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INVITED SURVEY PAPER

Review of Space-Division Multiplexing Technologies in Optical Communications

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SUMMARY The potential transmission capacity of a standard single-mode fiber peaks at around 100 Tb/s owing to fiber nonlinearity and the bandwidth limitation of amplifiers. As the last frontier of multiplexing, space-division multiplexing (SDM) has been studied intensively in recent years. Although there is still time to deploy such a novel fiber communication infrastructure; basic research on SDM has been carried out. Therefore, a comprehensive review is worthwhile at this time toward further practical investigations.

key words: *capacity crunch, multi-core fiber, few-mode fiber, transmission, amplifier, switching*

1. Introduction

Optical fiber communication systems can carry enormous volumes of aggregated traffic because of their broad available bandwidth and extreme low propagation loss, which enabled large capacity and long-distance communications. The phenomenon of internet explosion was accelerated because of the increasing capacity of the core network. However, recently, traffic demands have reached the capacity limit of fiber communications [1]. In order to satisfy further capacity demands, a new technology is indispensable in the near future. This turning point is recognized as "capacity exhaustion" or "capacity crunch". The main technical reasons are fiber nonlinearity in standard single-mode fiber (SSMF) [2] (Fig. 1) and bandwidth limitation of available optical amplifiers [1] (Fig. 2).

Before the capacity crunch, several multiplexing methods were utilized (e.g., wavelength-division multiplexing (WDM) and high spectral efficiency coding [3]) to increase the transmission capacity per fiber. For example, coherent modulation using optical phases was suggested to increase spectral efficiency and total capacity; however, such a transmission system would significantly suffer from fiber nonlinearity. The limit capacity of SSMF is generally considered to be 100 Tb/s [4]–[6]. Because it is a potential candidate of breakthrough technology against the capacity crunch, space-division multiplexing (SDM) was investigated (Fig. 3).

Spatial utilization in SSMFs is quite poor because a thick cladding width is used to accommodate only one propagation mode whereas the density of optical power and the capacity of payload reached to the limit of one core. Since this was inefficient, SDM was introduced to utilize the unused area of the fiber. The primary candidate of SDM is a multi-core fiber (MCF). An increase in the number of cores can simply achieve higher capacity; however, several related

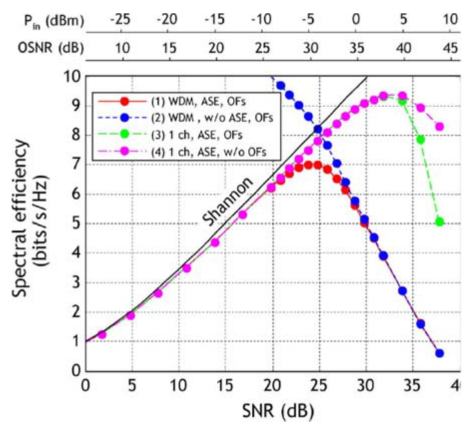

Fig. 1 Nonlinear Shannon limit [2]. ASE: Amplified spontaneous emission, OF: Optical filter.

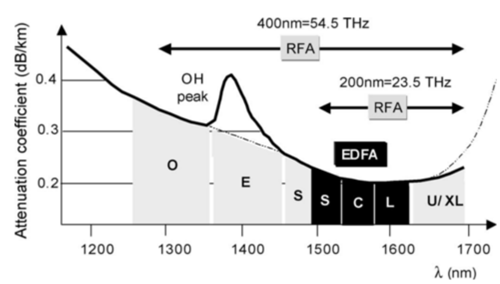

Fig. 2 Transmission window of fused-silica fibers showing standard optical amplification bands [1].

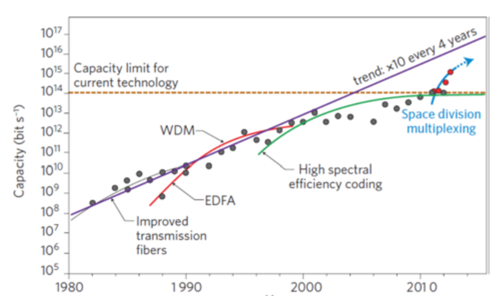

Fig. 3 Evolution of transmission capacity in optical fibers as evidenced by state-of-the-art laboratory transmission demonstrations [3].

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issues must be considered. Inter-core crosstalk (XT) is the most important parameter of MCF that is caused by mode-coupling/power-coupling between cores, and therefore, cores should be appropriately separated. Unfortunately, increasing the cladding diameter degrades the fiber's mechanical strength. Moreover, the adjustment of the propagation constant, effective area, cut-off wavelength, and bending loss should be considered.

Another major candidate is a few-mode/multi-mode fiber (FMF/MMF). By adopting optical discrimination or digital signal processing (DSP), higher order propagation modes can be determined, which can accommodate high bit rate modulated signals independently regardless of the fiber's modal dispersion.

2. Fibers for SDM

The early concept of MCF for transmission was created in 1979 [7], before the capacity crunch, when cost and compactness were greater issues.

The recent progress of fabrication technology enabled the MCF, which supports large capacity and long-distance transmission by adopting holey construction [8], [9].

The solid core is much easier to realize while mode confinement is rather weak. The reduction of XT is the major issue in MCF. Several methods were developed to reduce crosstalk by heterogeneous core layout [10], probable quasi-homogeneous result [11], and trench-assisted construction [12], [13] (Fig. 4). A different core pitch can adjust the crosstalk of inner core [14].

It has been previously reported that the behavior of XT is quite random/statistical and power-coupling is dominant than mode-coupling for practical fibers because of random fabrication errors [15]–[18].

The number of core/spatial channel counts is also an important factor for SDM fibers. A larger number of spatial channels is beneficial not only for total capacity but also for independently available optical paths for more granularity of network. There are two types of fibers with 10 or more spatial channels: single-mode MCF (SM-MCF) and few-mode MCF (FM-MCF). Such an increase of spatial channels is simply achieved by increasing the cladding diameter; however, it will decrease mechanical strength and long-term reliability. Therefore, a practical and optimal solution is still being pursued.

SM-MCF is much easier to achieve large capacity/long-distance transmission because single-mode propagation is stable and the increase in the core number directly reflects on the total capacity [19]–[23]. FM-MCF has a considerable potential of providing ultimate capacity and spatial channel counts [24]–[29]; however, the transmission system tends to be complex. In particular, the extension of fiber length and transmission distance is a severe issue.

As another candidate of SDM fiber, single-core FMF is also investigated for a practical transmission system. The key issues are number of modes, inter-modal crosstalk, and differential mode delay (DMD), which affects the complexity

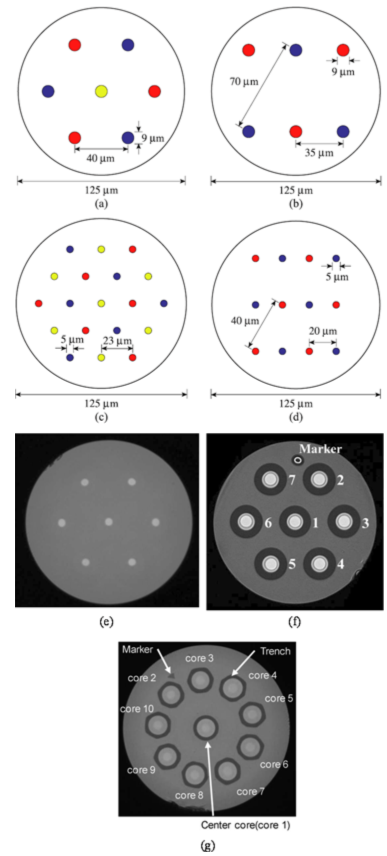

Fig. 4 Reduction of inter-core crosstalk in MCF: (a)–(d) Heterogeneous layout [10], (e) Quasi-homogeneous result [11], (f) Trench-assisted [12], [13], and (g) Variation of core pitch [14].

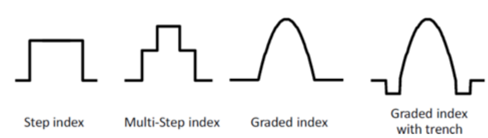

Fig. 5 Index profile types of FMF [30].

of DSP. A step index (SI) profile and a graded index (GI) profile are two major groups of the core. In general, the SI profile presents a larger DMD and is difficult to control inter-modal crosstalk, independently [30].

Figure 5 shows the representative core profiles, SI [31], multi-step index profile [32], GI [33], and trench-assisted GI [34], [35]. Other important parameters that affect the performance of transmission are mode coupling [36], [37] and mode-dependent loss (MDL) [38]. In order to increase the scalability of FMF capacity, investigations for precise optimization [39] or mitigation of DSP [40] are undergoing.

3. MCF Transmission

As the candidate for breakthrough technology against the capacity crunch, the primal and remarkable interest was in exceeding the capacity limit of 100 Tb/s.

The first record was 109 Tb/s achieved by using a 7-

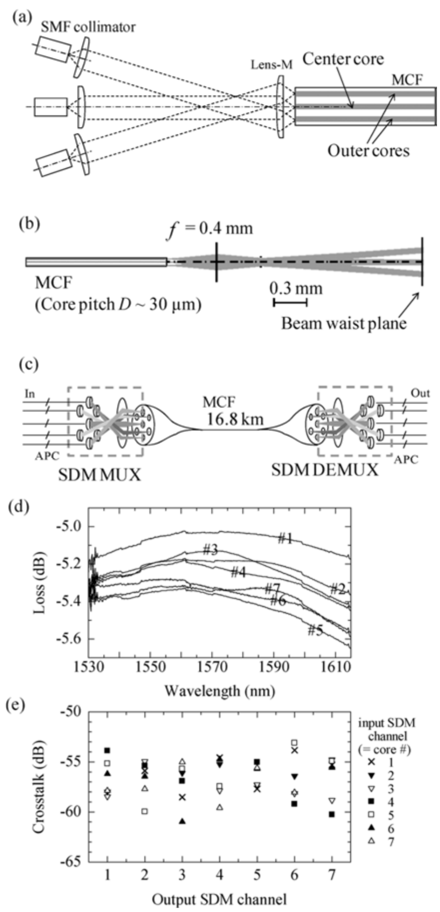

Fig. 6 SDM MUX/DEMUX [41]. (a) Schematic drawing, (b) Illustration of beam propagation, (c) Definition of SDM channels in this work, (d) SDM channel loss, and (e) SDM channel crosstalk.

core MCF [41], [42]. Two major enabling technologies were the design and fabrication of MCF [12], [13] and SDM-MUX/DEMUX device, which is the connection between SMFs and MCF. Free space optics (FSO) was adopted because of high power capability, adjustability, low insertion loss, and low crosstalk, as shown in Fig. 6.

The total length of the MCF was 16.8 km. The transmitted signal was 86 Gb/s QPSK multiplexed by 7 cores, 97 WDM, pol-mux, and the total capacity reached 109 Tb/s, after subtracting 7% of the FEC overhead. This demonstration was followed by another research group [43] that achieved 112 Tb/s in the same year. After these demonstrations, an international race of capacity record challenge started.

The next update of capacity record was 305 Tb/s [19], [20]; however, that was much more important as a challenge to increase the core number than the achievement of total capacity. 19 cores were accommodated within 200 μm diameter cladding as shown in Fig. 7. The total MCF length was 10.1 km.

FSO-based SDM MUX/DEMUX was also adopted. Upgrading from 7 cores to 19 cores was achieved by adding one core layer. The aggregated collimated-beams from MCF were steered by prisms as shown in Fig. 8. The total insertion

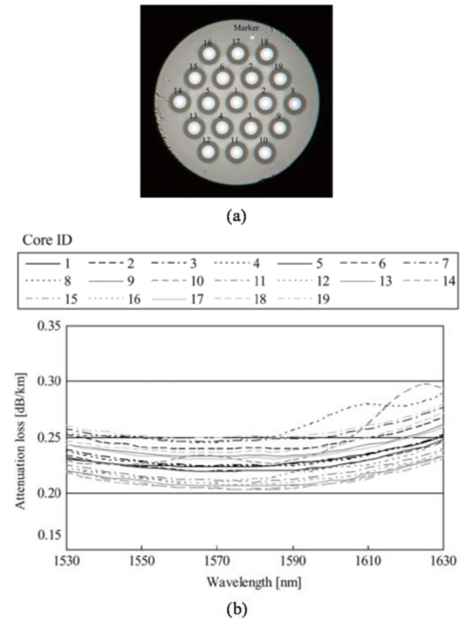

Fig. 7 19-core MCF [20]. (a) Cross section of MCF and (b) Attenuation spectra.

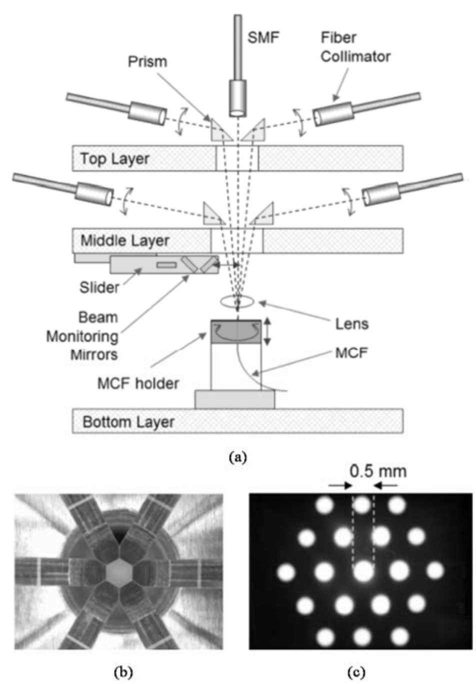

Fig. 8 SDM MUX/DEMUX for 19-core [20]. Schematic, (b) Top view of the six-prism array, and (c) Aggregated collimated-beam.

loss was 1.3 ± 0.2 dB across all 19 channels.

Because of dense cores within same cladding, XT was severer than that for the 7-core case. As the worst case, the average crosstalk of center core was −32 dB for 10.1 km; however, the inner core suffered aggregated crosstalk about −23 dB at 1550 nm and −17 dB at 1610 nm.

The transmitter/receiver configuration was almost same with previous 109 Tb/s experiment. An 86 Gb/s QPSK signal was multiplexed by 19 cores, 100 WDM, pol-mux, and the total capacity reached 305 Tb/s after subtracting 7% of the FEC overhead. Even with the worse crosstalk condition, the BER for every channel was measured as under the FEC limit of 1×10^{-3}.

One significant milestone was 1 Pb/s per fiber. The previous SDM transmission still had a margin of capacity because the spectral efficiency and WDM bandwidth were not maximized compared with the available technologies at that time. After the realization of MCF with 10 or more core numbers, achieving 1 Pb/s was only a matter of time. It was reported in same year as the 305 Tb/s record.

A transmission rate of 1.01 Pb/s was achieved with the 12-core MCF [21]. In fact, the 12-core MCF was realized by omitting the inner cores from the 19-core layout in order to avoid aggregated crosstalk in inner cores as shown in Fig. 9.

SDM MUX/DEMUX was fabricated from small diameter single-core fibers which were placed into a V-groove substrate and connected with MCF by fusion-splicing. The cladding diameter and span length of 12-core MCF were 225 μm and 52 km, respectively. Attenuation at 1550 nm and 1625 nm are 0.199 dB/km and 0.207 dB/km, respectively.

The average XT including MCF and SDM MUX/DEMUX was −38 to −32 dB at the wavelength range of 1526–1620 nm. The losses of SDM MUX/DEMUX including the fusion splice losses were 0.7–2.9 dB and 0.7–2.0 dB, respectively. The total losses between the SDM MUX/DEMUX including the 52 km of MCF ranged from 12.4–14.8 dB.

As shown in Fig. 10, a 32 QAM single-carrier frequency-division multiplexed (SC-FDM) signal with pol-mux was generated as a 456 Gb/s line rate for 222 wavelength channels. The total capacity multiplied by 12 core and 222 WDM was 1.01 Pb/s, subtracting 20% of the FEC overhead.

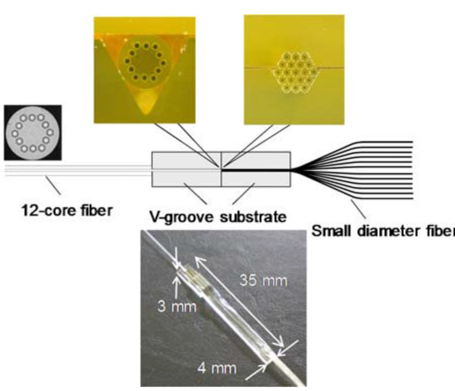

Fig. 9 12-core MCF and SDM MUX/DEMUX. As a courtesy of NTT.

Just after this achievement, another research group successfully achieved 1.05 Pb/s transmission by using a 14-core hybrid MCF [24] which has 12 single-mode cores and 2 three-mode cores. The MCF length was 3 km. 385 WDM channels of 19 Gbaud, DP-32QAM-OFDM signals for single-mode cores, and 354 WDM channels of DP-QPSK signals for three-mode cores were submitted. The SDM MUX/DEMUX was realized with FSO technique. The usage of FEC was rather complicated that 7% FEC in the L-band and 20% FEC in the C-band were used, respectively. These experiments used almost the full C+L band and 32 QAM, which has a much higher spectral efficiency than previous large capacity transmission. That is to say, additional resource margin brought by SDM were fully utilized. Therefore, it is indispensable to upgrade MCF itself to achieve higher capacity.

The next milestone was 2 Pb/s. There were two reports at same time.

The first one used a 22-core MCF [22] and optical frequency comb (OFC) light source in order to introduce the 64 QAM as a modulation format.

The homogeneous, 22-core MCF was based on a new 3-layer design with a two-pitch layout and total cladding diameter of 260 μm, as shown in the inset of Fig. 11. The 31.4 km span was spliced from 5 separately drawn sub-spans, giving rise to a total link crosstalk of −37.5 dB at the comb seed wavelength of 1559 nm. SDM MUX/DEMUX was the 3-D waveguide [44]. The dynamic skew between several core pairs of the fiber was measured which vary over only a few picoseconds range in 24 h in a lab condition. Such low variation in propagation delays between SDM channels is expected to be advantageous with respect to sharing of both transmitter hardware and DSP resources for which spatial super channels (SSC) can be realized [45]. In the SSC transmission scheme, groups of same-wavelength subchannels are transmitted through parallel spatial channels sharing the same light source and local oscillator. As a result, the DSP load will be reduced by exploiting information about common-mode impairments.

The frequency comb source consisted of a narrow linewidth (5 kHz) seed laser modulated with a low noise 25 GHz oscillator resulting with 25 GHz spaced comb spectrally broadened in a dispersion-engineered fiber mixer. 399

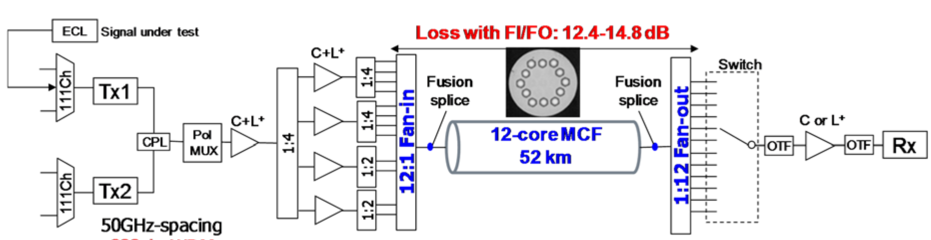

Fig. 10 Experimental setup for 1 Pb/s transmission. As a courtesy of NTT.

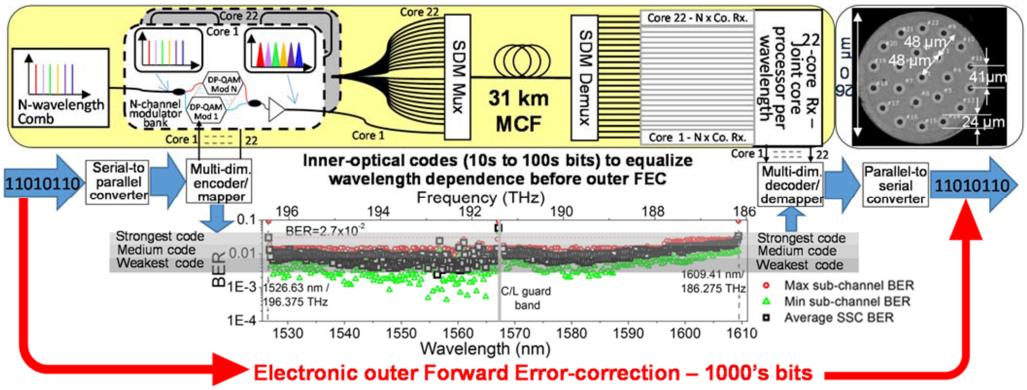

Fig. 11 Experimental setup for 2.15 Pb/s transmission through 22-core MCF and BER measurement result. SSC: Spatial super channel [22].

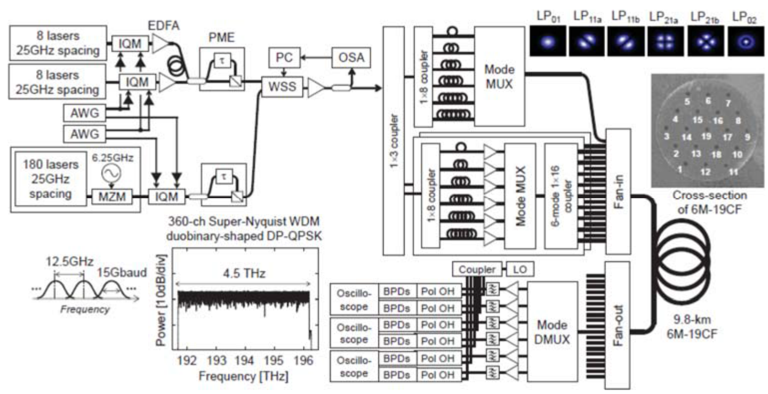

Fig. 12 Experimental setup for 2.05 Pb/s transmission through 6-mode 19-core MCF [47].

comb lines for the C+L band acted as 22-sub-channels of an SSC, each carrying 64 QAM modulation at 24.5 Gbaud (> 10 THz bandwidth) to transmit a total data rate of 2.15 Pb/s, subtracting 20% of the FEC overhead confirmed by BER measurements shown in the inset of Fig. 11.

Figure 11 also shows the schematic of how a transmitter and MCF could be integrated with such a joint-core reception and SSC coding. The BER plot shows that the uncoded channel has strong wavelength dependence with individual sub-channel BERs varying by over three orders of magnitude. Such variation can be problematic for choosing the most efficient outer FEC per channel because the overhead is usually determined by the pre-FEC and required post-FEC BER [46]. The option shown in Fig. 11 is to use some coding overhead on groups of channels, such as across SSCs, to reduce the variation of the pre-FEC BERs as shown by the lower variance in the average SSC BER (black squares). Furthermore, depending on the quality of each SSC, specific codes may be used to reach the target pre-FEC BER with the smallest possible overhead. Although not necessarily optimum grouping strategy, in this example, SSCs allow short optical codes of 100s bits to condition the pre-FEC BERs of serially coded electronic FEC using 1000s bits to attempt to maximize the overall throughput.

Another 2 Pb/s transmission used 6-mode 19-core MCF [47] as shown in Fig. 12. This MCF has 114 spatial channels that has the potential of 10 Pb/s capacity if all spatial channel ensure good isolation and both of C and L band were used. However, in this experiment, only the C-band was used for generating 360 wavelengths super-Nyquist WDM of 60 Gb/s DP-QPSK signals multiplexed by 114 spatial channels; the total capacity reached 2.05 Pb/s, subtracting 20% of the FEC overhead. This MCF sustained four mode groups of LP01, LP11a, LP11b, LP21a, LP21b, and LP02. The cladding diameter was 318 μm and the span length was 9.8 km, respectively. The core index profile was a graded index, which was designed to keep the coupling between the mode group small. The attenuation of LP01 was less than 0.5 dB/km. SDM MUX was the combination of FSO and multi-plane light converter, which generates the higher order mode from SMF input and their mode-multiplexed signal simultaneously [48]. At the receiver side, a half-symbol spaced 12×12 multiple-input and multiple-output (MIMO) equalizer was used for mode DEMUX regarding DMD dependency on the optical carrier frequencies of WDM channels. In the same manner, 10.16 Pb/s transmission was recently achieved [49].

On the other hand, the transmission distance is also an important benchmark. In such long-haul transmissions, a recirculation loop is indispensable whose configuration is distinguishing. A 2688-km transmission distance was achieved by using 7-fold, 76.8 km of 7-core MCF [50], [51]. In every loop, the source signal was launched to every core in sync through an optical switch, and simultaneously, core assignment was rotated in a cyclic fashion to average the variation of each core. The total net capacity was 7.50 Tb/s and the capacity-distance product reached 20.2 Pb/s·km.

In a simpler configuration, a 6160-km transmission distance was achieved by using 7-fold, 55 km of 7-core MCF [52], [53]. A loop was configured simply by connecting each core in series. The total net capacity was 28.9 Tb/s and the capacity-distance product reached 177 Pb/s·km.

In order to achieve a long-haul, large capacity transmission, core interleaving was proposed [54]. A double-ring structured, 12-core MCF was used as shown in Fig. 13. 12 cores were separated into 6 pairs and each neighboring pair was dedicated to counter direction in order to reduce XT. A 450 km transmission distance was achieved by using 12-fold, 50 km of 12-core MCF. In both directions, 409 Tb/s was transmitted: a total of 818 Tb/s and capacity-distance product reached 368 Pb/s·km.

A remarkable milestone of capacity-distance product was 1 Eb/s·km and two achievements were reported simultaneously.

In the first report [55], [56], as shown in Fig. 14, a 7326-km transmission distance was achieved by using 7-fold, 45.5 km of 7-core MCF. The total net capacity was 140.7 Tb/s with super-Nyquist WDM and capacity-distance product reached 1.03 Eb/s·km, subtracting 20% FEC overhead. The configuration of the recirculation loop was similar to Refs. [50], [51] with an optical switch in every fold that made synchronous 7-loops in a cyclic fashion. 30 Gbaud duobinary-pulse-shaped DP-QPSK signals were directly generated from 25 GHz spaced 201 WDM tones ranging from 191.2625 THz to 196.2875 THz.

As shown in Fig. 15, the second report [57], [58] achieved a 1500-km transmission distance by using 12-fold, propagation-direction interleaved 50 km of 12-core MCF same as [54]. The total net capacity was 2 × 344 Tb/s and capacity-distance product also reached 1.03 Eb/s·km subtracting 20% FEC overhead. 11.5-Gbaud Nyquist-pulse-shaped 16QAM signals were generated from 374 WDM tones for C+L (1533.28–1560.62, and 1567.68–1618.76 nm).

Recently, further achievement were reported as 1.51 Eb/s·km [59], [60], 4.59 Eb/s·km [61], respectively by using 12 fold, 46 km of 12-core MCF.

The summary of MCF transmission experiments are listed in Table 1.

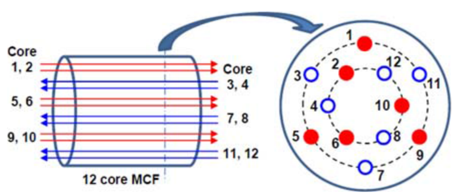

Fig. 13 Double-ring structure 12-core fiber with propagation-direction interleaving [54].

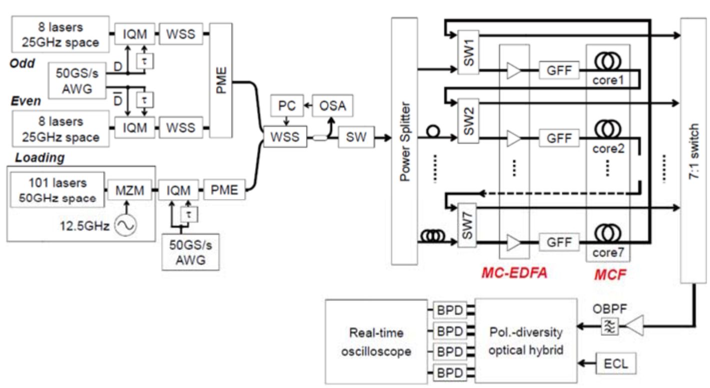

Fig. 14 Experimental setup for 140 Tb/s, 7326-km transmission [55], [56].

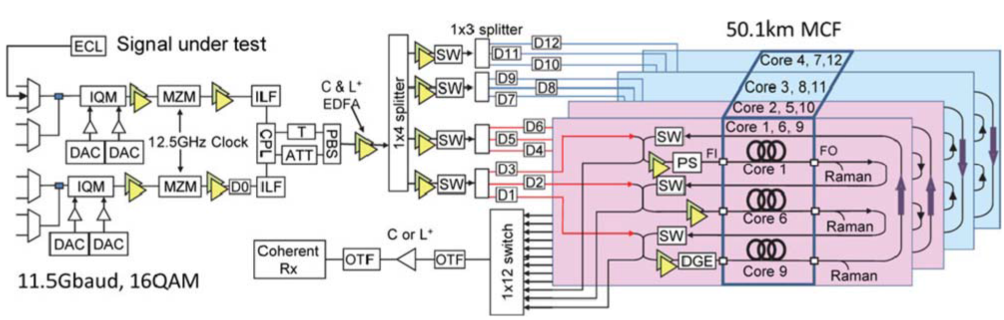

Fig. 15 Experimental setup for 2 × 344 Tb/s, 1500-km transmission [57], [58].

Table 1 Summary of MCF transmission experiments.

	[42,43]	[44]	[20,21]	[22]	[25]	[23]	[48]	[50]	[51,52]	[53,54]	[55]	[56,57]	[58,59]	[60,61]	[62]
Aggregated capacity [Tb/s]	109	112	305	1012	1048	2151	2052	10161	7.5	28.9	818 (409x2)	140.7	688 (344x2)	105.1	520
Number of Cores	7	7	19	12	12 +2(x3)	22	19 (x6)	19 (x6)	7	7	12	7	12	12	12
Cladding diameter [μm]	150	186.5	200	225	216	260	318	267	186.5	200	225	-	225	-	-
Fiber length (Distances) [km]	16.8	76.8	10.1	52	3	31	9.8	11.3	76.8 (2688)	55 (6160)	50 (450)	45.5 (7326)	50 (1500)	46 (14350)	46 (8830)

4. Spatial Super Channel Techniques/Self-Homodyne Detection

Another derivation of MCF technology is the usage of redundant spatial channels to enable new MCF-based optical transmission schemes that may be advantageous in terms of DSP resources and energy consumption.

SSC exploits the fact that the several cores of an MCF exhibit statistical correlation among different cores for some impairments, referred to as common-mode impairments. In SSC, one transmitter laser is split and shared among all channels, and at the receiver, one local oscillator (LO) is split and shared for all receivers. The fundamental idea of SSC was introduced in [46]. In addition, this relates to the self-homodyne detection (SHD) described below in the sense that the core-to-core signal coherence of SHD in MCF can also be exploited to realize core-joint DSP, and thus, to reduce the total cost per bit compared to an equivalent SMF or ribbon-fiber transmission system.

Previously, a transmitted pilot-tone (PT) originating from the transmitter laser, is space- or polarization-multiplexed [62] with the data signal and used as LO for coherent reception. Phase coherency between the data signal and the PT yields phase noise cancellation (PNC) after coherent detection, which can be exploited to reduce the impact of laser phase noise, and subsequently be used to enable spectrally efficient high-order modulation formats. Further, PNC in SHD can relax the required rate carrier-phase recovery by several orders of magnitude as demonstrated with shared carrier reception schemes in MCFs where both signal and PT are received with intradyne detection (ID) receivers [63]. SHD with a PT transmitted on an orthogonal polarization to the data suffers from a reduction of spectral efficiency (SE) of up to 50% compared to PDM transmission. On the other hand, the SE reduction due to PT transmission compared to an equivalent ID scheme is inversely proportional to the number of SDM channels. As an additional impairment in all SHD systems, the impact of the accumulation of noise on the PT during transmission was evaluated [64], [65].

The prospect of employing SHD in multi-mode fiber systems was investigated numerically [66] and implemented for an access network scenario in [67].

SHD demonstration in MCFs were achieved for linewidth sensitive 5 GBaud QPSK signals using low-cost DFB lasers with MHz linewidth [68], 105 Tb/s transmission [69], and 210 Tb/s WDM-SDM-PDM transmission with the use of PDM-QPSK signals. This transmission rate, assuming a 7% overhead for forward-error correction (FEC) gave an SE of 33.4 b/s/Hz [70]. A long distance SHD transmission for 6800 km was also investigated [71].

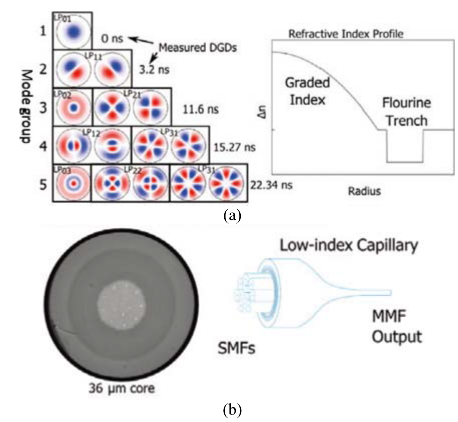

Fig. 16 15 mode optics [77]. (a) Properties of the 22.8 km 15 mode fiber supporting 30 spatial and polarization modes. (b) 15 mode photonic lantern.

5. Mode-Division Multiplexing Transmission

The advantages of mode-division multiplexing (MDM) transmission system based on FMF are larger effective area with relatively simpler fabrication than MCF. Further, channel scalability can be expected with increasing performance of DSP. A combination of optical discriminator and MIMO signal processing can distinguish higher order LP-modes that accommodate high data-rate coherent modulation. In an early trial, 2×2 MIMO with 100 Gb/s [72], [73] and 6×6 MIMO with 56 Gb/s [74], [75] were demonstrated. As a SDM-MUX/DEMUX, FSO is proposed in an early report. However, a photonic lantern (PL) is dominant in many papers. PL has a tapered structure and optical signals were converted adiabatically from single-modes to multi-mode. SDM-MUX of PL illuminates appropriate spots in the multi-mode core, and the combination of the spots generate individual higher order modes. By using SDM-DEMUX with the same configuration, representative spots were divided to single-mode cores, which were fed to MIMO processing.

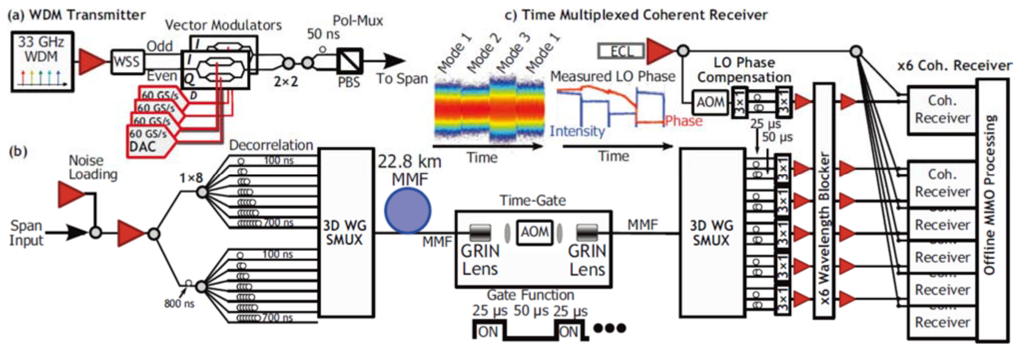

Fig. 17 Experimental setup of 15 mode, 30×30 MIMO MDM transmission [77]. (a) WDM transmitter, (b) Fiber span with AOM time-gate, (c) Time multiplexed coherent receiver setup. Insets show how modes are stacked in the time domain, and the measured LO phase correction.

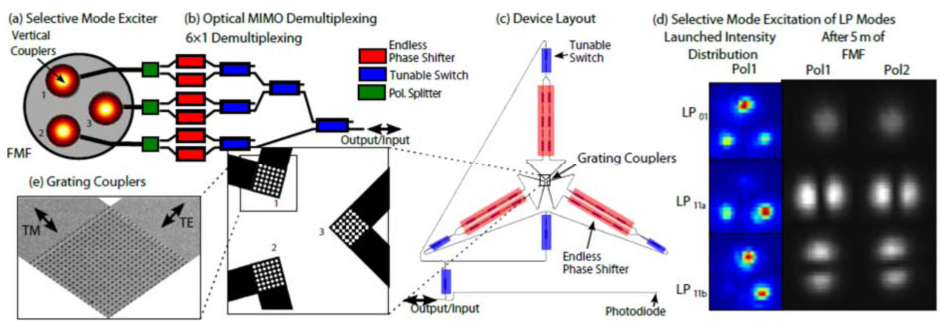

Fig. 18 All-optical MIMO configuration [78]. (a) SDM mode coupler. (b) Optical MIMO demultiplexing. (c) Device layout. (d) Selective excitation of each LP mode using the PIC. (e) 2D grating couplers and arrangement that collects light from a FMF and simultaneously acts as a polarization splitter.

The proposal to reduce MIMO complexity by the combination of several MIMO sets was also demonstrated [76]. Recently, available MIMO complexity has increased up to 30 × 30 [77] for 15 mode MDM transmissions, as shown in Figs. 16 and 17. Since it was quite difficult to prepare enough numbers of electronics, a kind of emulation technique, which included 3 multiplexing schemes consisting of five coherent receivers, was conducted in this experiment. 33 GHz spaced 12WDM of 30 Gbaud PDM-QPSK signal in 15 mode were transmitted.

In such MDM transmission demonstrations, MIMO complexity according to increase of the number of spatial channels (modes) was a serious problem. As an alternative candidate, all-optical MIMO was investigated.

In the first demonstration, all-optical MIMO was fabricated in photonic integrated circuit (PIC) [78] as shown in Fig. 18. In fact, it was an optical circuit that had tapping and re-construction of coupled signals in optical waveguide and components with the support of computer. Even though the computational load was not mitigated drastically, it could realize partial implementation of MIMO in optical manner, at least. In the experiment, PIC-based all-optical MIMO successfully demultiplexed MDM signals after 30 km differential group delay (DGD) compensated FMF.

The derivation of MDM transmission media is coupled multi-core fiber (CC-MCF), which supports spatial super-

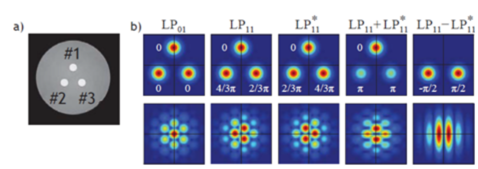

Fig. 19 Coupled multi-core fiber [79]. (a) Cross section, (b) Linearly polarized super-modes (upper row) and corresponding far-fields (bottom row).

mode consisting of each propagation modes in single-mode core as shown in Fig. 19 [79]. In previous review of MCF, XT was a serious issue in order to receive signals accommodated in each core independently with small amount of bit errors. CC-MCF transmission system presupposes the use of MIMO and increase XT by reducing core pitch intentionally. It can be treated the same as multi-mode with the help of MIMO and can achieve long-haul transmission.

In the same manner, the transmission distance increased to 4200 km with 3 cores [80], 1705 km with 6 cores [81], and recently 5500 km with 4 cores was achieved [82].

On the other hand, the increase of total capacity in MDM is rather difficult compared with MCF transmissions.

The total capacity challenge in MDM transmissions were conducted as 57.6 Tb/s [83], [84] and recently at 115.2 Tb/s [85].

6. SDM Amplifiers and Connectors

For practical transmission systems, amplifiers and connectors for SDM are indispensable. Because one of advantage of SDM is integration, these components are expected to contribute significantly to enhance integration.

Optical amplifiers need a combiner for signal lights and pumping light, an isolator, and a gain equalizer. In the case of multi-core amplifier, there are two derivations of the pumping scheme of core- and cladding-pumping, because of more complex waveguiding than a single-core fiber. The first 7-core EDFA demonstrated simply combined signal and pumping light, which is the same as conventional EDFA; then, 7 mixed lights were introduced to the individual cores of the 7-core EDF, as shown in Fig. 20 [86]. No integration other than the EDF was conducted. A similar configuration in a 7-core remotely pumped optical amplifier (ROPA) is also reported [87], [88].

A shared core-pumping scheme was demonstrated in a 19-core EDFA whose WDM coupler was configured by FSO, as shown in Fig. 21 [89]. The output of 10 pumping LDs (Laser diode) were split to 19 beams and combined with 19 signal beams by one dichroic mirror. The FSO coupling system for MCF to MCF was a key technology. A 19-core isolator was also realized in the same manner. Thereby, the WDM coupler and isolator were integrated.

Such sharing of pump LD is also applicable for Raman amplifier [90].

For further integration, cladding-pumping was proposed, as shown in Fig. 22 [91].

A multi-mode LD was used for pumping because it has higher energy efficiency and good coupling with inner cladding of EDF. A well-integrated WDM coupler was also realized by FSO. However, such end-pumping has the problem of thermal effect caused by uncoupled pump light.

Better performance can be expected by a side-pumping scheme, as shown in Fig. 23 [92].

The MMF carrying the pumping light was tapered while a short section of the MC-EDF (Multi-core Erbium doped fiber) was stripped off its low-index coating. A tapered MMF was wound by 1.5 turns around the stripped section of the MC-EDF. 4.7 W pumping power was successfully coupled to the EDF by launching 7 W from the pumping LD. By this configuration, a small signal gain of $>$ 20 dB for a full C-band was achieved.

Recently, a side-pumping scheme and a GRIN-lens based isolator realized 32-core fully integrated MC-EYDFA (Multi-core Erbium Ytterbium doped fiber amplifier) [93], [94].

An amplifier for MC-FMF (Multi-core few mode fiber) was also realized by using an annular cladding fiber design, as shown in Fig. 24 [95], [96].

The side-pumping scheme was used and the pumping power was concentrated within the annular cladding to improve the power efficiency. As shown in Fig. 24, the pump intensity in the ring is 1.4× brighter than the central cladding.

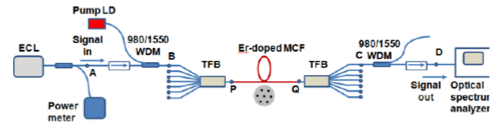

Fig. 20 7-core EDFA, individual core pumping [86]. TFB: Tapered fiber bundle.

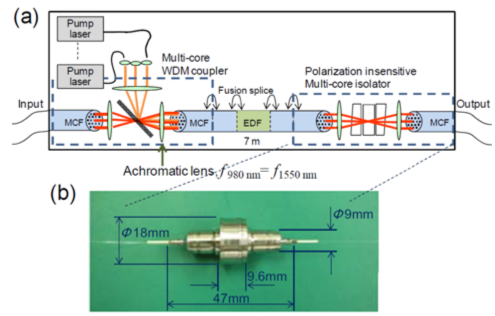

Fig. 21 19-core EDFA, shared core pumping with 19-core isolator [89].

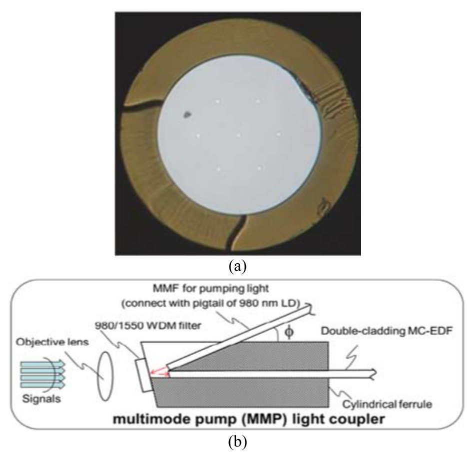

Fig. 22 Cladding-pumped 7-core EDFA [91]. (a) Cross section of double-cladding EDF. (b) Schematic of pump signal combiner.

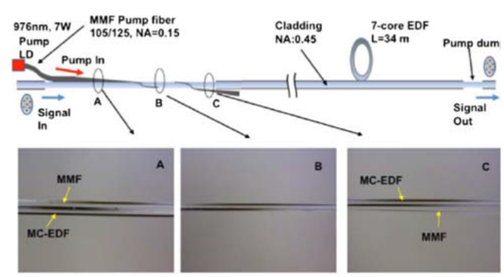

Fig. 23 Side-pumped 7-core EDFA [92].

Gain equalization is another important requirement of optical amplifiers. For MC-EDFA, LCoS (Liquid crystal on Silicon)-based SDM gain equalizer was proposed as shown in Fig. 25 [97]. Core distribution was steered by TE/TM splitter and FSO while the WDM signals were dispersed by grating. Both de-multiplexed components in free-space were attenuated by a single LCoS and re-combined in the same optical paths. Thus, a programmable gain equalization was realized.

On the other hand, amplifiers for MDM transmission were investigated. The configuration of multi-mode (MM) amplifier is much simpler than that of multi-core (MC) amplifier in principle because spatial channels co-exist in the same core. However, gain equalization is significantly important to reduce mode-dependent gain (MDG), because each mode has a different optical distribution in the core. This is different from the usage of an equalizer in the MC amplifier because every mode of the MM-amplifier is coupled with each other.

The first trials were conducted for 3-mode EDFAs [98]–[101] and Raman amplifier [102]. The WDM coupler was fabricated with FSO by using dichroic mirrors. In order to equalize the gain difference between the modes, several techniques were utilized, such as pump light adjustment of pumping power, mode conversion of pump light.

Different ring profiles for the refractive index and erbium doping of the MM-EDF can amplify LP01, LP11, and LP21 — a total of 6 modes. After this report, a ring doping profile become a major candidate for gain equalization [103].

The shaping of the launched pump light is also effective to equalize the MDG [104].

However, according to the increase in the mode number, the MM-amplifier also faces the issue of integration and scalability. One of proposed solution is cladding pumping, similar to that in the MC-amplifier [105].

The latest report of the MM-amplifier achieving 10-mode amplification, which adopted side-pump coupling with the cladding pumping scheme, is shown in Fig. 26 [106]. The amplifiers for both the types of SDM exhibit similar evolution scenarios.

Along with the amplifier, the SDM fiber connection progresses; the connection between the same SDM fibers can be realized by fusion-splicing [107] or detachable connector [108]–[110]. In the same manner, physical contact up to 19 cores was realized [111].

As described in the MCF transmission section, FSO is a good candidate to realize SDM-MUX/DEMUX between the MCF and SMF [112]–[114], which can also accommodate a functional optical device within the setup. Other technologies for MCF-SMF connection are tapered fiber bundle [43], [115], GRIN, and micro-lens array [116].

For the SDM-MUX/DEMUX between the FMF and SMF, PL is a major candidate [117], [118]; however, multi-plane phase plate also presents ideal mode conversion up to 10 modes, as shown in Fig. 27 [119]–[121]

A PIC based on silicon photonics can also realize mode-multiplexing to ring-core MMF [122]. Thus, the investiga-

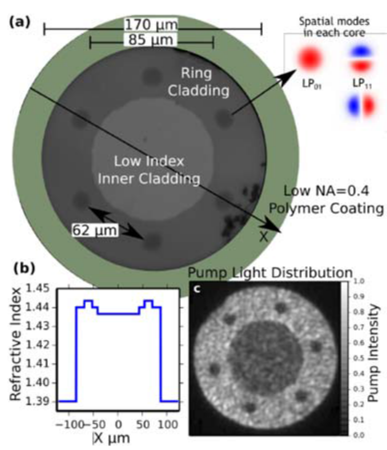

Fig. 24 3-mode, 6-core EDFA with annular cladding [95], [96]. (a) Facet image of amplifier with dimensions, (b) Refractive index profile. (c) Pump light distribution at 980 nm.

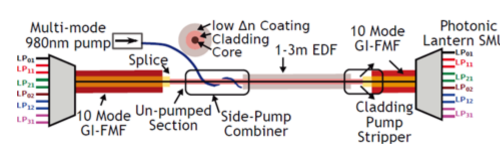

Fig. 26 10 mode EDFA [106].

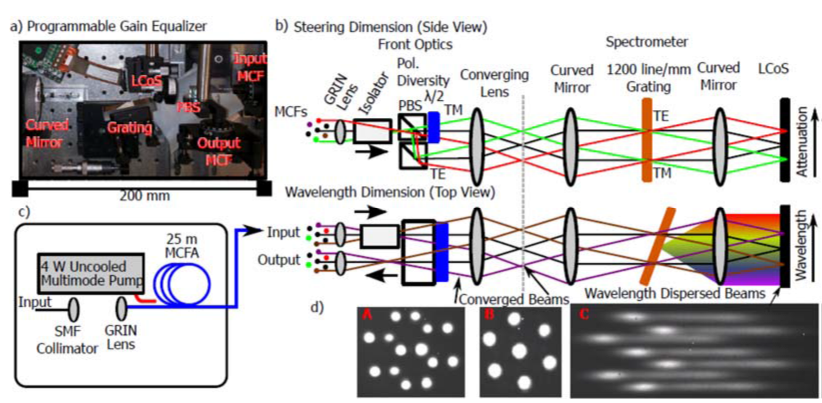

Fig. 25 Gain equalizer for MC-amplifier [102]. a) Image of the programmable gain equalizer, 100 mm FL curved mirror, 50 mm FL converging lens, 1.8 mm FL GRIN lens, b) Operation principle viewed from the top (wavelength) and side (attenuation and polarization diversity). Curved mirror is unfolded as two lenses to illustrate the operation principle, c) Side-pumped cladding pumped multi-core fiber amplifier (MCFA). d) Images of the beams at different locations when illuminated by C-band amplified spontaneous emission.

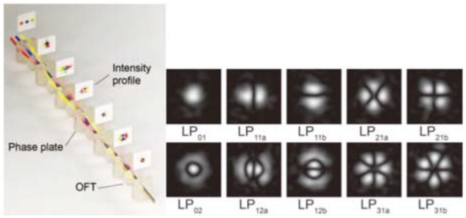

Fig. 27 Schematic of multi-plane phase plate and converted mode profiles, OFT: Optical Fourier transform [121].

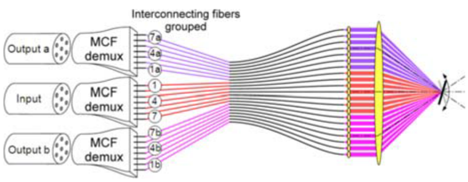

Fig. 28 ROADM with MCF interface [128].

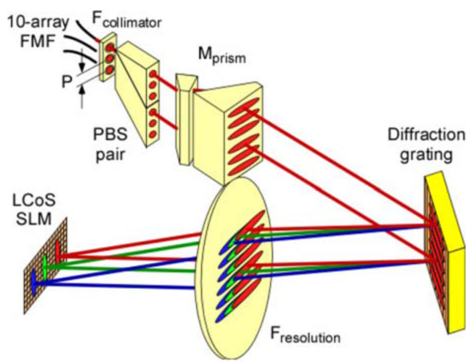

Fig. 29 WSS with MMF interface [130], [131].

tion of technologies for SDM connection is progressing.

7. Toward SDM Network

In addition to a point-to-point transmission demonstration, the experiments of switching and networking by architecture-on-demand (AoD) nodes have been proposed and also demonstrated to incorporate SDM links [123]–[127].

On the other hand, as a switch fabric for SDM, reconfigurable add-and-drop-multiplexers (ROADM) designs in the MCFs have also been proposed as shown in Fig. 28 [128], [129].

Commercial 1×20 wavelength-selective switches (WSS) were used to realize 1×2 switching for 7-core MCF. MC-ROADM comprised two WSSs in tandem in a switch-and-select configuration. Forty 50-GHz spaced PDM-QPSK at 128 Gb/s were introduced to MC-ROADM to support the SSC.

Almost in the same principle, WSS with MMF interface was also demonstrated, as shown in Fig. 29 [130], [131].

Both the switch fabrics have similar configurations with the ROADM for WDM switching based on LCoS. Hence, the fabrication technologies were easily used for commercial products.

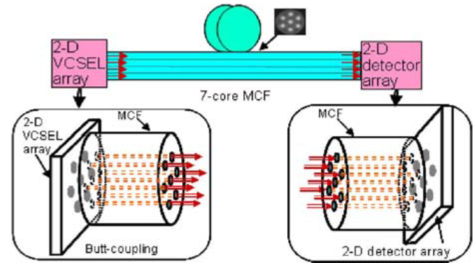

Fig. 30 VCSEL/PD array coupled with 7-core MCF [134].

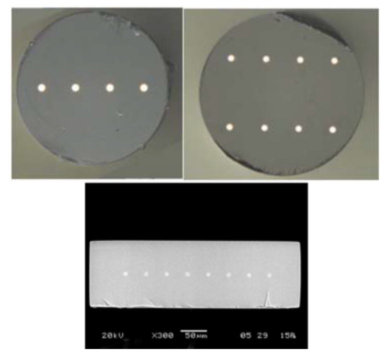

Fig. 31 Linear array MCFs for computer-compatibility [136], [137].

Summarizing these techniques, SDM joint switching between the SMF, FMF, and CC-MCF was conducted [132].

8. Short Reach/Datacom

It will take a little bit longer time that new SDM fiber is deployed in telecom infrastructure regarding the past time-frame that current SMF network was deployed. Pursuing earlier commercialization, short-reach communication was investigated. In such a case, the requirement for inter-core crosstalk will mitigate drastically as compared to long-haul applications.

Because VCSEL (Vertical Cavity Surface Emitting LASER) can provide an array layout by separating several tens of micrometers, multiple signal coupling to a MCF is much easier than that in pigtailed lasers. The first attempt to transport VCSEL light through 4-core MCF was demonstrated in 1999 [133]. 7-core MCF transmission was demonstrated with high-speed data modulation of the VCSELs [134], [135], as shown in Fig. 30.

In Datacom application, the core number and layout should take computer-compatibility into account. Four or eight cores with linear-array-structure MCFs were proposed as shown in Fig. 31 [136], [137].

Further specialization for high-performance computing (HPC) required much simpler commodity. Dual-core MCF and detachable connector, which support bi-directional transmission in one fiber, were demonstrated for datacenter applications, as shown in Fig. 32 [138].

In addition, an 8-core MCF for O-band short-reach application was also proposed [139], [140]. This MCF maintained a cladding diameter of 125 μm, which is the same

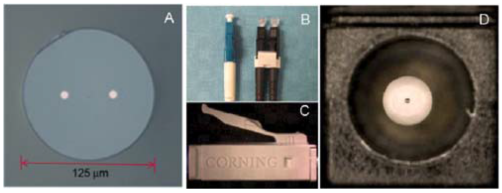

Fig. 32 Dual-core MCF and connector [139].

as that in a conventional SMF, to reduce the overhead of manufacturing equipment.

In order to explore practical application in Datacom, the SDM datacenter network was demonstrated [141] using a multi-element fiber, which accommodates three thin fibers with the same prime-coating.

9. Conclusion

SDM technology is attractive to achieve significant capacity and granularity in optical networks. However, the cost per bit in communication has to be considered carefully during the first commercial deployment. Many types of SDM fibers with different properties were investigated. The design of commercial SDM fiber has not to be unique. Variation in the SDM fiber can be acceptable in different applications that involve different requirements of capacity, distance, wavelength, environment, and so on.

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