Dense Space-Division Multiplexed Transmission Systems Using Multi-Core and Multi-Mode Fiber

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(Invited Paper)

***Abstract*—In this paper, we describe recent progress in space-division multiplexed (SDM) transmission, and our proposal and demonstration of dense space-division multiplexing (DSDM), which offers the possibility of ultra-high capacity SDM transmission systems with high spatial density and spatial channel count of over 30 per fiber. We introduce the SDM transmission matrix, which cross indexes the various types of multi-core multi-mode transmissions according to the type of light propagation in optical fibers and how the spatial channels are handled in the network. For each category in the matrix, we present the latest advances in transmission studies, and evaluate their transmission performance by spectral and spatial efficiencies. We also expound on technologies for multi-core and/or multi-mode transmission including optical fiber, signal processing, spatial multi/demultiplexer, and amplifier, which will play key roles in configuring DSDM transmission systems, and review the first DSDM transmission experiment over a 12 core × 3 mode fiber.**

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

I. Introduction

With the rapid increase in Internet traffic, demand for much higher capacity will increase in optical communication networks to accommodate future high definition videos and new data communication services. Fig. 1 shows the growth in transmission capacity per optical fiber as mentioned in research studies as well as commercial optical communication systems [1], [2]. Until the 1980s, time division multiplexing was studied actively. It uses an electric multiplexing technique. Gigabit/s class transmission capacity was realized by modulating optical signals at high speeds. Then, in the mid-1990s, wavelength division multiplexing (WDM) in combination with optical amplification techniques was employed for capacity expansion by multiplexing optical signals with different wavelengths in the C and L bands. Advances in WDM technology allowed the multiplexing of a large number of wavelengths of over 30. With 30 wavelength channels and 100-GHz spacing, the bandwidth is 3 THz, which is in agreement with the amplification range of an Erbium-doped fiber amplifier (EDFA) in the C-band. Such system was denoted as dense wavelength division multiplexing (DWDM), and terabit/s class capacity was realized with DWDM technology. In the late 2000s, digital coherent technology, which once was studied extensively before the emergence of EDFAs, regained its appeal with the emergence of large-scale integrated circuits and digital signal processing (DSP) technology. Recent digital coherent studies greatly improve the spectral efficiency by using multi-level modulation formats and high-performance compensation in optical fiber transmission lines. As a result, the transmission capacity per fiber has reached 100 Tb/s in research, and 10 Tb/s in commercial systems. The above three major technologies have led to increases in optical fiber transmission capacity by a factor of more than 100 000 times over the past three decades. As the capacity is growing at an annual rate of 1.4 times, and is anticipated to grow at an even faster rate, research and development continues to target larger capacity. However, around the year 2020, transmission capacity will supposedly reach the theoretical limit over a single-mode fiber (SMF) of around 100 Tb/s [3], [4]. This is due to the nonlinear effect and the limit of power transmissible through a single-mode core [5].

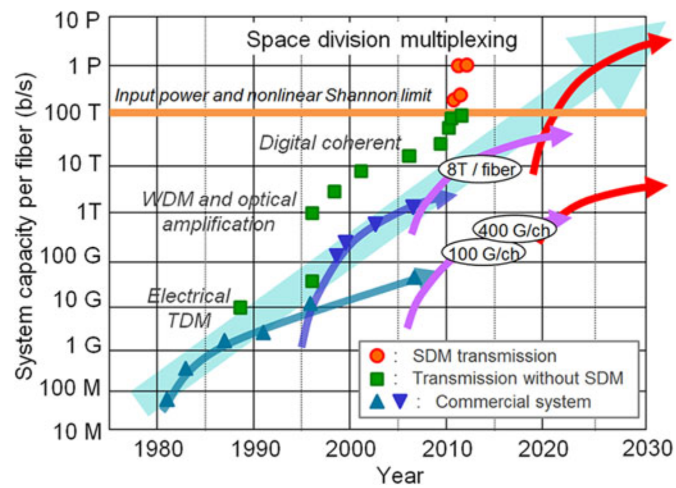

Fig. 1. Transmission capacity per optical fiber in research and commercial systems.

To overcome these limits, the additional use of the spatial dimension [1] has attracted a lot of research interest in recent years. Various space division multiplexed (SDM) transmission

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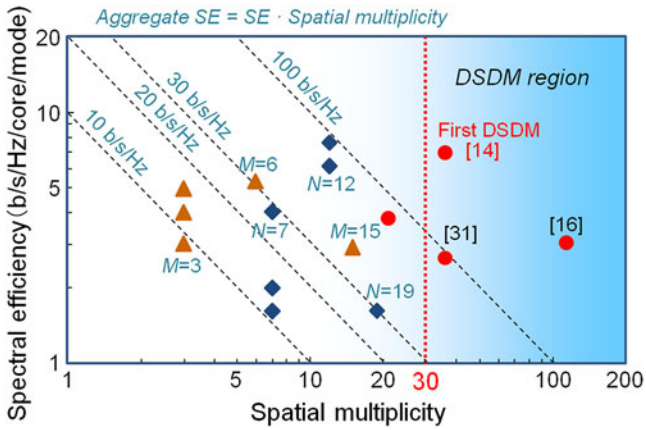

Fig. 2. Spectral efficiency versus spatial multiplicity of SDM-WDM transmission experiments (*N*: Number of cores, *M*: Number of modes).

schemes have been explored and have demonstrated their potential by setting milestones in transmission capacity [6], [7] and capacity distance product [8], [9] per fiber. Fig. 2 shows the relationship between spectral efficiency and spatial multiplicity of recent SDM-WDM transmission experiments. The spatial multiplicity is the total number of spatial channels multiplexed in cores or modes of a fiber, and excludes polarizations. The tilted dotted line represents the aggregate spectral efficiency, which is the product of the spatial multiplicity (horizontal axis) and spectral efficiency (vertical axis). The spatial multiplicity in early transmission experiments started from $M = 3$ in multi-mode transmission [10] and $N = 7$ in multi-core transmission [11], [12], where *M* is the number of modes, and *N* is the number of cores. Soon, the multiplicity was increased to the current maximum of $N = 19$ [13], yet spatial multiplicity values of over twenty remained unexplored. In order to increase scalability, we need to raise the multiplicity to the region we refer to as "dense SDM" (DSDM) region [14] with a spatial multiplicity of over 30. Further development of SDM technology was required to make a step forward and realize DSDM with higher spatial density and spatial multiplicity. We have developed fundamental technologies for both multi-core and multi-mode transmission, and have verified, for the first time, that it is possible to further increase the spatial multiplicity of a fiber into the DSDM region, opening the first step toward DSDM transmission systems [14]. DSDM, our proposal and demonstration, has been addressed by several research groups, and followup DSDM experiments on multi-core few-mode fiber (MC-FMF) were conducted a year later [15], [16].

This paper examines the latest SDM transmission experiments, and describes DSDM with a spatial multiplicity of 30 and higher, which we proposed and demonstrated for the first time utilizing both multi-core and multi-mode in transmission [14]. Similar to DWDM with dense wavelength spacing and high count of over several tens of wavelength channels [17], [18], we have shown that DSDM with high spatial density and large spatial multiplicity is effective in offering expanded scalability with the use of the spatial dimension.

The paper is organized as follows. Section II introduces the SDM transmission matrix to describe the various types of SDM transmission schemes reported, and Section III evaluates the efficiencies of using spectrum and space resources by each category in the matrix. Section IV presents the latest technologies for multi-core and/or multi-mode transmission including optical fiber, multiple-input and multiple-output (MIMO) signal processing, spatial multi/demultiplexer (MUX/DEMUX), and briefly elaborates on topics for future studies. Finally, Section V reviews the world's first demonstration of DSDM transmission, and Section VI summarizes the main contents and concludes the paper.

II. SDM Transmission Matrix

SDM transmission generally focuses on the optical fiber used as the transmission medium; either it is few-mode fiber (FMF) or multi-core fiber (MCF). From the viewpoint of transmission, signal processing and optical network application, there are diverse transmission types in SDM.

We introduce the SDM transmission matrix to summarize the various SDM transmission schemes [19] in Fig. 3. The entries identify the type of spatial channel transmission. The columns divide the state of light propagation along the fiber, namely, (I) single-mode in uncoupled single-mode core, (II) super-mode in coupled single-mode cores, or (III) multi-mode in multi-mode/few-mode cores. The rows distinguish the transmission fiber having (A) multiple spatial channel groups or (B) single spatial channel group. Transmissions in category A are the parallel form of category B, and contain multiple "spatial channel groups."

While the term spatial superchannel describes data streams of subchannels, which consist of separate modes/cores occupying the same wavelength, "spatial channel groups" describes the smallest unit of cores/modes that can be transmitted together in SDM networks. For example, in the case of category IIB and IIIB transmission, spatial channels in coupled cores or a multi-mode core are coupled, and signal processing is required after long-haul transmission to separate the spatial channels. We regard the channels as belonging to the same "spatial channel group." Spatially multiplexed tributary signals in the same spatial channel groups are routed together, and are received and processed at the same destination in a network. At the receiver of each destination, MIMO signal processing will be used to separate the coupled channels from the spatial channel group. The spatial channel groups can be transmitted, added, and dropped individually in the optical domain in network nodes.

We briefly summarize the latest transmission schemes for each category in the matrix.

IA. Uncoupled Multi-Core Transmission: This category, often regarded as multi-core transmission, has been studied actively from an early stage of SDM research. Various MCFs have been developed for this class of transmission, including 7, 12, and 19 core fibers. Initial transmission experiments using seven-core multiplicity reached the capacity equivalent to the SMF limit of around 100 Tb/s [11], [12]. Next, record transmission experiments were reported. 305 Tb/s capacity per fiber was achieved, which is approximately triple the SMF limit, by using 19-core multiplicity [13]. Further, an ultra-high capacity of more than

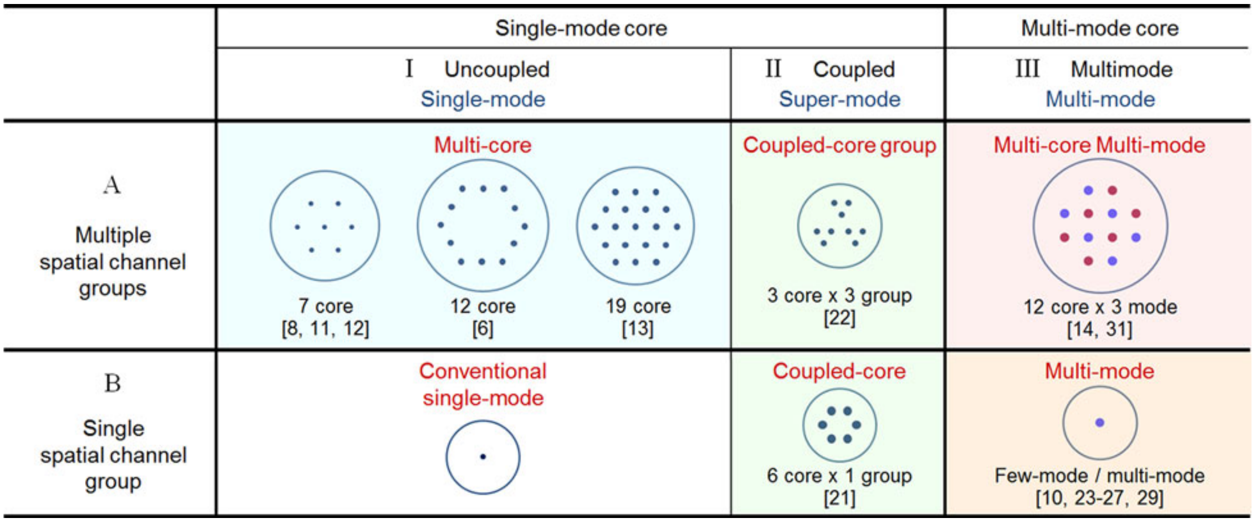

Fig. 3. SDM transmission matrix to organize various SDM transmission schemes. IA: multi-core, IIA: groups of coupled-core, IIB: coupled-core, IIIA: multi-core multi-mode, and IIIB multi-mode transmission. Typical fiber cross-sectional diagram is included for each category.

1 Pb/s was achieved for the first time over a 52-km low-crosstalk one-ring structured 12-core fiber with polarization-division multiplexed (PDM) 32-quadrature amplitude modulation (32 QAM) and an aggregate spectral efficiency of 91.4 b/s/Hz [6]. The highest capacity distance product of 1 Eb/s × km was achieved with 7 core [8] and 12 core [9] MCFs at transmission distances of 7326 and 1500 km, respectively. These transmission records were made possible in conjunction with the development of low crosstalk MCFs whose characteristics of each core are equivalent to those of an SMF, low-loss and low crosstalk fan-in/fan-out (FI/FO) devices, and multi-core amplifiers. Overviews of these technologies will be provided in Section III.

IIB. Coupled-Core Transmission: This category also uses an MCF as the transmission line but the signals in different cores are designed to couple with each other and form super-modes. The cores of the MCF can be arranged at a smaller spacing than that in category IA because their coupling is desired. However, as for multi-mode transmission, MIMO signal processing is required to uncouple the signals at the receiver. Three coupled-core transmission over 4200 km [20] and six coupled-core transmission over 305 km [21] have been reported.

IIA. Groups of Coupled-Core Transmission: This category is the parallel form of category IIB, where the transmission fiber contains groups of coupled-cores. The cores in the same spatial channel group will couple with each other and form super-modes, but the cores of different spatial channel groups are isolated. So far, an experiment on three groups of three coupled-cores over 715 km has been reported [22]. Spatial multiplicity can be further increased by adding more groups of coupled-cores in the fiber's cross-sectional area.

IIIB. Multi-Mode Transmission: Transmission research in this category has also been popular yielding the multiplexing of three or six spatial modes in a FMF [23]–[25], or mode group division multiplexing in a conventional graded-index (GI) multimode fiber (MMF) [26]. FMFs and various types of mode MUX/DEMUX are now commercially available. Mode division multiplexing of a few modes over a conventional GI-MMF [27] and photonic bandgap fiber [28] have also been demonstrated.

Modal impairments like differential mode delay (DMD) and mode dependent loss (MDL) greatly impact transmission performance. Using a GI type refractive index profile and a fiber management technique that combines multiple FMFs with positive and negative DMD values are common techniques for suppressing the maximum absolute DMD. The maximum transmission capacity is currently 57.6 Tb/s with three mode transmission over a total of 119 km FMF [23]. The longest distance for the three-mode transmission of WDM PDM quadrature phase shift keying (QPSK) signals is 1000 km [25]. The maximum six mode transmission distance is currently 177 km with WDM PDM-16 QAM signals [24]. Most recently, transmission of 15 mode PDM QPSK modulated signals with 43.63 b/s/Hz aggregate spectral efficiency over a 22.8 km MMF has been presented [29].

IIIA. Multi-Core Multi-Mode Transmission: This category is the parallel form of category IIIB. The spatial multiplicity scales with the product of the number of cores and modes and so provides efficient scalability. However, transmission in this category was difficult until present because problems in both category IA and in IIIB transmissions had to be solved simultaneously.

We have already developed the technologies required for the simultaneous use of multi-core and multi-mode, and successfully demonstrated the first transmission in this category [14]. Utilizing the multiplier effect of the multiple modes in multiple cores, we expanded the spatial multiplicity to 36 (12 cores × 3 modes), and transmitted 20 DWDM × 36 DSDM signals modulated at PDM-32QAM over 40.4 km. The aggregate spectral efficiency was 247.9 b/s/Hz and potential capacity is around triple that of the 1 Pb/s achieved in [6] and [7]. Additional studies in this category were reported from several organizations. They are 7 core × 3 mode transmission over 1 km [30], 36 core × 3 mode 5.5 km fiber [15], and 19 core × 6 mode

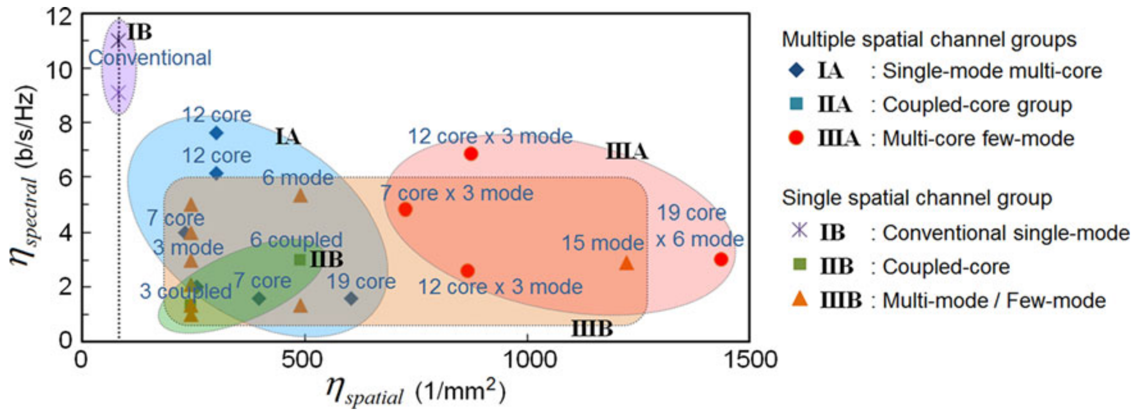

Fig. 4. Spatial and spectral efficiencies of SDM-WDM transmission experiments from various categories of the SDM transmission matrix.

transmission over 9.8 km [16]. However, the transmission distances were all limited to short reach. We have recently demonstrated the long distance DSDM transmission of PDM-QPSK signals over 527 km [31], which is more than ten times that of our original DSDM transmission [14].

The above are fundamental transmission schemes for SDM fiber, and there may be combinations of several categories such as mixtures of single-mode and multi-mode in a transmission fiber, or multi-mode coupled-core transmission.

From the optical fiber perspective, transmission in categories IA, IIA, and IIB use MCF, category IIIB uses FMF/MMF and category IIIA uses MC-FMF. From the optical components viewpoint, category IA transmission can use well-established conventional single-mode equipment, amplifiers, and devices. However, category II and III transmission require additional devices to handle the multi-modes, and the optimum number of modes or super-modes for transmission is under investigation. In terms of signal processing, transmission in category II and III requires MIMO signal processing, in particular, for long haul and high capacity transmission, and reducing DSP complexity is essential. Transmission studies are underway, and the potential for each category remains to be exploited.

III. Spatial and Spectral Efficiencies

The important metrics for evaluating SDM transmission performance are the efficiencies of use in terms of space and spectrum. The SDM fibers used in each transmission scheme in the previous section have different cladding diameters. Therefore, to make a useful efficiency comparison considering the space needed for spatial channel transmission in a fiber, we introduce the parameter of spatial efficiency, η_{spatial}, defined as the spatial multiplicity divided by fiber cross-sectional area:

$$\eta_{\text{spatial}} = \frac{\text{Spatial multiplicity}}{\text{Cross sectional area}}. \quad (1)$$

The above spatial multiplicity includes the total number of spatial modes and cores used for transmission, but excludes polarization.

Fig. 4 shows spectral efficiency η_{spectral} per core/mode versus spatial efficiency η_{spatial} of the fibers used in some recent SDM-WDM studies. As a reference, the vertical dotted line shows the spatial efficiency $(\eta_{\text{spatial}} = 81.5(1/\text{mm}^2))$ of the conventional SMF. The plot visualizes the current performance of each category of the SDM transmission schemes in terms of efficiencies. The transmission capacity per fiber is given as:

$$\begin{aligned}\text{Capacity} &= \text{Net data rate} \times n_{WL} \times \text{Spatial multiplicity}\\ &= (\eta_{\text{spectral}} \times \text{Bandwidth})\\ &\quad \times (\eta_{\text{spatial}} \times \text{Fiber area}) \end{aligned} \quad (2)$$

where n_{WL} is the number of WDM channels, and bandwidth is the product of n_{WL} and frequency spacing. The bandwidth used for transmission is mainly determined by the characteristics of the light source and amplification technique being used, and the fiber cross sectional area is determined by the fiber design and fabrication techniques. Thus, to realize ultra-high capacity, increasing η_{spectral} and η_{spatial} are essential by advancing DWDM and DSDM transmission technologies, respectively.

The uncoupled multi-core transmission, category IA, has higher η_{spatial} than conventional SMF, and the value increases with the number of cores *N*. However, as we increase *N*, intercore crosstalk will increase, and it becomes more difficult to transmit high order modulation signals over long distances, resulting in a lower η_{spectral}. If we are to realize DSDM-WDM transmission over a single-mode MCF transmission media, higher scaling technology is required that can increase both η_{spatial} and η_{spectral}. Coupled MCF transmission, category IIB, has higher η_{spatial} with fewer cores than category IA because of the smaller core pitch. However, its η_{spectral} is lower than that of uncoupled multi-core transmission at present, and extensive research is needed to improve η_{spectral}. Multi-mode transmission, category IIIB, can increase η_{spatial} in proportion to the number of modes by spatial mode-multiplexing within the 125 μm-diameter cladding. Its parallel form, the multi-core multi-mode transmission in category IIIA, provides both the highest η_{spatial} and η_{spectral}. This result suggests that it is possible to transmit data spatially efficiently at higher capacities via the multi-core multi-mode approach.

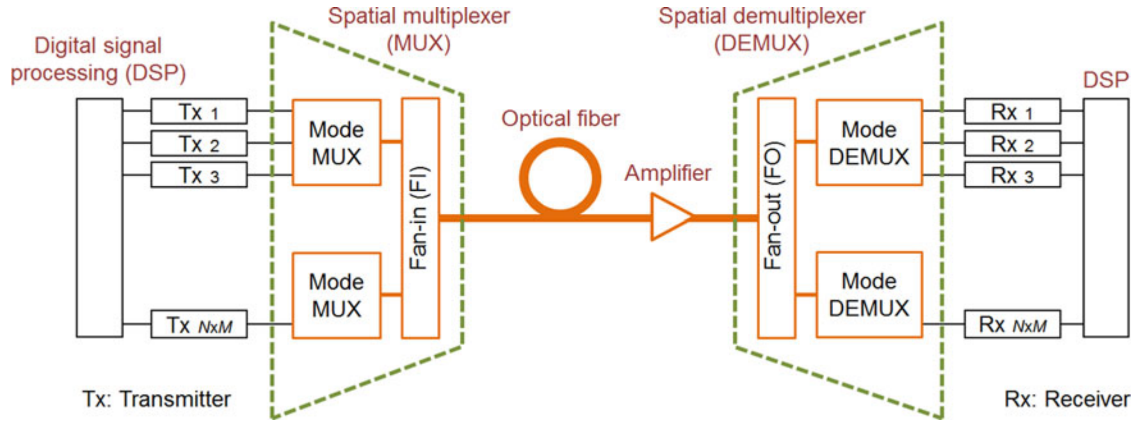

Fig. 5. Example configuration of a DSDM transmission system. The system includes optical fiber, DSP, spatial MUX/DEMUX, integrated devices, and amplifiers for multi-core and/or multi-mode.

IV. Technologies for Multi-Core and/or Multi-Mode Transmission

Fig. 5 shows an example configuration of a point-to-point DSDM transmission system with multi-core and multi-mode scheme. Technologies such as transmission, optical fiber, MIMO DSP, spatial MUX/DEMUX, device integration, and amplifiers designed for multi-core and/or multi-mode will be required to construct the system. We review some of the technologies as follows:

A. SDM Fiber

As described in Section II, various types of MCF and/or MMF have been developed. For fiber in Category A transmission, it is essential to reduce crosstalk from spatial channels belonging to different spatial channel groups. A common way to reduce crosstalk in an MCF for category IA and a MC-FMF for category IIIA transmissions is to set a trench around each core. Low crosstalk of $< -55\ \mathrm{dB/100km}$ was obtained with the trench structure [32], [33]. It is also known to help ease the bending radius limits of single-core FMF [34]. Another means to reduce inter-core crosstalk is to use heterogeneous MCF where the cores have different propagation constants [35]. This is, in particular, effective in reducing crosstalk in densely-packed MC-FMF since the mode field diameter of higher order mode is larger than that of the fundamental mode, and has larger effect on adjacent cores. Heterogeneous MC-FMFs with two [14], [33] and three [15] types of cores have been experimentally tested. Having diverse types of heterogeneous cores will allow dense core arrangement, but the penalty is greater difficulty in fabrication. Moreover, the fiber becomes fragile when the cladding diameter exceeds 0.3 mm or so. In practice, fiber designs with dense core allocation using fewer types of cores within a reliable cladding diameter are imperative. The MCFs for Category II transmission require good uniformity among cores since deviation in core positions and fluctuation in refractive indices cause impairments. The FMF/MMF used in Category III transmission requires DMD suppression. Designing few-mode cores with a multi-step-index and a GI profile can notably reduce DMD relative to the conventional step-index profile. A low DMD of $<$0.025 ns/km over the C-band [34], and $<$0.070 ns/km over the C + L band [36] were shown using a single-core six-LP mode GI FMF. A low DMD of $<$0.52 and $<$0.063 ns/km was shown with multi-step-index [33] and GI 12 core $\times$ 3 mode MC-FMF [31], respectively.

B. MIMO DSP

In order to implement mode-division multiplexing in an optical transport system, current DSPs need to offer the new functionality of MIMO signal processing. Single carrier time-domain equalization (TDE) and frequency-domain equalization (FDE) have been used in multi-mode transmission experiments. The number of taps required per carrier increase with the maximum DMD. Considering the ease of convergence of calculation and adaptation to environmental variations, there are bounds to the enlargement of circuit scale. Reduction in DMD and signal processing complexity is thus important for making the MIMO DSP feasible. We have proposed the parallel MIMO TDE [14] and FDE [31], a novel MIMO DSP technique that use low baud-rate multi-carrier signals to reduce the scale of the FIR filter and make convergence easier with $2M \times 2M$ MIMO signal processing.

C. Spatial MUX/DEMUX for Multi-Core: FI/FO Device

The spatial MUX/DEMUX for multi/demultiplexing signals into/from spatial channels in multiple cores, namely the FI/FO device, configures the individual SMFs cores into a position that matches the core arrangement of MCFs by means of tapered fibers, laser-inscribed three-dimensional (3-D) waveguides [37], free-space optics, grating coupler array, planar lightwave circuit (PLC), and fiber bundle [38]. High position accuracy and good uniformity are needed for low-loss, low crosstalk, and highly reliable connections. Record transmission experiments have proven the excellent connectivity of the fiber bundle physical-contact-type FI/FO device with various types of SDM transmission fibers, namely, hexagonal 7-core MCF [39], one-ring 12-core MCF [6], dual-ring 12-core MCF [9], and square-lattice heterogeneous 12 core $\times$ 3 mode MC-FMF [14], [31].

TABLE I
BASIC TYPES OF MODE MUX/DEMUX

Type	Reference	Principle of operation	Materials	Loss	Mode conversion efficiency	Configuration
1	[10]	LP mode converters and combiners	Free-space optics or long period gratings, and couplers	High	High	Simple
2	[41]–[45]	Index matching by asymmetric mode couplers	Silica PLC, stacked polymer waveguide, optical fiber, MCF	Low	High	Simple
3	[46], [47]	Simultaneous mode conversion	Reflective phase plate and free-space optics, grating coupler	Low	High	Require precise adjustment
4	[48], [49]	Spot-based mode coupler with arrayed cores	Fiber or waveguide photonic lantern, stacked waveguides, free-space optics	Low	Low	Simple

D. Spatial MUX/DEMUX for Multi-Mode: Mode MUX/DEMUX

Spatial MUX/DEMUXs reported so far for multi/demultiplexing signals into/from spatial channels in multiple modes can be classified into four types [40]. Table I summarizes their features. All four types have proven their usefulness in recent transmission experiments [15], [16], [29], [31].

1) LP mode converters and combiners.
This type converts single mode signals into LP modes by means of phase plates [10] or long period gratings, and combines them with beam combiners. It is simple but the loss is large, particularly for large numbers of modes because the theoretical loss rises each time modes are combined.
2) Index matching by asymmetric mode couplers.
This type uses index matching by asymmetric couplers to couple specific modes into a common multi-mode port. Mode MUX/DEMUX using asymmetric directional couplers based on PLC waveguides [41], [42], fused fibers [43], and multiple cores of a MCF [44] have been reported. The insertion loss is low with high mode conversion efficiency since each mode is sequentially coupled to the common port while retaining the original modes. Fiber-tapered photonic lantern with dissimilar single-mode cores [27], [45] also use the same principle to provide mode selectivity.
3) Simultaneous mode conversion by phase plate or gratings.
This type converts single-mode signals into plural modes simultaneously by a reflective phase plate and free space optics. It also offers low insertion loss and high mode conversion efficiency [46]. Grating couplers [47] can also perform simultaneous mode conversion, but require control with phase shifters and lower polarization dependence.
4) Spot-based mode coupler with arrayed cores.
This type, based on the photonic lantern [48], is originally from the field of astro-photonics. It can be made by means similar to that used for FI/FO devices including fiber-tapered photonic lantern, laser-inscribed photonic lantern, free-space optics, grating coupler array, and stacked planar waveguides [49], but the major difference from the FI/FO devices is the close distance between the cores to allow strong core-coupling for generating supermodes. Different from the first three types, spatial modes are mixed and MIMO is used to uncouple the modes.

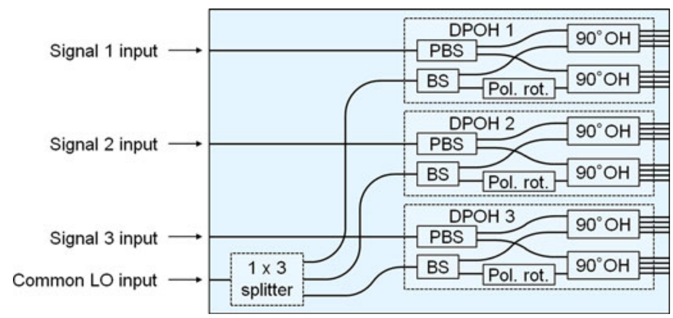

Fig. 6. Schematic diagram of 3-array integrated dual polarization coherent receiver front-end circuit (PBS: polarization beam splitter, BS: beam splitter, OH: optical hybrid, and DPOH: dual polarization optical hybrid).

E. Device Integration

To maximize the benefit of SDM, efficient use of space by device integration is also of great interest. As an example of device integration, we have demonstrated an integrated silica-PLC coherent receiver front-end targeting the $2M \times 2M$ MIMO DSP [14]. Fig. 6 shows the schematic configuration of our proposed integrated dual polarization coherent receiver frontend. The coherent receiver consists of 90° optical hybrids. It can contain a polarization beam splitter, beam splitter, and polarization rotator on a same chip or in a module. Conventionally, *M* numbers of devices were required to receive *M* sets of signals simultaneously. In addition, *M* local oscillator (LO) light sources, or an LO light source and a $1 \times M$ splitter was needed. Our proposed receiver integrates all these passive devices on one silica PLC chip. The PLC integrated dual polarization optical hybrid (DPOH) offers excellent IQ phase control, signal processing stability, and excellent scalability. LO light launched into the common LO input port is split with the 1×3 splitter circuit and shared among the three optical hybrid circuits.

Table II summarizes the SDM fiber, MIMO DSP, spatial MUX/DEMUX for multi-core and multi-mode, and spatial and spectral efficiencies of some recent SDM-WDM transmission experiments in each category of the SDM transmission matrix.

Although not covered in this paper, amplification technology is also crucial in DSDM transmission systems. Multicore EDFAs [50] and multimode EDFAs [51]–[53] have been developed. Seven core [8], 12 core [9], 19 core [54], and 3 mode [23], [25], [31] EDFAs have been applied in long distance transmission experiments. As one of the most practical applications of SDM, we demonstrated unrepeatered transmission of more than 120 Tb/s

TABLE II
TECHNOLOGIES USED IN VARIOUS TRANSMISSION SCHEMES

Category	Reference	SDM Fiber		MIMO DSP	FI/FO	Mode MUX/DEMUX		Efficiencies	
		Fiber type	Cladding DIA (μm)			Type	Means	η_{spatial} (1/mm^2)	η_{spectral} (b/s/Hz)
IA	[11]	7 core	150	–	Free-space	–	–	396.1	1.6
	[12]	7 core	186.5	–	Tapered fiber	–	–	256.2	2.0
	[8]	7 core	196	–	Fiber bundle	–	–	232	4.0
	[6]	12 core	225	–	Physical contact	–	–	301.8	7.6
	[9]	12 core	225	–	Physical contact	–	–	301.8	6.1
	[13]	19 core	200	–	Free-space	–	–	604.8	1.6
IIA	[22]	3×3 coupled	143	$6 \times 6 \times 900$ TDE	3-D waveguide	4	Photonic lantern	560.4	n/a
IIB	[20]	3 coupled-core	125	$6 \times 6 \times 400$ TDE	–	4	Collimators	244.5	1.3
	[21]	6 coupled-core	125	12×12 FDE	–	4	Photonic lantern	488.9	3.0
IIIA	[14]	12 core $\times$ 3 mode	229	$6 \times 6 \times 61$ parallel TDE	Physical contact	2	Silica PLC waveguide	874.1	6.88
	[31]	12 core $\times$ 3 mode	230	$6 \times 6 \times 128$ parallel FDE	Physical contact	2	Silica PLC waveguide	866.5	2.6
	[30]	7 core $\times$ 3 mode	192	$6 \times 6 \times 128$ FDE	3-D waveguide	4	Photonic lantern	725.3	3.8
	[15]	36 core $\times$ 3 mode	306	6×6 sparse TDE	Free-space	1	Phase plate	1468.6	n/a
	[16]	19 core $\times$ 6 mode	318	Two (6×6) TDE	Free-space	3	Reflective phase plate	1435.4	3.0
IIIB	[10]	3 mode	125	$6 \times 6 \times 120$ TDE	–	1	Phase plate	244.5	n/a
	[23]	3 mode	125	$6 \times 6 \times 401$ TDE	–	1	Phase plate	244.5	4.0
	[25]	3 mode	125	$6 \times 6 \times 801$ TDE	–	1	Phase plate	244.5	2.5
	[27]	3 mode	125	$6 \times 6 \times 1000$ FDE	–	2	Mode selective lantern	244.5	3.0
	[24]	6 mode	125	$12 \times 12 \times 800$ TDE	–	4	Photonic lantern	488.9	5.3
	[29]	15 mode	125	$30 \times 30 \times 1800$ FDE	–	4	Photonic lantern	1222.3	2.9

over 204 km by employing an MCF remote optically pumped amplifier (ROPA) having no passive/active elements other than an MC-EDF in the transmission lines [39].

V. FIRST DSDM TRANSMISSION EXPERIMENT

In this section, we review the first demonstration of DSDM transmission with spatial multiplicity of over 30 [14]. We designed the DSDM transmission setup, shown in Fig. 7, to incorporate prospective technologies for constructing practical DSDM transmission systems.

For the optical fiber, we employed a 40.4 km low-loss, low crosstalk and low DMD 12 core $\times$ 3 mode MC-FMF composed of two types of heterogeneous cores. The two types of cores were designed to have a multi-step index profile and a trench structure, and transmit LP_{01} and LP_{11} modes. They were allocated within the 229 μm diameter cladding, placed adjacent to each other in a novel square lattice arrangement. The loss at 1550 nm was 0.205 and 0.204 dB for the LP_{01} and LP_{11} modes, respectively, the worst crosstalk was < -54 dB/100 km, the maximum DMD in the C-band was <0.52 ns/km [33].

We implemented our low baud rate multicarrier signals and novel parallel MIMO TDE. The multi-carrier signals generated at the Tx for each wavelength and spatial channel consisted of 0.525 Gbaud $\times$ 20 subcarriers modulated with PDM-32QAM. At the Rx, 6×6 parallel MIMO TDE was performed to recover the signals on each wavelength and spatial channel, with only 61 taps per subcarrier to compensate 21 ns total DMD after 40.4 km transmission [14].

For the spatial MUX/DEMUX, we combined physical-contact-type multi-mode FI/FO devices based on fiber bundle, and the type 2 mode MUX/DEMUXs based on silica PLC. The FI/FO device consisted of a newly developed high precision ferrule with a square hole for fixing twelve small diameter FMFs into place. The cores of the FMFs and those of the MC-FMF were connected by physical contact with low-loss and low intercore crosstalk. The loss arising from misalignment between the cores of the FI/FO device and the MC-FMF ranged from 0.2 to 0.7 and 0.5 to 1.7 dB for the LP_{01} and LP_{11} modes, respectively. The device was housed in a compact 5 mm $\times$ 5 mm $\times$ 32 mm package. We selected the type 2 mode MUX/DEMUX to attain low theoretical loss, high mode conversion efficiency, and small footprint. The silica PLC, in particular, offers low loss and excellent reliability. Two silica PLC chips, each with an asymmetric LP_{11} coupler, were connected at right angles to each other by the 3-D assembly technique. The excess loss in the C-band was <2.5 dB and <5.0 dB for the LP_{01} and LP_{11} modes, respectively, including SMF and FMF coupling losses at both ends of the device. The chip was assembled to yield a 100 mm $\times$ 27 mm $\times$ 14 mm module.

For the coherent receiver front-end, we fabricated a 3-array silica PLC integrated DPOH circuit, whose structure is shown in Fig. 6. The PLC chip was packaged in a 90 mm $\times$ 40 mm $\times$ 7 mm module.

We brought together the technologies and constructed a DSDM transmission line. Details of the DSDM transmission experiment are presented in [14]. Twenty continuous wave light sources were used to generate 12.5 GHz-spaced, 20 wavelength channels in the C-band. Each wavelength was modulated by PDM-32QAM format with 0.525 Gbaud $\times$ 20 subcarrier signals. Fig. 8 shows the spectrum (measured with 20 MHz resolution) of the signal generated at the Tx. It shows the 20 independent

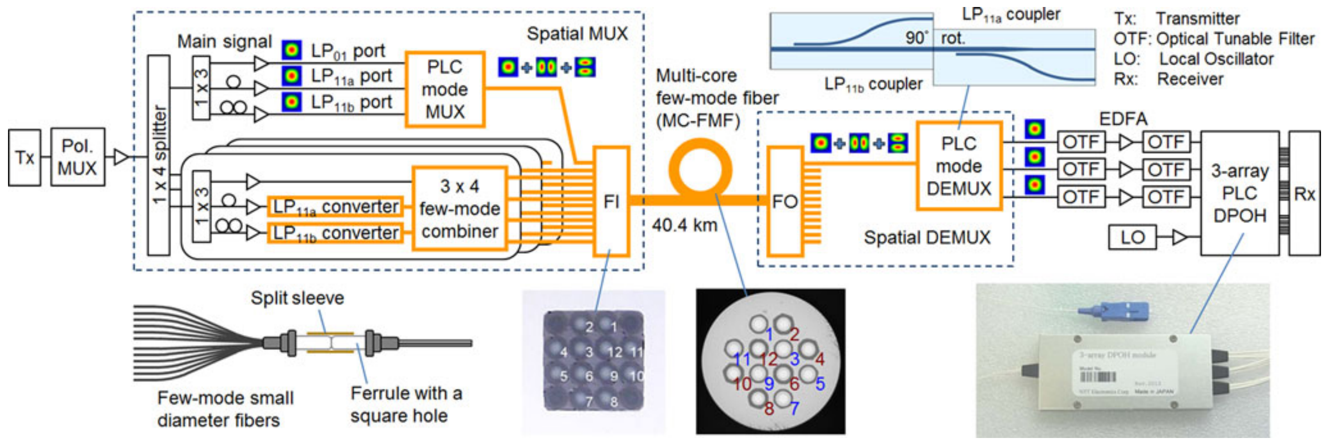

Fig. 7. Experimental setup of the first DSDM transmission experiment.

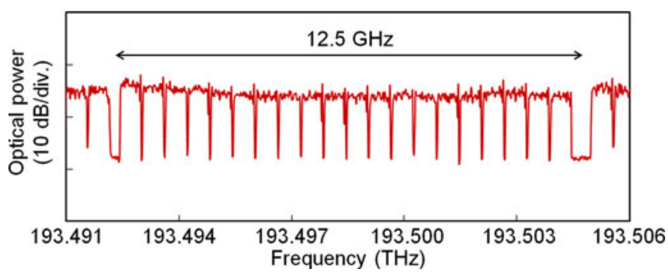

Fig. 8. Signal generated at the Tx, containing 20 independent subcarriers within the 12.5 GHz WDM slot.

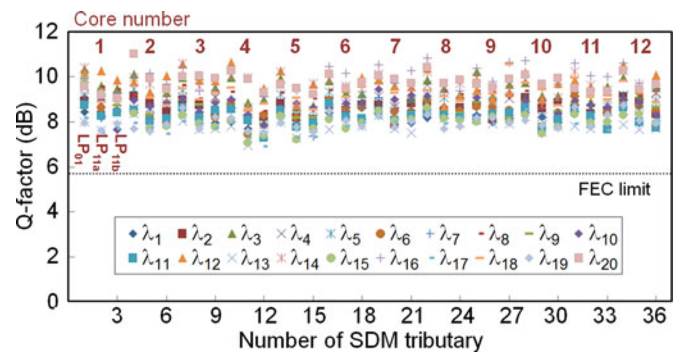

Fig. 9. Measured Q-factor versus the number of SDM tributaries after 40.4 km transmission. The number of SDM tributaries equals $(n-1) \times M + m$, where n is the core number, M is the total number of modes $(M = 3)$, and $m = 1$ for LP_{01}, $m = 2$ for LP_{11a}, and $m = 3$ for LP_{11b}.

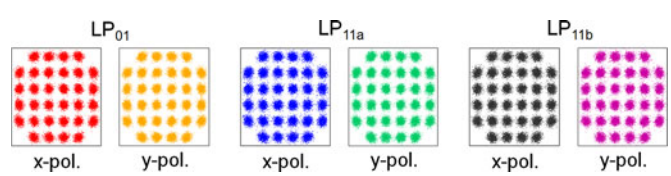

Fig. 10. Measured constellation diagram for core #2, wavelength #10, subcarrier #10 after 40.4 km transmission.

subcarriers within the 12.5 GHz WDM slot. The signals were split, relatively delayed for decorrelation, amplified, and were mode and core multiplexed by the spatial MUX. All 36 spatial tributaries had optical power of −6 dBm/wavelength/core/mode at the input of the MC-FMF. After transmission over 40.4 km, the signals were core and mode demultiplexed. The MDL was around 2.8 to 3.5 dB at the FO device and the mode DEMUX. No MDL compensation was performed in this initial DSDM transmission experiment. The three sets of signals were wavelength filtered, amplified, and input to the three signal input ports of the silica PLC coherent receiver module. They were converted into electrical signals and stored in a 12 channel digital storage oscilloscope. The data acquired were processed offline by the 6×6 parallel MIMO TDE with 61 taps per subcarrier.

Fig. 9 shows the Q-factors for all 36 DSDM and 20 DWDM channels. The number of SDM tributaries equals $(n-1) \times M + m$, where M is the total number of modes $(M = 3)$, and n and m is the core and mode number of the spatial tributary ($m = 1$ for LP_{01}, $m = 2$ for LP_{11a}, and $m = 3$ for LP_{11b}), respectively. Unlike the conventional optical fiber transmission experiments reported thus far, where the horizontal axis displays the wavelength channel, our axis plots the spatial channel, which is believed to be the first such case corresponding to the DSDM channels surpassing DWDM.

The Q-factors for all 720 tributaries were above the forward error correction limit of 5.7 dB assuming 20% overhead. Fig. 10 shows an example constellation diagram for core #2, wavelength #10, subcarrier #10. The net data rate was 86 Gb/s, the transmission capacity was 61 Tb/s (refer to Eq. (2)), the spectral efficiency was 6.88 b/s/Hz/core/mode, and the aggregate spectral efficiency was 247.9 b/s/Hz over 40.4 km transmission [14].

VI. Conclusion

We have reviewed the latest progress in SDM transmission, and evaluated the spatial and spectral efficiencies for various transmission schemes in the SDM transmission matrix. As the next significant step toward ultra-high capacity, we have demonstrated the world's first DSDM transmission with a spatial multiplicity higher than 30, and verified for the first time that the combination of multi-core and multi-mode in transmission provides high spatial and spectral efficiencies. Increasing spatial efficiency to over several thousand per mm^2 of fiber cross section is essential to raising spatial scalability by factors of over 100. Technologies essential to DSDM transport systems were elaborated, including SDM fiber, MIMO DSP, spatial MUX/DEMUXs, and device integration. The studies are in early stages, and future ultra-high capacity and long distance DSDM transmission should find further advancements in transmission scaling, optical fiber, DSP, device integration, SDM networking, and power efficient multi-core and/or multi-mode amplification technologies.

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