Dense Space Division Multiplexed Transmission Over Multicore and Multimode Fiber for Long-haul Transport Systems

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(Invited Paper)

***Abstract*—In this paper, we review recent progress on space division multiplexed (SDM) transmission and our proposal of dense SDM (DSDM) with more than 30 spatial channels toward capacities beyond petabit/s. Furthermore, we discuss the requirements for realizing long-haul DSDM transport systems using multicore and/or multimode fiber, including power and space efficient amplification schemes, the use of fibers with large effective areas and transmission lines with low intercore crosstalk, low differential mode delay (DMD), and low mode dependent loss (MDL). Graded index heterogeneous 12-core × 3-mode fiber with low crosstalk, low DMD, and low MDL, parallel multiple-input and multiple-output signal processing, low mode dependent gain Erbium-doped fiber amplifiers, and MDL equalization technologies are significant as regards extending the reach of multicore and multimode transmission. We review our long-distance transmission experiment on polarization-division multiplexed 16-quadrature amplitude modulation signaling over 12-core × 3-mode fiber.**

***Index Terms*—Digital signal processing (DSP), optical communication systems, optical fiber communication, optical fibers, space division multiplexing, spectral efficiency.**

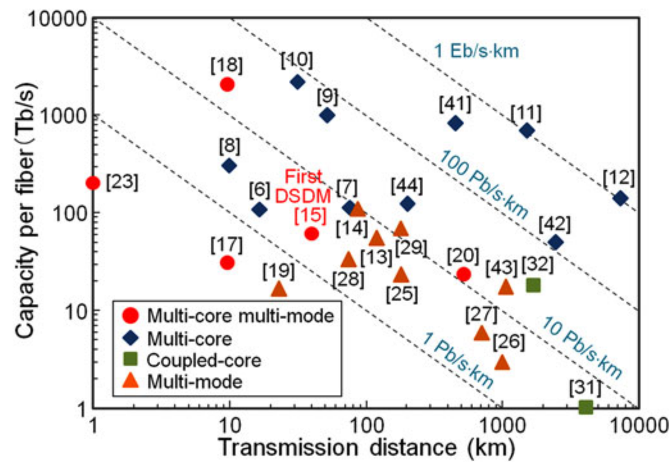

Fig. 1. Transmission capacity per fiber versus transmission distance obtained in recent SDM experiments.

I. Introduction

SINCE the single-mode fiber (SMF) capacity limit became clear, the use of space division multiplexing (SDM) in optical fiber communications has attracted a lot of research interest since it offers hundred times the capacity of SMF-based transport systems [1]. Many transmission experiments have been reported over the past few years starting with a small number of spatial channels multiplexed in multiple cores or modes in a multi-core fiber (MCF) or a few-mode fiber (FMF). SDM technologies have advanced over the years, and have demonstrated good potential with a view to realizing ultra-high capacity long-haul transport systems. Fig. 1 shows the capacity versus distance results obtained in recent SDM transmission experiments. The highest transmission capacity over an SMF realized experimentally is around 100 Tb/s over several hundred kilometers [2], [3], and it decreases for long-haul transport systems because of the tradeoff between spectral efficiency and transmission reach [4], [5]. The transmission capacity with SDM technology first exceeded 100 Tb/s when using 16.8 and 76.8 km seven-core MCFs with capacities of 109 [6] and 112 Tb/s [7], respectively. A higher capacity, namely 305 Tb/s, was demonstrated by increasing the number of cores to 19 [8]. In the same year, our study using a 52 km 12-core MCF achieved the first petabit transmission with a capacity of 1.01 Pb/s [9]. The highest capacity yet realized is 2.15 Pb/s over a 31 km 22-core MCF [10]. The highest capacity distance products are 1.032 [11] and 1.031 Eb/s × km [12], with capacities of 2 × 344 Tb/s over 1500 km using 12-core MCF, and 140.7 Tb/s over 7326 km using seven-core MCF, respectively. For mode division multiplexed transmission, the highest capacity was 57.6 Tb/s over 119 km using a three-mode FMF [13], and it was recently increased to 115.2 Tb/s over 87 km of FMF with the number of multiplexed modes increased to 10 [14].

To further increase scalability with SDM beyond the petabit/s system capacity, in 2014, we presented dense SDM (DSDM) with a spatial multiplicity of over 30 [15]. Moreover, we demonstrated the first DSDM transmission over 40.4 km using a 12-core × 3-mode multi-core FMF (MC-FMF) [15]. Our proposal initiated studies focusing on even greater levels of spatial multiplicity. A year after our study, DSDM was addressed

Manuscript received October 29, 2015; revised January 12, 2016; accepted January 22, 2016. Date of publication February 2, 2016; date of current version March 3, 2016.

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Digital Object Identifier 10.1109/JLT.2016.2524546

by two research groups and their work included a demonstration of a spatial multiplicity of 108 in a 5.5 km 36-core × 3-mode MC-FMF [16], and a DSDM transmission of 114 spatial channels over a 9.8 km 19-core × 6-mode MC-FMF [17], [18]. The mode multiplexing number was also increased to 10 over 87 km [14] and 15 over 22.8 km [19]. To realize DSDM technology in future optical transport systems, it is essential to develop fundamental technologies that enable long-distance transmission along with ultra-high capacity.

This paper discusses DSDM transmission using multi-core and/or multi-mode fiber for future long-haul transport systems. We first describe the background to our DSDM study using a multi-core multi-mode approach to achieve a further scalability increase. We then examine the recent trend in spatial multiplicity, and the spatial and spectral efficiencies of the latest SDM- wavelength division multiplexing (WDM) transmission experiments. Furthermore, we investigate the issues posed by DSDM in relation to future long-haul transport systems, and finally, we review technologies developed for extending the reach of multi-core multi-mode DSDM transmission [20].

The paper is organized as follows. Section II reviews and evaluates the performance of recent SDM transmission experiments over multi-core and/or multi-mode fiber in terms of efficiencies and transmission distance. Section III discusses transmission systems with various amplification schemes, and Sections IV and V discuss issues related to extending the reach of multi-core and multi-mode transmission, respectively. Section VI presents the latest technologies that enable long-distance multi-core multi-mode DSDM transmission. Section VII summarizes the main content and concludes the paper.

II. DSDM Toward Ultra Scalability

SDM transmission over an optical fiber is based on multiplexing signals in multiple cores or modes. As with integrated optical circuits that use multiple waveguides on a chip as independent light paths, an MCF, or MC-FMF can be viewed as the integration of multiple single-mode or few-mode cores in one optical fiber.

To reach ultra-high capacity at transmission speeds exceeding petabit/s, we must increase the multiplicity to more than several tens of channels. As with dense wavelength division multiplexing (DWDM) systems that typically have 30 wavelength channels with a 100 GHz spacing throughout the C-band amplification range of Erbium-doped fiber amplifiers (EDFAs), we define "DSDM" as SDM with over 30 spatial channels [15]. In addition to high spatial multiplicity, a large effective area in a core is needed to prevent nonlinear effects. Moreover, assuming that the system will be implemented in core networks, we need a low crosstalk of less than −30 dB to transmit high-level modulation formats over around 1000 km. We have thus set the target specification of DSDM transmission at a spatial multiplicity of >30, an effective area $(A_{\mathrm{eff}}) > 80$ μm^2, and an inter-core crosstalk of <−30 dB after 1000 km [21]. If we disregard fiber reliability, we can realize the above requirements simply by increasing the cladding diameter. It has been shown that increasing the MCF cladding diameter above 300 μm will provide more space and thus higher multiplicity levels [16]–[18]. Unfortunately, a fiber with large cladding area will be weak against strain and will have a higher failure probability. In addition, cores further from the center of an MCF will suffer from impairments caused by a large optical axis misalignment at connection points. The real challenge is to meet the above requirements while retaining a practical cladding area and a cladding diameter of up to around 250 μm, based on the simulated failure probability as a function of cladding diameter for different bending diameters [22].

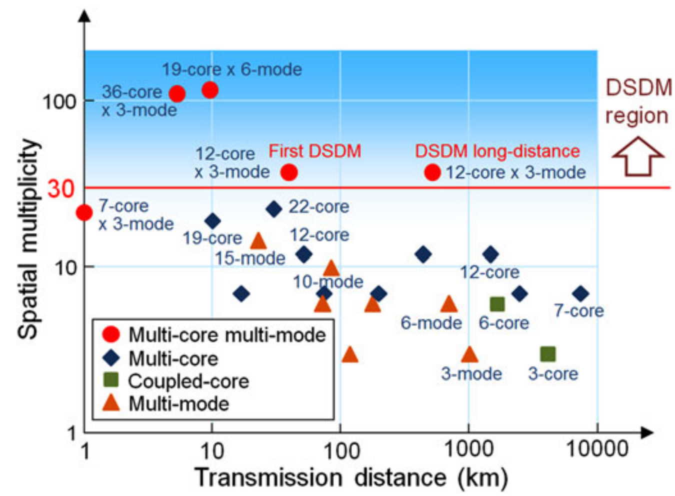

Fig. 2. Spatial multiplicity versus transmission distance obtained in recent SDM-WDM experiments.

Fig. 2 plots the spatial multiplicity versus distance achieved in recent SDM-WDM transmission experiments. We designated the region with a spatial multiplicity >30 as the "DSDM region." We previously demonstrated the first DSDM transmission with a multiplicity of 36 using a 12-core × 3-mode fiber [15], which was around twice the multiplicity of conventional 19-core fiber [8].

Our demonstration of DSDM transmission has led to the recent trend in SDM studies of increasing scalability, in particular, by combining multi-core and multi-mode approaches. The results of these studies include spatial multiplicities of 21 with 7-core × 3-mode fiber [23], 108 with 36-core × 3-mode fiber [16], and 114 with 19-core × 6-mode fiber [17], [18]. The numbers of cores and modes in an MCF and FMF have also been increased to 22 [10] and 15 [19], respectively. Extending the transmission distance is another important step towards realizing long-haul DSDM systems. We recently demonstrated a 527 km transmission of DSDM signals over a 12-core × 3-mode fiber [20].

Spatial efficiency η_{spatial}, defined as the spatial multiplicity divided by the fiber cross-sectional area, was previously employed to examine efficiency in terms of the use of space per fiber [24]. Fig. 3 plots the spectral efficiency η_{spectral} versus the spatial efficiency η_{spatial} of recent SDM-WDM transmission experiments. The plots are grouped based on the categories in the SDM transmission matrix, which cross indexes various types of multi-core and/or multi-mode transmissions according to the state of the light propagation in optical fibers as well as the way in which the spatial channels are handled in a network. Such categories include IA: uncoupled multi-core, IIB:

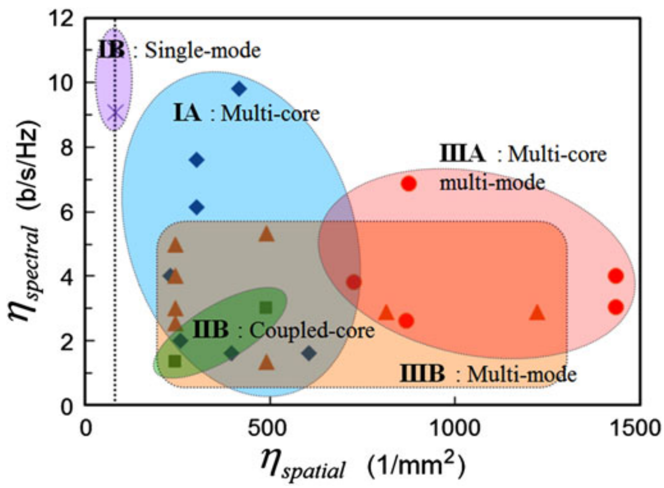

Fig. 3. Efficiencies of recent SDM-WDM experiments from various categories of SDM transmission matrix.

coupled multi-core, IIA: coupled core group, IIIB: few-mode or multi-mode, and IIIA: multi-core few-mode transmission [24]. Multi-core transmission, category IA, exhibits a high η_{spectral} value since we can handle each spatial channel as a conventional SMF when crosstalk from other cores is sufficiently suppressed. On the other hand, multi-mode transmission, category IIIB, can increase η_{spatial} by increasing the number of modes within the 125 μm diameter cladding area [25]–[29]. Meanwhile, multi-core multi-mode transmission, category IIIA, offers the potential for both high spectral and spatial efficiencies.

We have also discussed the fact that increasing both η_{spectral} and η_{spatial} leads to higher capacity, since capacity is given as $\eta_{\mathrm{spectral}} \times \mathrm{bandwidth} \times \eta_{\mathrm{spatial}} \times \mathrm{fiber\ area}$ [24]. The efficiencies obtained in recent SDM transmission experiments are summarized in Table I, and Fig. 4 shows the aggregate spectral efficiency per fiber area, which is equivalent to the product of η_{spectral} and η_{spatial}, versus transmission distance [30] for each category in the SDM transmission matrix. SDM transmission studies have aimed at extending the reach, and multi-core [6]–[12] and coupled-core [31], [32] transmissions in categories IA and IIB have achieved distances of up to 7326 km [12] and 4200 km [31], respectively. Since the emergence of DSDM, studies have aimed at increasing the levels of spatial multiplicity. Many studies on few-mode and multi-core few-mode transmission in categories IIIB and IIIA, respectively, have reported much higher aggregate spectral efficiencies, which were achieved by the dense multiplexing of more spatial channels and by DWDM along with the use of higher order modulation formats. The highest aggregate spectral efficiency per cladding area is currently 6013 b/s/Hz/mm^2, which we achieved in our first DSDM demonstration [15]. To realize ultra-high capacity DSDM long-haul transport systems, we require further increases in aggregate spectral efficiency per cladding area and transmission distance with the ultimate target being around ten thousand b/s/Hz/mm^2 over 1000 km.

In the next three sections, we discuss issues related to long-haul transport systems including the optimization of transmission systems based on space- and power-efficient amplification schemes, reducing inter-core crosstalk and increasing the effective area in multi-core transmission, and reducing differential mode delay (DMD) and mode dependent loss (MDL) in multi-mode transmission.

III. Transmission With Various Amplification Schemes

Aside from the SDM transmission matrix, which classifies transmissions by the type of light propagating in the fiber, SDM systems can be classified by the type of amplifiers used in the transmission line. Fig. 5 shows SDM transmission systems with amplification schemes based on (a) conventional single-mode EDFAs, (b) multi-core and/or few-mode EDFAs, (c) Raman amplification, and (d) remote optically pumped amplifiers (ROPAs). The transmission systems consist of a transmitter (Tx), a spatial multiplexer, SDM fiber for transmission, SDM amplifiers, a spatial demultiplexer, a receiver (Rx), and digital signal processing (DSP) for Tx and Rx.

In a transmission system using conventional single-mode EDFAs, fan-in/fan-out (FI/FO) devices or mode multiplexer (MUX)/demultiplexers (DEMUXs) can be used to demultiplex the spatial channels. Each channel is amplified by a different single-mode EDFA, and then re-multiplexed into the multi-core or multi-mode fiber transmission line. With this scheme, we can control the gain of each spatial channel, and use single-mode components. Its downside is the high cost of amplification. A more attractive scheme employs SDM amplifiers [33]–[39], which offer cost effectiveness through amplifier integration. The major challenge as regards implementing this type of system is ensuring gain uniformity among the spatial channels. We require good gain uniformity between the cores in a multi-core EDFA or low mode dependent gain (MDG) between the modes in a multi-mode EDFA. Multi-core long distance transmission experiments have used a core pumped MC-EDFA [11], [12], [40], [41], while recently, transmission using a cladding-pumped MC-EDFA has been reported [42]. Several multi-mode transmission experiments using FM-EDFAs have also been reported [13], [20], [26], [29]. To realize lower cost and power consumption, cladding-pumped multi-core and/or multi-mode EDFAs are desired. Further progress on this scheme is expected.

The Raman amplification seen in Fig. 5(c) can be used individually in multi-core or multi-mode transmission lines [43], or in combination with multi-core/multi-mode EDFAs [11], [41]. We have reported transmission over multi-core ROPA [44] as shown in Fig. 5(d) with the target application being undersea systems. Systems that require no active components in the transmission line are very practical and support the use of SDM in current optical communication systems.

IV. Issues With Multi-Core Transmission

In this section, we discuss issues with transmission in a fiber with multiple spatial channel groups, namely, uncoupled multi-core (IA), groups of coupled core (IIA), and multi-core multi-mode (IIIA) transmissions.

1) *Inter-Core Crosstalk*

Crosstalk from other spatial channels will affect signal quality, and crosstalk suppression is necessary if signals

TABLE I
TRANSMISSION PERFORMANCE OBTAINED IN RECENT SDM EXPERIMENTS (CATEGORY IA: UNCOUPLED MULTI-CORE, IIB: COUPLED MULTI-CORE, IIIA: MULTI-CORE FEW-MODE, AND IIIB: FEW-MODE OR MULTI-MODE TRANSMISSION)

		SDM Fiber						Efficiencies		
Category	Reference	Fiber type	Cladding DIA (μm)	Amplification scheme	Distance (km)	Capacity (Tb/s)	BW (THz)	η_{spatial} (1/mm^2)	η_{spectral} (b/s/Hz)	Aggregate spectral efficiency (b/s/Hz)
IA	[6]	7-core	150	-	16.8	109	9.7	396.1	1.6	11.2
	[7]	7-core	186.5	-	76.8	112	8.0	256.2	2.0	14.0
	[12]	7-core	196	MC-EDFA	7326	140.7	5.0	232.0	4.0	28.0
	[44]	7-core	195	MCF-ROPA	204	120.7	2.25	234.4	7.6	53.6
	[42]	7-core	n/a	MC-EDFA	2520	51.1	5.1	n/a	1.5	10.6
	[9]	12-core	225	-	52	1014	11.1	301.8	7.6	91.4
	[41]	12-core	230	MC-EDFA and Raman	450	2×409	10.2	288.8	6.7	80.6
	[11]	12-core	230	MC-EDFA and Raman	1500	2×344	9.4	288.8	6.1	73.6
	[8]	19-core	200	-	10.1	305	10.0	604.8	1.6	30.5
	[10]	22-core	260	-	31	2150	10.0	414.4	9.8	215.6
IIB	[31]	3 coupled-core	125	SM-EDFAs	4200	1.2	0.25	244.5	1.3	4.03
	[32]	6 coupled-core	125	SM-EDFAs	1705	18	1.0	488.9	3.0	18.0
IIIA	[15]	12-core $\times$ 3-mode	229	-	40.4	61.97	0.25	874.1	6.88	247.9
	[20]	12-core $\times$ 3-mode	230	FM-EDFAs	527	23.58	0.25	866.5	2.62	94.3
	[23]	7-core $\times$ 3-mode	192	-	1	200	2.5	725.3	3.8	80.0
	[16]	36-core $\times$ 3-mode	306	-	5.5	-	-	1468.6	-	-
	[17]	19-core $\times$ 6-mode	318	-	9.8	30.3	0.09	1435.4	3.03	345.0
	[18]	19-core $\times$ 6-mode	318	-	9.8	2050	4.5	1435.4	4.0	456.0
IIIB	[13]	3-mode	125	FM-EDFA	119	57.6	4.8	244.5	4.0	12.0
	[26]	3-mode	125	FM-EDFA	500	27.7	3.7	244.5	2.5	7.6
					1000	3.0	0.4			
	[43]	3-mode	125	Raman	1050	18	2.0	244.5	3.0	9.0
	[25]	6-mode	125	SM-EDFAs	177	24.6	0.8	488.9	5.3	32.0
	[27]	6-mode	125	SM-EDFAs	708	6.1	0.4	488.9	2.7	16.0
	[28]	6-mode	125	-	74.17	34.6	4.3	488.9	1.3	8.1
	[29]	6-mode	125	FM-EDFA	179	72	4.0	488.9	3.0	18.0
	[14]	10-mode	125	-	125	23.2	0.8	814.9	2.9	29.0
					87	115.2	4.0			
	[19]	15-mode	125	-	22.8	17.2	0.4	1222.3	2.9	43.6

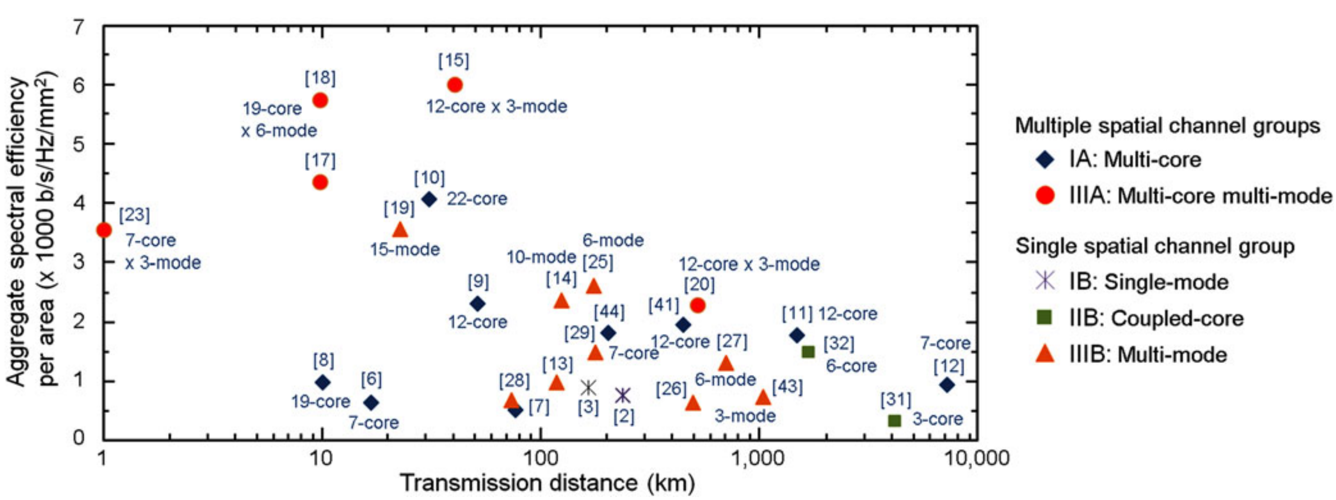

Fig. 4. Aggregate spectral efficiency per fiber area (equivalent to $\eta_{\text{spatial}} \times \eta_{\text{spectral}}$ in Table I) versus transmission distance.

are to be transmitted over long distances. For transmission in categories II and III, multiple-input and multiple-output (MIMO) signal processing can be used at the receiver to compensate for the coupling of spatial channels within the same spatial channel group. Some studies suggest that strong coupling may be beneficial in reducing the effects of DMD and MDL [45]. For transmission in category A, it is essential to minimize the crosstalk from other spatial channel groups within the fiber because we assume that signals in each spatial channel group will be optically routed without the application of MIMO processing. Therefore, it is important to develop MCF designs and fabrication techniques that can simultaneously maintain low crosstalk among spatial channel groups, minimize the core pitch, and maximize the effective area used for transmission within the constraint of a reliable cladding diameter. The inter-core crosstalk tends to be large for multi-core multi-mode transmission because the higher order modes

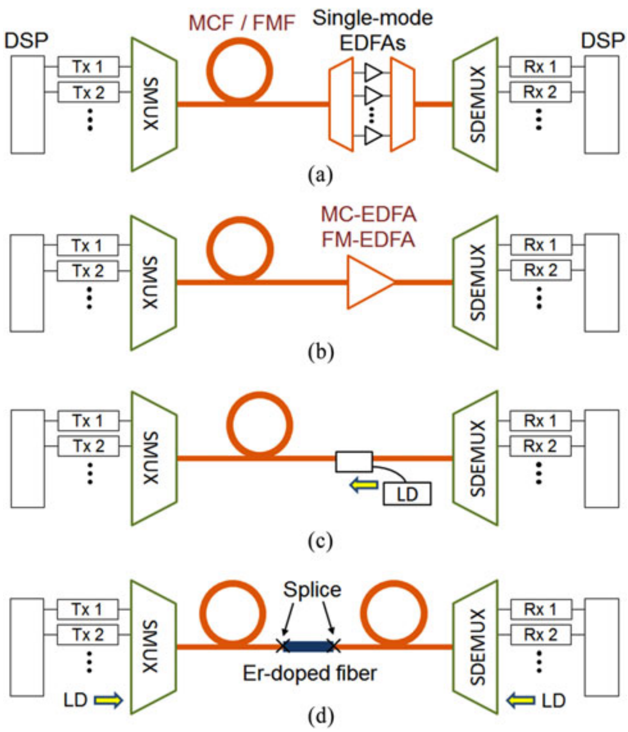

Fig. 5. SDM transmission systems with an amplification scheme based on (a) conventional single-mode EDFAs, (b) multicore and/or few-mode EDFA, (c) Raman amplification, and (d) a ROPA.

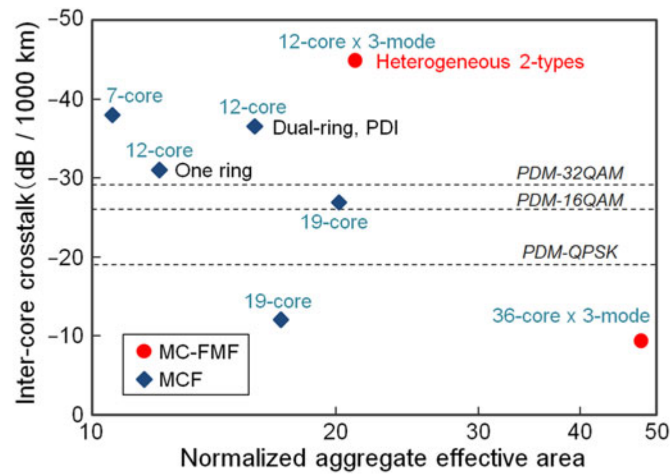

Fig. 6. Estimated inter-core crosstalk after a 1000 km transmission as a function of normalized aggregate effective area given by (1). The dotted lines show the minimum necessary crosstalk for a < 0.5 dB penalty with PDM-QPSK, PDM-16QAM, and PDM-32QAM.

have large mode fields. As measures for reducing inter-core crosstalk, a trench-assisted structure [46], [47] and air-holes [23] around cores have been shown to be effective. Another approach is to use heterogeneous MCF [48] with non-identical cores. The dissimilar cores suppress the power transfer. A heterogeneous MC-FMF with two [49] and three [16] types of cores, and a heterogeneous MCF with four [50] types of cores have been reported. We have proposed propagation-direction interleaving (PDI) [41] as a transmission technique. The bi-directional transmission of signals through adjacent cores reduces crosstalk.

Using the trench-assisted structure and two heterogeneous cores, a 12-core × 3-mode MC-FMF was designed whose cores were arranged in a square lattice structure with a 41 μm core pitch within a 229 μm cladding diameter. It was shown that even with the larger effective area of 141 μm^2 provided by higher order modes, the worst inter-core crosstalk can be as low as −55 dB/100 km [49].

Even when the inter-core crosstalk within an MCF is negligible, suppressing the crosstalk that arises in the FI/FO devices is equally important. Fiber bundled FI/FO devices provide low crosstalk and low-loss physical contact connections [51]. Good connectivity with many types of MCFs was demonstrated in transmission experiments involving hexagonal seven-core [44] and 12-core MCFs [9], [11], [41], and square lattice 12-core heterogeneous MC-FMF [15], [20].

2) *Effective Area* (A_{eff})

Since the maximum transmissible power is another factor limiting SMF transmission, increasing A_{eff} per fiber is essential in long-haul transport systems together with increasing the capacity per fiber. MCF is particularly beneficial in enhancing A_{eff} since the effective area used for transmission per fiber is multiplied by the core number N, yielding aggregate $A_{eff} (= N \times A_{eff})$. To evaluate the degree of A_{eff} enhancement, we extend the idea in [21] to multi-core multi-mode fiber. We define the normalized aggregate A_{eff} of an N-core MCF in a generalized form as

$$Normalized\ aggregate$$
$$A_{eff} = aggregate\ A_{eff}/A_{eff,\,SMF} = \left(\sum_{i=1}^{N} A_{eff,\,MCF_i}\right)/A_{eff,\,SMF} \quad (1)$$

where $A_{eff,MCFi}$ is the effective area of the *i*th core, and $A_{eff,\,SMF}$ is the effective area of a standard SMF, typically 80 μm^2.

Fig. 6 shows the inter-core crosstalk as a function of normalized aggregate A_{eff} [52]. The estimated inter-core crosstalk includes crosstalk from pairs of FI/FO devices, and crosstalk in a fiber assuming a length of 1000 km. For MC-FMF, we assumed $A_{eff,MCFi}$ to be the effective area of the highest order mode in the *i*th few-mode core, since the largest A_{eff} from the high order mode will affect the neighboring cores the most in the form of inter-core crosstalk. The minimum necessary crosstalk for a < 0.5 dB penalty with various modulation schemes is also shown in the figure. The crosstalk values required for a 0.5 dB penalty are <−19 dB, <−26 dB, and <−29 dB, for QPSK, 16 quadrature amplitude modulation (QAM), and 32QAM, respectively [53]. In general, the inter-core crosstalk increases with A_{eff}. As seen in the figure, by employing crosstalk reduction techniques, such as PDI transmission with dual-ring structured MCF [41], or heterogeneous MC-FMF with a square lattice arrangement

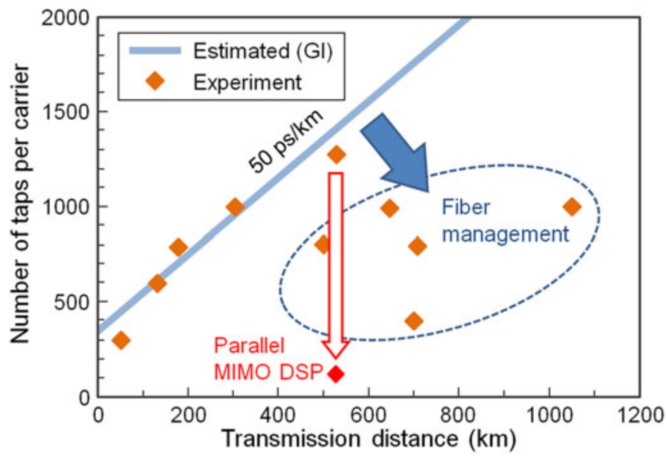

Fig. 7. Number of taps per carrier used in recent mode division multiplexed transmission experiments as a function of distance.

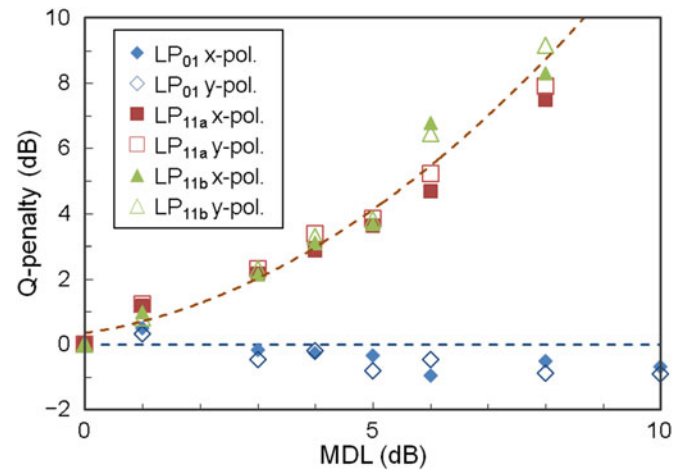

Fig. 8. Q-penalty as a function of MDL measured with PDM-16QAM.

[49], the conflicting requirements of enhancing A_{eff} and reducing crosstalk can be realized simultaneously.

V. Issues With Multi-Mode Transmission

1) *Differential Mode Delay*

DMD is a major issue impacting long-distance few-mode transmission in category III, since signal processing complexity increases with DMD. Various fiber designs have been explored for FMF transmission including step-index (SI), depressed cladding, and multi-SI refractive index profiles. FMFs have evolved over the years with the development of design and fabrication techniques, and most of the latest transmission experiments use a fiber with a graded-index (GI) refractive index profile. SI FMF typically has a DMD of 3 ns/km, but it can be less than 25 ps/km for three-mode GI-FMF. A low DMD of $<$63 ps/km has been reported for GI type MC-FMF [54] in the C-band. Fig. 7 shows the number of taps used for MIMO signal processing versus distance in recent FMF transmission experiments. The tilted line indicates the required number of taps as a function of distance when we assume that the baud rate of the signal exceeds ten Gbaud, a spool of GI FMF with 50 ps/km DMD is used in the transmission line and the DMD increases linearly with distance in the weak coupling regime. The obvious way to reduce signal processing complexity is to reduce the DMD in an FMF. Similar to the case of chromatic dispersion in an SMF, fiber management is useful in reducing the maximum DMD in an FMF. DMD compensation that combines FMF spools with DMDs with opposite signs has been reported to suppress the overall maximum absolute DMD. Another approach involves using the strong mode coupling regime where the DMD increase is reduced to the square root of the distance instead of being proportional to the distance as in the weak mode coupling regime [45]. Along with reducing the DMD of the transmission line, it is important that the DSP has sufficient MIMO processing capability since different forms of signals, fibers, and spatial channels are likely to coexist in future DSDM transport networks, and we must still be able to process all received signals.

We have proposed and demonstrated parallel MIMO DSP with a view to realizing advanced MIMO processing capability in a multi-mode transmission. We attribute the reduction in complexity achieved by using parallel MIMO DSP to two techniques. One is parallel MIMO equalization employing multi-carrier signals. A single carrier signal is divided into individual low baud-rate Nyquist-filter-shaped subcarrier signals. We can perform MIMO processing individually with each subcarrier in parallel, and consequently reduce the complexity per carrier by a factor of approximately the number of subcarriers [15]. The other technique involves incorporating frequency domain equalization (FDE) in MIMO processing. It is widely known that FDE reduces the signal processing complexity more effectively than time domain equalization (TDE) since the convolution computation in the time domain is replaced by fast Fourier transform-based scalar multiplication. The complexity is estimated to be 1/11th and 1/33rd that of an equivalent single carrier MIMO TDE with parallel MIMO TDE and FDE, respectively [20]. All complexity comparisons were performed for the same total capacity.

2) *Mode Dependent Loss*

MDL is another challenge posed by long distance few-mode transmission in category III. Several studies have reported the impact of MDL on system performance [55]–[57]. As with polarization dependent loss, signal processing cannot fully compensate for the impairment caused by the combination of MDL and noise, and this will directly affect transmission reach. With the development of fiber designs and manufacturing techniques, MDL in an FMF has been reduced to negligible values. Several types of FM-EDFAs with low MDG have been developed and demonstrated in FMF transmission experiments including Er doping with a ring profile [26], FM-EDFA using a reconfigurable pump mode, and a

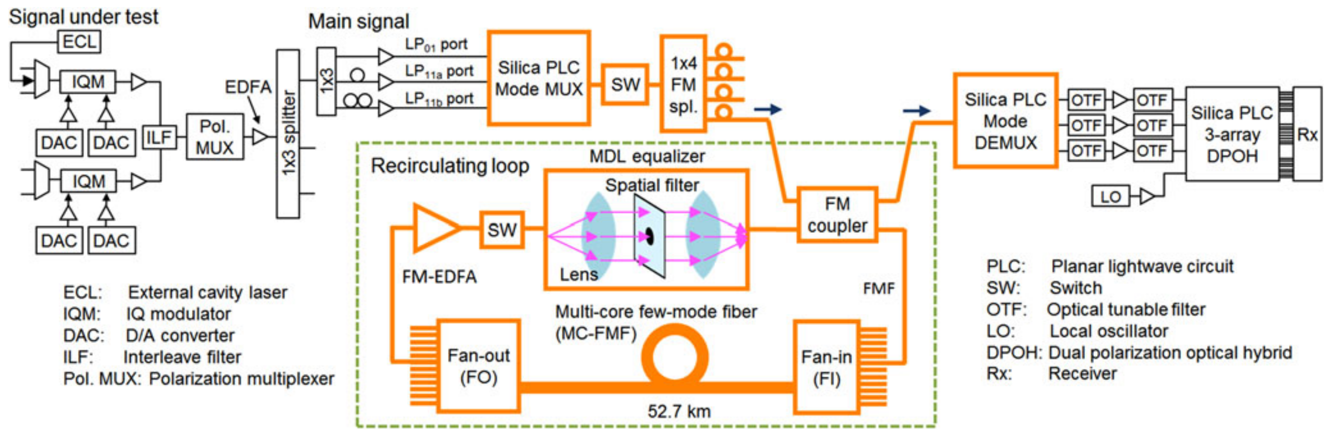

Fig. 9. Experimental setup.

ring-core FM-EDFA [34]. However, MDL can occur in various places in a network, for example in components and connection points [58], and still remains a major issue thwarting long-haul multi-mode transmission.

Fig. 8 shows the measured Q-penalty of polarization-division multiplexed 16-QAM (PDM-16QAM) signals as a function of MDL. The MDL was changed by attenuating the power input into the LP_{11a} and LP_{11b} ports of a mode MUX in a 3-mode point-to-point transmission system. The initial input power was set at -17 dBm/wavelength per mode. The Q-penalty for the LP_{11} modes increased with the MDL, and reached 3.2 and 8.2 dB for MDLs of 4 and 8 dB, respectively. If we assume a 0.5 dB penalty, the permissible MDL for long-haul transmission is suggested to be ± 2 dB [59].

VI. Long Distance DSDM Transmission Experiment

In this section, we review technologies that are useful for extending the reach of multi-core multi-mode transmission, and a demonstration of a 316.2 km transmission of PDM-16QAM signals over a 12-core $\times$ 3-mode fiber based on the amplification scheme shown in Fig. 5(b). Fig. 9 shows the experimental setup. The setup consists of a transmitter (Tx), a 1 $\times$ 3 splitter, optical delays, pre-amplifiers, a silica planar lightwave circuit (PLC) mode MUX, a recirculating loop, a PLC mode DEMUX, and a PLC integrated coherent receiver (Rx). The recirculating loop system consisted of a 3 dB few-mode coupler, an FI device, core #6 of the 52.7 km MC-FMF, an FO device, a ring-core FM-EDFA with $>$18 dB gain and $<$1.4 dB MDG [34], a few-mode switch, and a free space optics type MDL equalizer to compensate for the 3 dB residual MDL in the loop with an insertion loss of 3.2 dB. The experiment is described in detail in [59]. In this particular experiment, only one core was used to evaluate the capability of the reach extension by MDL equalization. As we confirmed in another experiment [20], the effect of other cores is negligible thanks to the low worst inter-core crosstalk of <-48.4 dB / 500 km between LP_{11} modes, and we can handle each core as an independent light path.

The Tx generated 12.5 GHz-spaced 20-WDM signals in the 1556.0 to 1557.9 nm range, which were then modulated by PDM-16QAM. Each wavelength channel contained ten Nyquist-filter-shaped 1 Gbaud subcarriers. After the signals were split into three and delayed for de-correlation, pre-amplifiers were set so that the power of the spatial tributaries input into the 52.7-km transmission fiber was -9 dBm per wavelength per mode.

As discussed in Sections IV and V, low crosstalk, low DMD, and low MDL are essential for long distance multi-core multi-mode transmission. As the optical fiber, we used a 52.7 km heterogeneous 12-core $\times$ 3-mode fiber with two types of trench assisted cores that had different GI profiles, placed in a square lattice arrangement. The core pitch and the cladding diameter were 43 and 230 μm, respectively. The DMD was $<$63 ps/km, and the MDL of the fiber was 0.01 dB/km [54]. The span loss with fiber bundle physical contact type FI/FO devices was 12.0–13.4 and 11.9–14.9 dB for the LP_{01} and LP_{11} modes, respectively.

The received sets of signals were mode DEMUXed, wavelength filtered, amplified, and received by the Rx module. The data stored in a 12-channel digital storage oscilloscope were offline processed by using a 6 $\times$ 6 parallel MIMO FDE technique with 128 taps per subcarrier to recover signals for a total DMD of 19.92 ns after a 316.2 km transmission.

Fig. 10(a) and (b) plot the measured Q-factors as a function of transmission distance without and with MDL equalization, respectively. The forward error correction (FEC) limit is set at 5.7 dB assuming a 20% overhead. The Q-factor variation between modes is small at short distances, and it increased with transmission distance because of larger accumulated MDL and noise, causing the Q-factors to fall below the FEC limit. Without the MDL equalizer, the transmission distance was 105.4 km, whereas it was extended to 316.2 km with the equalizer. Fig. 11 shows a typical constellation diagram for core #6, wavelength #10, and subcarrier #7. This transmission distance is about 1.8 times longer than the longest distance yet reported over an FMF using a PDM-16QAM or higher modulation format. We thus confirmed the effectiveness of reducing inter-core crosstalk, DMD, and MDL with heterogeneous GI MC-FMF,

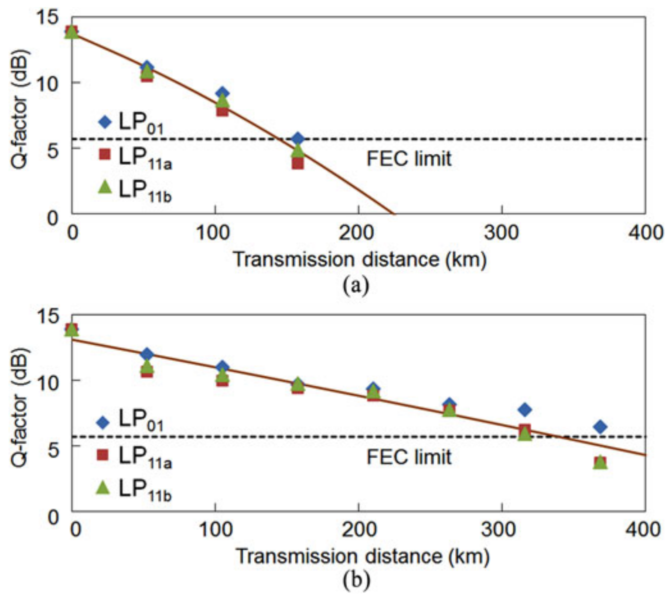

Fig. 10. Measured Q-factors of wavelength #10 (a) without and (b) with an MDL equalizer as a function of distance.

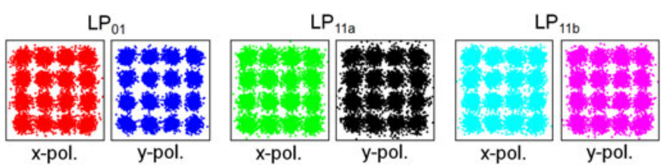

Fig. 11. Measured PDM-16QAM constellations of wavelength #10, subcarrier #7 after 316.2 km transmission.

low complexity parallel MIMO FDE, low MDG multi-mode amplification, and MDL equalization techniques to extend the reach in multi-core multi-mode transmission systems.

VII. Conclusion

We have reviewed recent SDM transmission studies, and evaluated various transmission categories in terms of spectral and spatial efficiencies. A further increase in aggregate spectral efficiency per cladding area and transmission distance is expected with the ultimate target area being of the order of ten thousand b/s/Hz/mm^2 over 1000 km to realize ultra-high capacity DSDM long-haul transport systems.

We have also discussed major challenges as regards realizing DSDM long-haul transport systems including amplification schemes, crosstalk, effective area, DMD, and MDL, which restricts the maximum reach of multi-core and/or multi-mode transmission. To realize long distance DSDM transmission, we have developed low crosstalk, DMD, MDL GI MC-FMF, low complexity parallel MIMO signal processing, low MDL transmission line with a low MDG FM-EDFA and an MDL equalizer, and have demonstrated long distance DSDM transmission. In future work, topics of interest will include power efficient multi-core/multi-mode amplifiers, optical device integration, network architecture, nonlinearity and power limit.

Acknowledgment

The authors would like to thank our colleagues at NTT Corporation for their continuous support, and the members of Fujikura Ltd., Hokkaido University, Osaka Prefecture University, and the Technical University of Denmark for their collaboration. Part of this research uses results from the research commissioned by the National Institute of Information and Communications Technology of Japan.

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