-core MCF was used to demonstrate a 4200 km transmission of 5-WDM PDM-QPSK signals over 3-coupled core MCF [20] and a 1705 km transmission of 30-WDM PDM-QPSK signals over 6-coupled core MCF [38]. Uniform characteristics for the coupled cores, and the MIMO digital signal processing performance are important for realizing this type of transmission.

2.4. Dense space division multiplexing (DSDM) transmission

To achieve a further increase in capacity, we realized the first dense SDM transmission with a spatial multiplexing of more than 30 spatial channels in a fiber [11]. 12.5-GHz 20-DWDM PDM-32QAM signals with a high aggregate SE of 247.9 b/s/Hz were transmitted over 40.4 km of 12-core × 3-mode multicore few-mode fiber (MC-FMF). Several studies followed with the goal of increasing multiplicity, which included 5.5 km 36-core × 3-mode fiber [12], 19-core × 6-mode 9.8 km transmission experiments [14], and 8.85 km 19-core × 6-mode fiber with a reliable cladding diameter of less than 250 μm [15]. Furthermore, using low MDL and low DMD transmission line, and in combination with an MDL and DMD mitigation technique achieved by optical and digital signal processing, we have shown the first multicore multimode recirculating loop experiment transmitting 20-DWDM 36-DSDM PDM-QPSK signals over 527 km [13]. More recently, we reported a DSDM transmission using uncoupled multicore fibers with 30 and 31 cores [39–41].

Assuming the application of SDM to terrestrial networks, the ability to realize a long-haul transmission of over 1000 km is required in DSDM. In the latest study, we have targeted a reach of over 1000 km with a spatial multiplicity exceeding 30, and succeeded in the first long-haul DSDM transmission of 32-core PDM-16QAM signals over 1644.8 km [16]. The result was achieved using a crosstalk-managed transmission line consisting of a 51.4-km heterogeneous 32-core MCF with a low loss of 14.1 dB/span and a low crosstalk of <−34.5 dB/span including FI/FO devices, and a novel partial recirculating loop system suitable for evaluating the long-distance transmission characteristics of MCFs. Further advances in DSDM studies are expected to realize ultra-high-capacity and long-haul transmission systems.

3. Space division multiplexing technologies

3.1. Spatial multiplexing in optical fibers

We have previously defined an SDM transmission matrix, which classifies the type of light transmission in SDM fibers [17]. Fig. 4 shows a cross-section of the SDM fibers used in each category of the matrix consisting of (IA) multicore single-mode, (IIA) groups of coupled-core and (IIIA) multicore multimode elements, which are the parallel forms of (IB) single-mode, (IIB) coupled-core, and (IIIB) multimode transmission. Here, n designates the number of spatial channel groups, and m shows the number of spatial channels in each spatial channel group.

For transmission in category B, n is equal to 1, since all the spatial channels are handled as a single group. Transmission in category A consists of multiple spatial channel groups, and $n \geqslant 2$. Typically, uncoupled n-core single-mode MCF, n groups of m-coupled core MCF [42], and n-core × m-mode MC-FMF [43] are used in category IA, IIA, and IIIA transmissions, respectively, and m-coupled core MCF and m-mode MMF are used in category IIB and IIIB transmissions, respectively.

Fig. 5 shows the spatial multiplicity versus cladding cross-sectional area of various SDM fibers. The tilted dotted line shows spatial multiplicity per cladding area, which we have already defined as spatial efficiency (η_{spatial} = spatial multiplicity/cladding area) [17]. Plots on the same dotted line are equivalent regarding the usage of space in a fiber. In reliability terms, the cladding diameter should be within 125–250 μm. SDM has attempted to raise spatial efficiency by utilizing core and mode multiplexing. The multicore multimode approach is most effective in enhancing spatial efficiency, while the multimode approach requires more advanced transmission technology than the single-mode approach to utilize this space efficiency, and achieve high-capacity long-distance transmission. The multicore single-mode approach has moderate efficiency in terms of spatial usage. On the other hand, it has the advantage of high spectral efficiency values comparable to that of a conventional SMF, and thus has successfully demonstrated high-capacity and long-haul SDM-WDM transmissions.

For single-mode transmission (I), m is equal to 1 with each core containing a single spatial channel. The transmission medium can be bundled SMF [44] or uncoupled MCF. For coupled-core (II) and multimode (III) transmissions, each spatial channel group contains multiple spatial channels within the group, and $m \geqslant 2$. The m spatial channels in each spatial channel group mix during transmission, and $2m \times 2m$ MIMO can be used at the receiver to separate the coupled signals and also dual polarizations. On the other hand,

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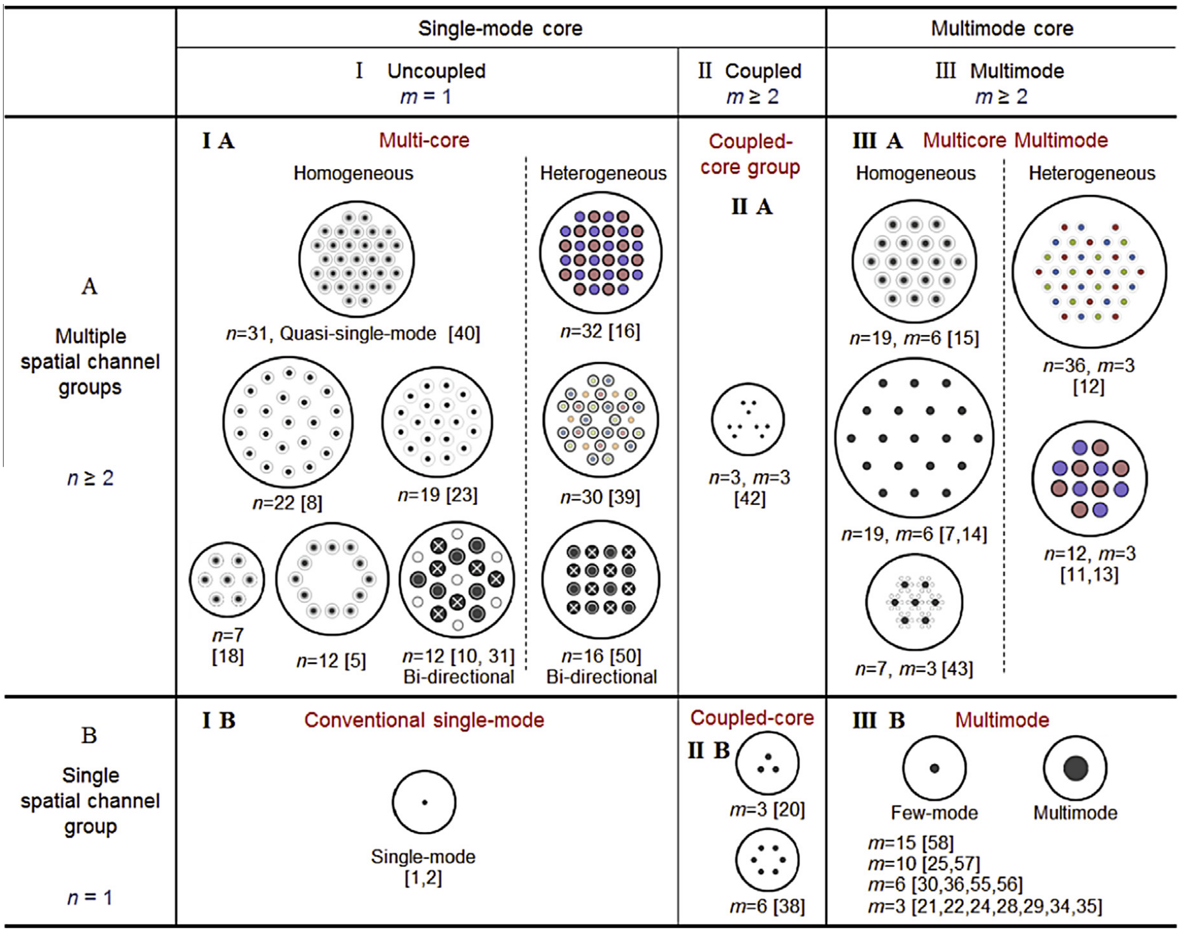

Fig. 4. Cross-section of SDM fibers used in transmission experiments organized in SDM transmission matrix [17]. Categories include (IB) single-mode, (IIB) coupled-core, and (IIIB) multimode for transmission in a single spatial channel group, and (IA) multicore single-mode, (IIA) groups of coupled-core and (IIIA) multicore multimode for transmission in a multiple spatial channel group, which are the parallel forms of (IB), (IIB), and (IIIB), respectively. *n* designates the number of spatial channel groups, and *m* shows the number of spatial channels in each spatial channel group.

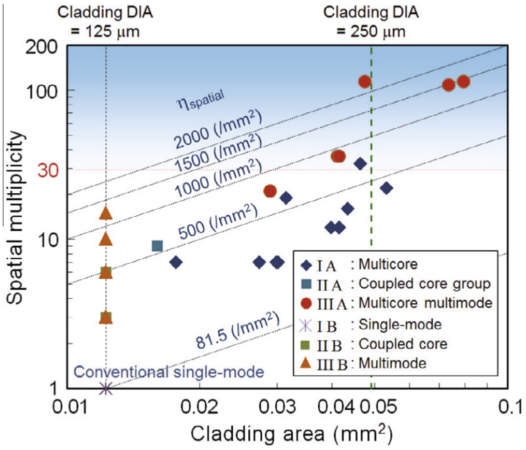

Fig. 5. Spatial multiplicity versus cladding area. The tilted line shows spatial efficiency $\eta_{spatial}$ defined as spatial multiplicity per cladding area. $\eta_{spatial} = 81.5$ for a conventional SMF.

the *n* spatial channel groups must be handled individually in an optical network. Therefore, it is important to develop MCF technology that can reduce the crosstalk from different spatial channel groups.

For the uncoupled multicore single-mode and multicore multimode fibers used in category IA and IIIA transmissions, respectively, a trench structure around a core is typically employed to reduce the crosstalk from adjacent cores [45]. Alternatively, air holes around cores can be used [43]. Additionally, inter-core crosstalk can be reduced by certain types of core arrangements. One arrangement involves reducing the number of adjacent cores, as is the case with one-ring structured 12-core MCF [46]. The maximum number of adjacent cores in a hexagonal structure MCF is six, while it is reduced to two with a one-ring structure. Another MCF design employs non-uniform core spacing. A 4–5 dB reduction in the inter-core crosstalk was obtained with a 19-core fiber by off-setting the cores from the hexagonal symmetry [47].

Heterogeneous MCF is another useful technique, where the fiber has several types of cores with different refractive index profiles [48–51]. Because of the difference between the propagation constants of different index types, signals from different core types interfere destructively, and have negligible effect as inter-core crosstalk. By using two [11,13,16,49–51], three [12], and four [39] types of refractive index designs, and by allocating the cores to minimize the number of adjacent cores with the same refractive index type, inter-core crosstalk can be reduced even with a dense core arrangement. With the same core distance of around 29 µm, the signals in a homogeneous 3-core fiber were coupled [20], whereas the signals in a heterogeneous 32-core fiber were uncoupled over a long distance [16]. Heterogeneous MCFs have

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demonstrated their effectiveness in multicore single-mode, and multicore multimode long-distance transmission experiments [16,13]. Propagation direction interleaving (PDI) has a similar effect to heterogeneous MCF with two types of cores in that it reduces the number of adjacent cores propagating in the same direction [52]. The combined use of the heterogeneous MCF and the PDI may further reduce inter-core crosstalk.

For MMFs used in a category IIIB transmission, reducing the DMD was one of the major research interests in early three-mode transmission research. Depressed cladding FMF was initially used, and it was then combined with GI-type FMF [22]. Most of the current transmission experiments use a GI-FMF as the standard transmission medium. Fiber development efforts have led to FMF with a low DMD. A three-mode fiber with a low DMD of <25 ps/km [53] at 1550 nm and a six-mode fiber with a low DMD of <85 ps/km [53] at 1550 nm and <70 ps/km over the C + L band [54] have been reported. Even with low DMD fiber, DMD accumulates over long distances. GI-FMFs with opposite signs were combined to reduce the total DMD in a transmission line and transmit mode division multiplexed signals over long distances. MDL is another impairment that arises, and is a factor limiting the transmission reach in the latest multimode transmissions. The typical MDL in three-mode fiber is <0.01 dB/km [49]. Corresponding to the advances made on few-mode/multimode fibers and mode MUX/DEMUXs, the multiplicity has risen from the early level of three modes to six [30,36,55,56], ten [25,57], and 15 modes [58]. This increase has greatly improved spatial efficiency.

3.2. Spatial multiplexing of amplifiers

There are important functional elements other than optical fibers that are essential for realizing SDM transmission systems. One such element is an SDM amplifier to compensate for the signal intensity lost during transmission.

We can use M or N conventional single-mode EDFAs in an SDM fiber transmission system, where M and N are the numbers of modes and cores, respectively. For example, three- and six-mode/coupled-core transmissions use three and six single-mode EDFAs in combination with three- and six-channel spatial multiplexers, respectively. A more favorable approach involves using multicore and/or multimode EDFAs that can simultaneously amplify multiple spatial channels in transmission lines. This approach is useful in terms of reducing the required space, power consumption, and the number of optical components. Core and cladding pumped EDFAs have been reported based on multicore and multimode fibers. A core pumping EDFA for multicore fiber has the advantage that the gain in each core can be controlled individually. On the other hand, an EDFA based on cladding pumping has the possibility of offering a lower power consumption and requires less space. Various EDFAs are becoming readily available, and so more transmission studies are employing SDM EDFAs in experiments. Three-mode [59,60], six-mode [61], ten-mode [62], six-core cladding pump [63], seven-core cladding pump [64], 12-core cladding pump [65], 19-core pump [47], and six-core × three-mode [66] EDFAs have been reported. In a transmission line employing an SDM-EDFA, uniform power among wavelength and spatial channels, that is, the gain flattening of the wavelength channels and a reduction of the core and mode dependent gains are required, and remains a topic for further study. Table 1 shows example characteristics of SDM EDFAs, including gain, mode dependent gain (MDG), and noise figure (NF).

Another way of increasing the intensity of optical signals carried through SDM fibers is Raman amplification, which provides gain with a low noise figure. Long-distance transmission experiments using Raman amplification have been reported including a three-mode 1050 km transmission [35], and a 1500 km transmission over 12-core MCF [10].

A multicore fiber remote optical pump amplifier (MCF-ROPA) provides another method of amplification in SDM. An MC-EDF is directly fusion spliced between MCFs, and amplified by forward and/or backward pumping. Since it does not require active elements in the transmission line, it is one of the most practical applications of SDM technology. A 120.7-Tb/s unrepeatered transmission was demonstrated using MCF-ROPA over 204 km of seven-core fiber [67].

3.3. Spatial multi/demultiplexing devices

Spatial multi/demultiplexing devices for multicore fiber, namely, FI/FO devices, are realized by using tapered fibers, laser-inscribed three-dimensional (3-D) waveguides, free-space optics, grating coupler arrays, planar lightwave circuits (PLC), and by bundling single-mode optical fibers.

Spatial MUX/DEMUX for multimode fiber, in other words mode MUX/DEMUX, can be classified into four types based on its operating principle. They are mode-MUX/DEMUX based on (1) LP mode converters and combiners, (2) index matching asymmetric mode couplers, (3) simultaneous mode conversion by reflective phase plate or grating couplers, and (4) spot-based mode couplers with arrayed cores [17]. Up to six-mode MUX/DEMUX can be realized by all four types. Multi/demultiplexing of higher order modes are reported with photonic lantern MUX/DEMUXs based on the fourth type and are used in 10- and 15-mode transmission experiments. Table 2 shows example characteristics of the mode selective mode MUX/DEMUX based on types (1) to (3) using phase plates [12,15], silica PLC [11], micro-structured optical fibers [68], and reflective phase plate [14,69].

3.4. Other technologies for SDM transmission

There are other technologies that are essential for constructing SDM transmission lines. Such technologies include optical devices to compensate for MDL [70] and DMD [71] in transmission lines, SDM optical interconnection, and the spatial multiplexing of optical devices, namely device integration. A measurement technique and equipment for SDM will also be useful for enhancing SDM systems.

MIMO signal processing is essential for unscrambling spatial channel coupling in multicore and multimode transmission lines. Weakly coupled MDM transmission employing mode MUX/DEMUX with high mode selectivity and weakly coupling FMF is known to be effective in reducing MIMO complexity at the receiver side [72]. MDM using orbital angular momentum (OAM) modes are also studied as possible means for reduction of MIMO processing complexity in short reach application, but require specially designed fibers [73]. Advanced MIMO digital signal processing (DSP) [74] has been developed for low-complexity DMD compensation [75] and MDL-tolerant transmission [76].

4. SDM transmission technologies

One of the most important issues as regards realizing long-haul transmission with multicore technology in category A is the suppression of inter-core or inter-group crosstalk. Fig. 6 plots the crosstalk after a 1000-km transmission versus spatial efficiency. The 1000-km crosstalk values were estimated from the crosstalk measured in the references, and spatial efficiency [17] is defined as spatial multiplicity divided by core cross-sectional area as mentioned earlier. The open squares and open circles show plots of the crosstalk of multicore single-mode fiber and multicore multimode

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Table 1
Example characteristics of SDM EDFAs.

Refs.	*n*	*m*	EDF type	Gain (dB)	MDG (dB)	NF (dB)
[59]	1	3	Ring profile doping	20	<5	n/a
[60]	1	3	Ring-core EDF	>22.7	<1.8	<5
[61]	1	6	Cladding-pumped FM-EDF	>20	3	<7
[62]	1	10	Cladding-pumped MM-EDF	20	<2	<6
[63]	6	1	Cladding-pumped	>16	–	<6
[64]	7	1	Cladding-pumped	>23	–	<4
[65]	12	1	Cladding-pumped	>11	–	<7.8
[47]	19	1	Core-pumped	>19.6	–	<7
[66]	6	3	Cladding-pumped	>20	<3	<9

Table 2
Example characteristics of mode MUX/DEMUXs.

Type	Refs.	*m*	Material	Loss (dB)	MDL (dB)	Crosstalk (dB)
1	[12]	3	Phase plate	<8.6	<5.1	n/a
	[15]	6		n/a	n/a	n/a
2	[11]	3	Silica PLC	<5.0	<2.5	n/a
	[68]	6	Fibers	n/a	n/a	n/a
3	[14]	6	Reflective phase plate	n/a	n/a	n/a
	[69]	10		<5.5	<1.6	<−16

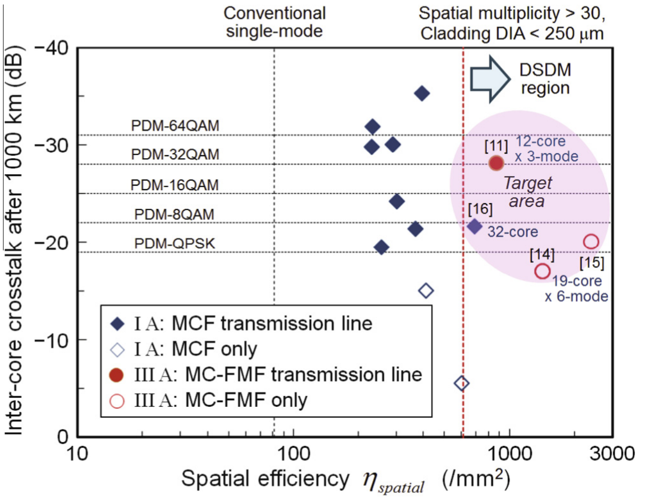

Fig. 6. Spatial efficiency and inter-core crosstalk. The 1000-km inter-core crosstalk (vertical axis) values were estimated from the crosstalk measured in the references, and spatial efficiency (horizontal axis) is defined as spatial multiplicity divided by core cross-sectional area. The plots show crosstalk of multicore transmission lines including FI/FO devices (closed plots) and multicore fibers (open plots), respectively.

fiber, respectively. The closed squares and closed circles show plots of the total crosstalk in multicore single-mode and multicore multimode transmission lines, respectively, and include the crosstalk in the FI/FO devices. The vertical dotted line at 81.5/mm^2 shows the spatial efficiency of a conventional single-mode fiber with 125 μm cladding diameter, and the vertical red dotted line shows the spatial efficiency when the spatial multiplicity is 30 and the cladding diameter is 250 μm. The horizontal dotted lines also shown in the figure are the crosstalk required for transmission with various modulation formats assuming a 0.5-dB Q-penalty. To transmit dense SDM signals with a spatial multiplicity of over 30 and high spatial efficiency signals over uncoupled MCF over a long distance, an inter-core crosstalk of less than −20 to −30 dB, depending on the modulation format, is required for 1000 km. We can thus draw a target area for DSDM long-haul transmission as shown in Fig. 6.

As we increase the spatial efficiency, the crosstalk generally degrades for multicore single-mode transmission, category IA, since the core arrangement in the cladding area becomes denser. By using a multicore multi-mode approach, namely category IIIA, we can relax the inter-core crosstalk, and realize low crosstalk even with a large spatial efficiency because the spatial multiplicity can be increased with fewer numbers of cores than for a multicore single-mode transmission. Therefore, the main issues in relation to multicore multi-mode transmission are reducing the MDL and DMD, which are major impairments that limit transmission reach, and not the inter-core crosstalk. Meanwhile, with the multicore single-mode approach, category IA, the main issue is reducing the inter-core crosstalk. Such a target can be met by overcoming the tradeoff between a low crosstalk, a high core count of over 30, and a large effective area in each core, within the limited cladding area of a fiber. We have recently realized a 32-core DSDM transmission line with a low inter-core crosstalk of <−34.5 dB per 51.4-km including FI/FO devices even with a large spatial multiplicity of 32, and a large effective area, in a cladding diameter of 243 μm [51], and thus attained the target area with category IA transmission. Using the DSDM transmission line, we demonstrated the first long-haul DSDM transmission exceeding 1000 km by transmitting 12.5 GHz-spaced 20-DWDM, PDM-16QAM signals over 1644.8 km in our novel partial recirculating loop system [16].

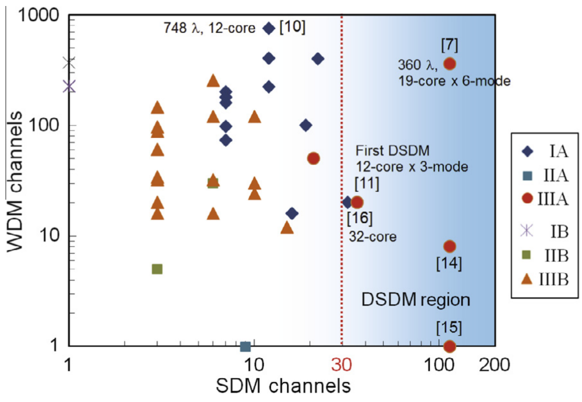

Fig. 7. Number of spatial and wavelength channels transmitted over SDM fibers.

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Fig. 7 plots the number of spatial and wavelength channels transmitted over SDM fibers. With an uncoupled multicore transmission, namely category IA, the largest number of wavelengths of up to 748 was transmitted in 12 parallel cores using the full C- through extended L-band with dense wavelength channel allocation [10]. The maximum number of spatial channels increased and was recently raised to 32 cores [16]. With multicore multimode transmission, category IIIA, we demonstrated the first transmission in this category by transmitting 36 DSDM spatial channels over 12-core × 3-mode 40.4 km MC-FMF, in which the number of spatial channels exceeded the number of wavelengths [11]. Recently, transmissions with a larger number of spatial channels exceeding 100 have been realized [12,14,15]. Considering the large spatial multiplicity, there is potential for a further increase in capacity by improving the SE using a higher baud rate and a higher level modulation format and with a larger number of wavelength channels.

Transmission characteristics of recent SDM experiments are summarized in Table 3, including transmission capacity, distance, SE, experimental setup of transmission line, and amplification scheme. SDM transmissions can be realized using a single-span, multiple-spans, the serial connection of cores in an MCF, a recirculating loop with core averaging by the serial connection of cores in an MCF, and a parallel recirculating loop system. Fig. 8 shows the

Table 3
Transmission performance in SDM experiments.

Category	Refs.	n	m	Span length (km)	Experimental setup of transmission line	Amplification	Capacity (Tb/s)	Distance (km)	Spectral efficiency (b/s/Hz)
IA	[18]	7	1	16.8	1 span	–	109	16.8	1.6
	[19]	7	1	76.8	1 span	–	112	76.8	2.0
	[9]	7	1	45.5	Loop, 7-core average	MC-EDFA	140.7	7326	4.0
	[67]	7	1	204	1 span	MC-ROPA	120.7	204	7.6
	[27]	7	1	40	Loop, 7-core average	MC-EDFA	51.1	2520	1.5
	[5]	12	1	52	1 span	–	1014	52	7.6
	[31]	12	1	50	Loop, 3-core average, Bi-directional	MC-EDFA and Raman	2 × 409	450	6.7
	[10]	12	1	50	Loop, 3-core average, Bi-directional	MC-EDFA and Raman	2 × 344	1500	6.1
	[50]	16	1	55	Serial, 16-core, Bi-directional	EDFAs	–	880	–
	[23]	19	1	10.1	1 span	–	305	10.1	1.6
	[8]	22	1	31	1 span	–	2150	31	9.8
	[16]	32	1	51.4	Parallel single-mode loops	MC-EDFA	50	1644.8	6.29
IIA	[42]	3	3	35.7	Parallel loops	EDFAs	–	715	–
IIIA	[11]	12	3	40.4	1 span	–	61.97	40.4	6.88
	[43]	7	3	1	1 span	–	200	1	3.8
	[12]	36	3	5.5	1 span	–	–	5.5	–
	[13]	12	3	52.7	Parallel multimode loops	FM-EDFAs	23.58	527	2.62
	[7]	19	6	9.8	1 span	–	2050	9.8	4.0
	[15]	19	6	8.85	1 span	–	–	8.85	–
IIB	[20]	1	3	60	Parallel loops	EDFAs	1	4200	4.03
	[38]	1	6	31	Parallel loops	EDFAs	18	1705	18.0
IIIB	[28]	1	3	50	1 span	FM-EDFA	26.4	50	2.09
	[29]	1	3	119	1 span	FM-EDFA	57.6	119	4
	[21]	1	3	70	Parallel loops	EDFAs	6.5	700	1.33
	[34]	1	3	50	Multimode loop	FM-EDFA	3.04	1000	2.53
	[29]	1	3	60	1 span	FM-EDFA	15	60	5
	[71]	1	3	43.5	Parallel loops	EDFA	9	305	3
	[35]	1	3	70	Parallel loops	Raman	18	1050	3
	[55]	1	6	59	Parallel loops	EDFAs	24.6	177	5.33
	[36]	1	6	59	Parallel loops	EDFAs	6.1	708	2.67
	[56]	1	6	74.17	1 span	–	34.68	74.17	1.35
	[30]	1	6	179	1 span	FM-EDFAs	72	179	3
	[25]	1	10	125	1 span	–	23.2	125	2.9
	[25]	1	10	87	1 span	–	115.2	87	2.9
	[58]	1	15	22.8	1 span	–	17.28	22.8	2.91

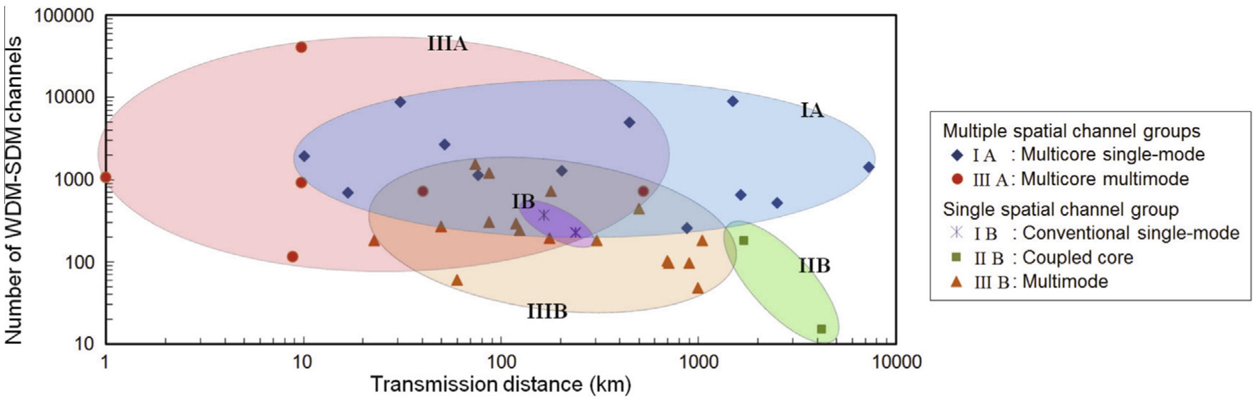

Fig. 8. Number of spatial and wavelength channels transmitted versus transmission distance.

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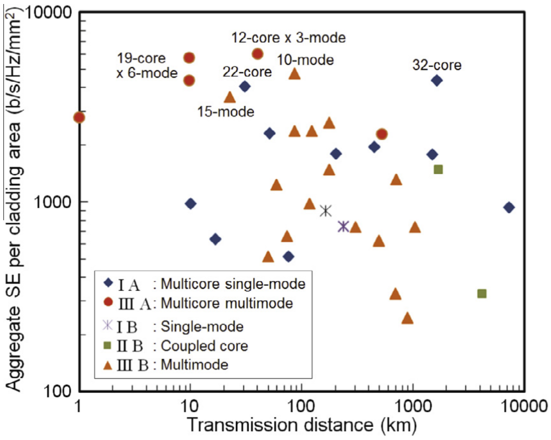

Fig. 9. Aggregate spectral efficiency per cladding area versus transmission distance. The vertical axis is equivalent to the product of spectral efficiency and spatial efficiency.

total number of spatial and wavelength channels transmitted in experiments versus transmission distance. The multicore transmission in category IA has demonstrated excellent transmission performance transmitting large number of wavelength and spatial channels over a long distance. So far, around 10,000 channels have been transmitted over a distance exceeding 1000 km. The multicore multimode transmission in category IIIA has potential for higher capacity, while the transmission reach is currently limited to around 500 km. It is still a challenge to transmit a large number of channels over long distances with the multimode transmission in category III. Further improvements in transmission technology are necessary for extending capacity and reach with the multimode approach.

Fig. 9 shows the aggregate spectral efficiency per cladding area and transmission distance of recent SDM-WDM transmission experiments. With the recent advances in transmission over SDM fibers, transmission with an aggregate SE of over several hundred b/s/Hz, and an aggregate SE per cladding area of over several thousand b/s/Hz/mm^2 have been realized. Targeting 100 times the scalability with SDM fibers compared with conventional SMF, there are still possible improvements that can be made in the transmission characteristics to push the aggregate SE to over 1000 b/s/Hz, and using a wide bandwidth, may achieve 10 Pb/s class ultra-high capacity over SDM fibers.

5. Conclusions

We have reviewed recent progress on high capacity dense space division multiplexing (DSDM) transmission over multicore and multimode fibers. Various spatial multiplexing approaches for SDM systems, and recent transmission performances were reviewed. SDM studies have made rapid progress as regards increasing the transmissible capacity, distance and spatial multiplicity over SDM fibers. When the large spatial multiplicity provided by current DSDM fibers is taken into account, a higher capacity is possible by improving the fibers and components used in transmission lines, and SDM amplification technologies. Further advances in SDM technology should make future optical transport systems capable of ultra-high capacity long-haul transmission.

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