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Review

Recent progress in optical devices for mode division multiplex transmission system

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A B S T R A C T

The idea of adopting the space domain as the next frontier for optical communication has received increasing attention in the last few years. Optical devices are the integral parts of a mode division multiplexing (MDM) transmission. Therefore, conducting an intensive study on the devices is paramount to the successful realization of the overall system. This paper presents a review of the recent advances in the inline components of an MDM system, consisting of mode converters, spatial (de) multiplexers, optical amplifiers, and few-mode fibers (FMFs). Also presented are different mode conversion and multiplexing schemes. Recent techniques of minimizing differential mode gain (DMG) in the optical amplifiers are also reviewed. The review covers other types of amplification schemes and their current standing in the MDM system. These include optical semiconductor amplifiers (OSAs), and the Raman amplifiers (RAs). Finally, the review also highlights the role of FMF, multicore fiber and their relationship with fan-in/fan-out devices.

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1. Introduction

The impetus that necessitates the move towards the adoption of space domain, as the next frontier in optical fiber network is the impending capacity crunch due to the single-mode fiber having achieved its fundamental transmission limits of 100-Tb/s in the early 2010s. This is further fuelled by Kerr nonlinearity [1], and the emergence of bandwidth-demanding systems and applications such as Internet Protocol Television (IPTV), video-on-demand (VoD), and multimedia broadcasting, etc. [2–4]. In recent years, coherent detection has been considered as an alternative approach towards increasing capacity of an optical communication network. It enhances the signal-to-noise ratio (SNR) of fiber network channels beyond that of the direct detection [5]. Optical quadrature amplitude modulation (QAM) with coherent detection helps in enabling high spectral efficiency (SE) as data are transmitted using both amplitude and phase of the carrier signals. The scaling in SNR can only be realised by maximising power, where channel capacity scales logarithmically as the signal power increases. Ultimately, increasing channel capacity by way of maximising power is not feasible to address the demands of the rapid traffic growth from both the technical and power consumption perspectives as the intrinsic nonlinearity nature of optical fibers limits the amount of signal powers.

The experimental capacities evaluation of the single-mode fiber (SMF) over the last couple of decades comprises different multiplex schemes. These include time division multiplex (TDM), which consists of producing a series of time slots and allowing a single scalar quantity of the amplitude or phase to change in accordance with a pattern within each time slots, hence the formation of symbols, which are transported in temporal succession at a given symbol rate. If each symbol represents one out of M possible level, for a pulse amplitude modulation (PAM), there will be $\log_2(M)$ bits of data transported per symbol. Pulse shaping can be further implemented to compress the network spectral pulses subject to time-frequency constrain [6]. Frequency division multiplex (FDM) involves transporting multiple communication signals in parallel to a K-independent carrier frequency over the same medium such as on the existing shared-transporting medium of mobile wireless channels. Scalability of FDM is typically bounded by regulatory bandwidth constraints, while natural physical properties are added constraints when twisted-pair or fiber cables are employed [7]. Polarization division multiplex (PDM) via coherent detection optical network exploits the vector nature of electromagnetic (EM) waves to transmit two separate information streams simultaneously on a set of dual orthogonal polarization. PDM increases transmission capacity by 2-fold compared to the non-polarized network. The dual polarization can be further enhanced by introducing correlations between symbols to give four-dimensional modulations that optimize network performance at the expenses of spectral efficiency [8]. It is important to mention that the significant difference between the TDM and wavelength division multiplexing (WDM) is the system requirements. Where the former requires an increase in the electronic speed and optical transmitter and receiver, whilst the latter requires a broadband optical amplifier and optical signal components. In addressing the earlier mentioned challenges and fulfilling the future requirements of high-capacity optical transmission systems, space divisions multiplexing appears to be a viable solution and has recently received a lot of research attention [1].

The concept of space division multiplexing (SDM) allows for the minimization of the network cost per bit for data capacity enhancement. Cost savings can effectively be improved by implementing device integration, which includes integrating multiple transmitters (TX), receivers (RX), and optical amplifiers such as erbium-doped amplifiers (EDFA) in a single circuit with the aid of switches. Different proposal to achieve multiple spatial signal channels has been studied. Figure 1(a)–(c) illustrates the three basic SDM fibers: fiber bundle; multicore fiber (MCF); and multimode fiber (MMF)/few-mode fiber (FMF). The least complex is to utilize fiber bundle (fiber ribbon/multi-element fiber) as the fiber management is similar to the multiple SMF systems. Hence, it can accommodate a smooth transition during system upgrade by adopting the existing components [9]. MCF is another interesting SDM fibre where individual fiber cores are incorporated in a common glass cladding. Among the superior features are: the optical path length of neighboring cores of MCF suffers less temperature instability, and MCFs can adopt a simpler system architecture as the local oscillator (pilot tone) can be transmitted and shared on one of the MCF core [10]. Also, weakly-coupled MCFs provide a more straightforward and promising approach as it targets minimum crosstalk in the adjacent cores so that multiple-input-multiple-output (MIMO) digital signals processing is not required for signal recovery. FMF uses mode orthogonality to constitute multiple signal channels [11]. Here, eliminating mode coupling is a major concern, compelling the use of MIMO and digital signal processing. There are also strongly-coupled MCFs, which are in some manner similar to FMF but it has additional advantages [12]. It is also plausible to combine MCF with FMF of a common cladding [13]. The highly achieved spatial mode signal multiplicities demonstrated to date adopted fibers of this configuration, which comprises 3-modes × 36-core FM-MCF, and 6-mode ×19-core MCF [14].

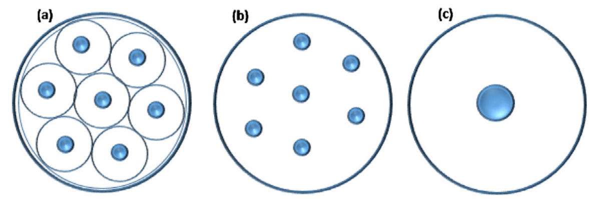


Fig. 1. SDM fibers, (a) fiber bundle, (b) multicore fiber, (c) multi-mode/ few-mode fiber.

Recently, it was reported that a net data capacity of 10.68 Tb/s was achieved using 96 WDM-MDM signal channels (32-wavelength x 3-mode) and a 111 Gb/s bit rate per signal channels. After spatial mode (de)multiplexing, all the 96 channels have the bit error rates (BERs) less than 1.8e $\times 10^{-2}$ as depicted in Fig. 2 [18].

This is the most recent study on advance modulation signal close to 100 Gb/s per lane on MDM silicon chips. The successful deployment of an MDM relies solely on the successful development of new optical components such as mode converters, multiplexers,

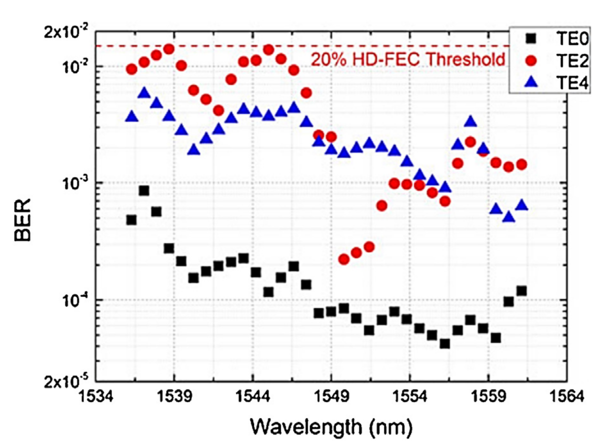


Fig. 2. BER performance for 96 WDM-MDM signal channels (32-wavelength x 3-mode) [15,16].

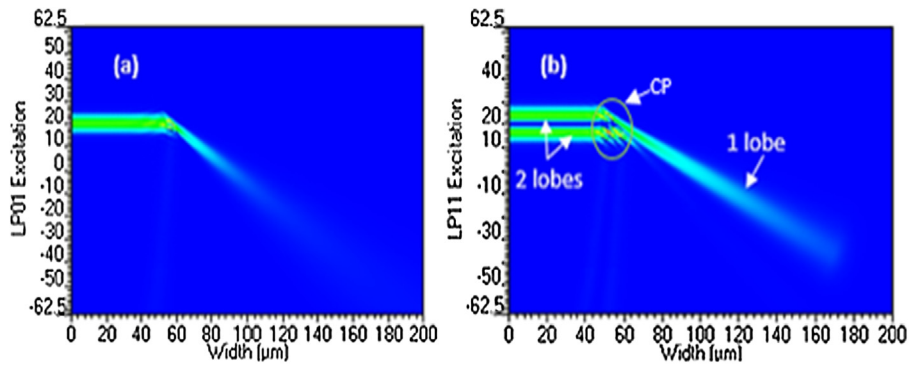


Fig. 3. Simulated example of mode conversion caused by the bending effect of (a) LP_{01}, (b) LP_{11} (after the bending, the two degenerates seem to couple because of the coupling).

optical amplifiers etc. [17,18]. In addition, FMFs for MDM poses various challenges such as large differential mode group delay (DMGD), mode-coupling effect, modal dispersion, and bending loss. Crosstalk and mode dependent loss (MDL) also requires careful design, fiber modeling, and overall system level control.

This paper focuses on the review of the recent progress in the optical devices applicable to the MDM optical system; these include components such as mode converters, (de)multiplexers, optical amplifiers, transmission media, and their challenges. The paper is organised as follows: Sections 2 and 3 provide reviews on mode conversions and multiplexing in the MDM system, respectively. Section 4 gives a detailed study on the recent progress in the optical amplification; these include the recent research on semiconductor optical amplifiers (SOAs) and Raman amplifiers (RAs). Section 5 presents progress and challenges in the FMFs and Section 6 gives a brief on the SDM system. Section 7 concludes the review paper.

2. Mode conversion in MDM system

Mode converter is one of the critical optical devices used for multiplexing in the MDM system and can be realised using various types of mode conversion (MC) techniques such as phase plate, a spatial light modulator (SLM), spot, planar lightwave circuit (PLC), fiber coupler, and photonic lantern. Some of the mentioned types can achieve selective linearly polarized (LP) mode excitation, which is a crucial aspect of an MDM network in which separate signal channels are combined using distinct excitation modes. Most of the available mode conversion techniques concentrate on conversion between the fundamental LP_{01} mode and higher order LP modes. Conversion of higher order LP modes was reported in Ref. [19], where a PLC-type mode rotator was designed and fabricated for the conversion of an LP_{11^a} (LP_{11^b}) mode to LP_{11^b} (LP_{11^a}) mode [22]. Perturbation of an incident field propagating in an optical fiber can induce mode coupling where modes are converted as it traverses the structure. For example, cleaving a fiber at an angle can influence coupling between mode degenerates (modes of similar propagating constant).

Figure 3(a–b) depicts the simulated example of such effects. Figure 3(a) shows the mode excitation of LP_{01} at the input of a horizontal fiber, where on propagating to the fiber output, which was cleaved at an angle, no coupling effect was observed. However, in Fig. 3(b), the two degenerates of the LP_{11} (LP_{11^a} and LP_{11^b}) modes were seen to couple at the output facet of the cleaved point (CP). The light coming from the output of a cleaved-fiber is deflected, the level of deflection depends on the cleaved-angle value [20]. From Fig. 3(b), only one lobe is dominant at the output due to the coupling effect.

Mode conversion/(de)multiplexing using liquid crystal on silicon (LCOS) [21] was realised by utilising SLM. On exciting the device with an LP_{01} mode, the power losses of the (de)multiplexer are around 16 dB, which was increased to 25 dB when employing the masks for an LP_{11} conversion. The additional multiplexing losses were contributed from mode conversion. Furthermore, the use of a phase plate technique was demonstrated [22] with a beam splitter, mirror, phase plate, and lenses aiding the mode multiplexing by means of conversion with coupling loss in the LP_{01}, LP_{01^a}, and LP_{01^b} of 9.6 dB, 9 dB, and 7.8 dB, respectively. Thus, the mode multiplexer/converter demonstrates mode selectivity of greater than 28 dB.

Free space optics mode conversion approach is insensitive to polarisation; broadband at the expenses of higher insertion loss (IL); and is usually bulky. An all-fibre MC based on long period fibre grating (LPFG) written in the FMF is reviewed [23]. An LP_{01} to high order mode conversion (LP_{11}, LP_{21}, and LP_{02} modes) was demonstrated using a single LPFG. The conversion efficiency (CE) of 99% was realised at 1553 nm wavelength. Inter-modal crosstalk on system capacity performance can be enhanced using dynamic routing, spectrum and mode assignment (MC-CA-RSMA) algorithm over SDM-EONs [24]. Here the converter was not only implemented and positioned at each node for flexibility in the conversion but is capable of converting up to twelve spatial modes. The algorithm adopted can highly mitigate crosstalk that influences system-blocking performance when compared to other algorithms. General purpose converter capable of converting virtually any given mode to any desired mode in FMF/MMF for spatial mode application was reported [25]. This was achieved using a phase-only SLM by programming it to a binary phase filter using the SA algorithm. The work precisely demonstrates conversion within LP_{01}, two degenerates of LP_{11} (LP_{11^a}, LP_{11^b}), LP_{02}, two degenerates of LP_{21} (LP_{21^a}, LP_{21^b}), and two degenerates of LP_{12} (LP_{12^a}, LP_{12^b}) with more than 80% correlation coefficient and selectivity of over 12 dB was achieved. In addition, MC contributes to the interferometric composition, wavelength filtering, and loss compensation in the MDM system. Finally, the overall applications of MCs contribute greatly to the success of mode multiplexing and amplification in the MDM system. Tables 1 and 2 summarise the recent advancement in MCs and show that most of the recent reported work concentrates on the conversion of an LP_{01} to the higher order modes. The conversion approach with minimum IL (0.2-0.5 dB) reported here is the mechanical mode converter [26], which employs periodic structure using the grating period (PSG). The all-fiber-doubly tapered converter demonstrates higher conversion efficiency (CE) close to 97–99% [27].

The following abbreviations were used in Table 1: converter model types (Conv. Type), mode conversion involved (M-Conv.), techniques applied (Method), insertion loss (IL) and extinction ratio (ER). In addition, operating wavelength (OP-WL), and applications (Appl.) of each of the converters are highlighted. Other abbrevia-

Table 1
Recent progress in conversion device for MDM system.

S/N	Conv. Types	Method	M- Conv.	IL(dB)	ER (dB)	CE (%)	OP-WL	Appl.	Ref.
1	Mode-selective couplers	CeL	LP_{01} SMF to LP_{01} MMF	1.7-2.1	Not reported	62-71%	C-band	WDM	[28]
2	integrated MC	FLT	LP_{01} to LP_{02}	<1	Not reported	>80%	C-band	MDM	[29]
3	Mechanical MC	PSG	LP_{01} to LP_{11}	0.2-0.5	Not reported	89 %	Not reported	MDM	[26]
4	All fiber MC	BCS	LP_{01} to LP_{02}	0.5	12	89%	C-band	MDM	[30]
5	Perturbed waveguide	U-CMC	LP_{01} to LP_{lm}	0.5	>13	Not reported	C-band	MDM	[31]
6	All-fiber-doubly tapered MC	DF-MC	LP_{01} to LP_{02}	Not reported	19-30	97-99%	O-, S-, C-Band	WDM/MDM	[27]
7	Reflective MC	FM-FBG	LP_{01} to LP11	Not reported	Not reported	99.5%	C-band	MDM	[32]

tions used in the table are centre launching (CeL), femtosecond laser techniques (FLT), periodic structure using the grating period (PSG), and bipyramid combined structure (BCS). Also, the remaining abbreviation used include ultra-compact mode converter (U-CMC), double fiber taper-based mode converter (DT-MC), 1.6°-tilted FM-FBG (FM-FBG), and spatial spectral matching (SSM), higher order mode (HOM) and original to any desired mode (O-ADM).

3. Mode multiplexers in MDM system

One of the vital devices in an MDM network is the S-Mux which combines K spatial modes into an FMF. S-deMux operates in the inverse way in which it separates the combined modes back to K spatial signal modes. Different strategies are employed to control the spatial modes of the FMF/MMF. For example, by launching the input mode into a random set of orthogonally combined eigenmodes of the fibre [1]. Thus, the mode channels are strongly coupled. This brings complexity in demultiplexing and requires full modal diversity and using complicated data signal processing (DSP). Another option may include using fibre and optical components that employ weakly coupled (uncoupled) spatial modes, reducing the DSP complexity to jointly detect the degenerate mode groups [33]. Regardless of the two approaches chosen, there must be a mode-selective S-deMux. The uncoupled approach requires a reduced modal cross talk generated by the S-deMux, so that mode selectivity ensures low MDL. This gives room to compensate the DMGD [34], which drastically reduces DSP complexity during transmission. Other essential issues for S-deMux are IL and the bandwidth to be large enough for compatibility with the WDM. Mode selectivity in multiplexers has been proposed using different techniques. The currently used mode of multiplexers in the MDM network is designed based on the free space components such as SLM [21], and phase plate [35]. These are relatively large, with a high cost of productions, and above all demonstrates high IL. Phase plate converters [36] are widely adopted because of their simplicity, at the expenses of high IL. Using mode-selective photonic lantern (MSPL) as an alternative with the distinct input SMF can minimise the IL [34]. However, achieving mode selectivity still remains a concerning issue due to the complication in the fibre modeling. A 10-mode S-deMux that demonstrates higher mode-selectivity, using MPLC, with a reduced IL over the full C-band and L-band was reported [37]. It demonstrates an average cross-talk of -26 dB, mode selectivity of 26 dB, and higher CE (low IL less than 4 dB when coupled to the MMF) and very low MDL (average MDL 1.2 dB).

Moreover, all fibre MDM multiplexers which include LPFBG [38], mode selective coupler [39], adiabatic tapered fibre multiplexer [40], photonic lantern [41], and PLC [42] are compact, cheap to produce, and demonstrate low IL with high CE. The photonic lantern has the ability of multiplexing many modes with low loss at the expenses of fabrication difficulty. LPFBG multiplexers are small interm of size and demonstrate low IL, with the narrow operating bandwidth. In opposed to the LPFBG multiplexers, selective mode couplers have the larger working bandwidth, minimum loss, and can be fabricated easily. All fibre selective mode (de)multiplexer for weakly coupled application is reported [43]. Based on the selective mode coupling, a composition of an SMF and FMFs was used with the LP_{01} mode in the SMF coupled to an FMF supporting high order modes. It was achieved by adopting cascaded couplers with the distinct matched-effective indices, and by so doing a pair of 6-mode (de) multiplexer was fabricated. The performance of the device was evaluated experimentally by transmitting 6-mode using the DP-QPSK modulation. An OSNR penalty of 3 dB while using partial 6×6 MIMO equaliser was achieved. On replacing it with the full 12×12 MIMO, the OSNR penalty was lowered to less than 1 dB. Recently, a novel three mode scrambling-type multiplexer [44] was reported with a less wavelength dependence and low ER. Nevertheless, the design is still superior over the conventional S-Mux that works based on asymmetric directional coupler, especially in terms of scalability to accommodate higher number of modes and fabrication tolerance. This multiplexer was made by cascading a y-branch waveguide with the rotator on silica planar circuit. Table 2 presents a summary of the recent technology reported in mode multiplexing for MDM system; under each device, a brief of the basic finding is highlighted. These include XT, IL, MCP, and ER.

4. Optical amplifiers in MDM system

The most recent and crucial optical amplification technique is the EDFA. This technology has the advantage of avoiding optical signal conversion into an electrical signal before it undergoes reconversion again into an optical one. Unlike other conventional optical amplification schemes, it has the advantage of reduced system complexity and power consumption. Figure 4(a)–(b) shows the schematic and mode of operation of an EDFA. It consists of an optical fibre doped with Erbium ions. The input signal is coupled into the fibre with help of a pump signal at a wavelength of $\lambda = 980$ or 1480 nm. Signal pumping can be injected from both or either side into the Erbium-doped fibre (EDF). This results in co- or contra-propagating pump signal [Fig. 4(a)]. Within the EDFA, photons of the input signal at a wavelength of around 1550 nm can force the Erbium ions to go back to the initial lower energy state and, hence, generating replicas of the signal photons by a process called stimulated emission [54]. In some cases, the Erbium ions can fall back to their initial energy level without experiencing any stimulation by signal photons, which referred in the literature as spontaneous emission. The produced photons amplified by the same mechanism as the initial photons

This process describes the amplified spontaneous emission (ASE) [55] and is considered as the main source of noise generation in optical amplifiers. The noise figure (NF) is a quantity of an amplifier due to generated ASE and quantified by analysing the physical process inside the amplifier.

Optical amplifiers are crucial to the successful deployment of large data capacity within an MDM system. MDM fibre amplifier design to support many spatial mode channels can be engaged to extend transmission to a longer distance (long-haul communications) and improve bandwidth in the SDM system. However, there are certain issues with the erbium-doped amplifiers in FMF. One of which is getting an adequate amplification gain at less differential

Table 2
Summary of the recent technology in mode multiplexing for the MDM system.

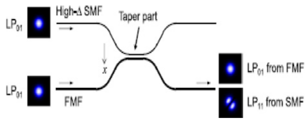
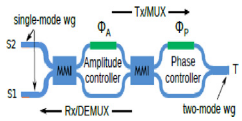
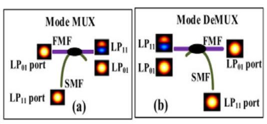
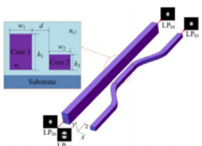
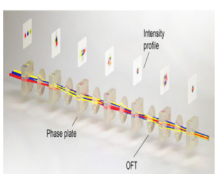
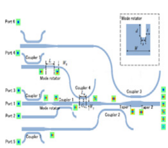
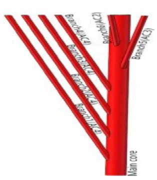
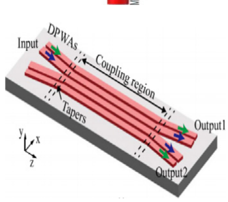
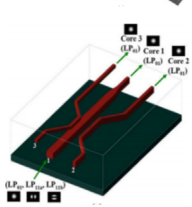
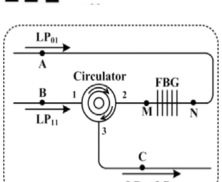
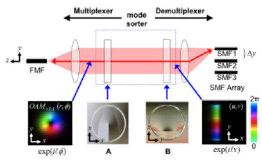
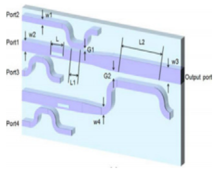
Device Technology	Device Properties				
	XT (dB)	IL (dB)	MCP(dB)	ER(dB)	Ref.
	<−20	−2.2 to 1.5	<−20	Not reported	[43]
	−20	<2	Not reported	14.5 to 16.3	[45]
	−22 to −20	0.3 (LP_{01}) 1.8 (LP_{11})	Not reported	15	[46]
	< −55 (LP_{01})	9.6 (LP_{01}) to 12.8 (LP_{11b})	0.95	Not reported	[47]
	−26	<4	Not reported	Not reported	[48]
	−23 to −16	1.3	Not reported	>15	[42]
	< −20	< − 0.05	Not reported	Not reported	[49]
	14	0.25 (average)	< 1	Not reported	[50]
	−23.2 to −14.6	1.7 to 6.4	10	Not reported	[51]
	> −20	4	Not reported	Not reported	[38]

Table 2 (*Continued*)

Device Technology	Device Properties				
	XT (dB)	IL (dB)	MCP(dB)	ER(dB)	Ref.
	Not reported	– 9	< 1.5	Not reported	[52]
	Not reported	<3.5	<1	> 20 (S,L), >15 (C)	[53]

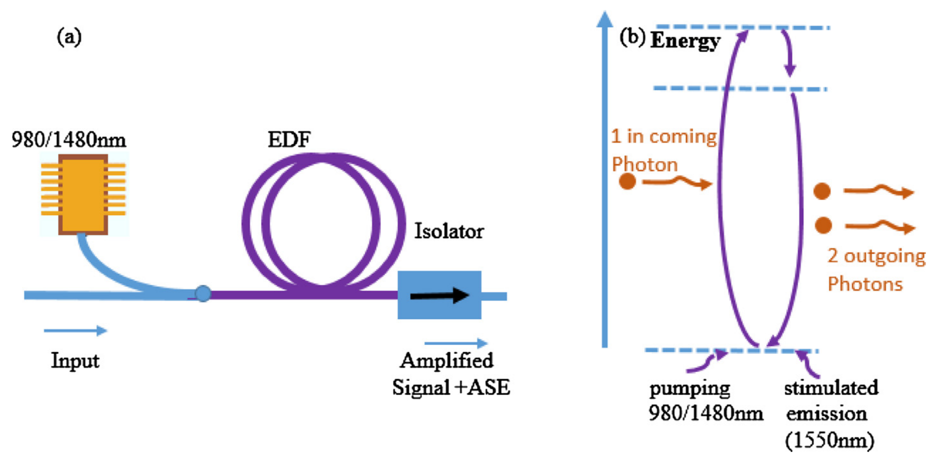


Fig. 4. (a) Schematic of a typical EDFA (b) Basic amplification principle in Erbium-doped amplifier.

mode gain (DMG) between the entire transporting mode channels for the overall performance of the MDM network. This is because the translation of the DMG to excessive MDL and can lead toward system outage [56]. In reducing DMG in MM-amplifiers, it is crucial to limit the overlapping integrals of the distinct modes which serve as a measure to minimise the overlapping between the excited ion and signal mode intensity profile.

Different techniques can be used to reduce DMG. For example, it can be achieved through adaptive equalisation or reconfigurable mode gain. This can be achieved in two different approaches. One of which is to put a control measure for the modal content of the pump (core or cladding). Here, the distinct pump modes powers are excited to a few-mode-EDF with parallel mode signals. The differential gains can be reduced by varying the pump power to the desired value. Some theoretical explorations have been adopted using this approach, in which the gain of an MM-EDFA can be controlled by turning the mode contents of the pump. It has been achieved by varying the power and input orientation which allows a dependent gain to be tuned over a given dynamic range. Thus, reducing the differential gain [57]. In addition, using SLM was also proposed as a technique to equalise the differential gain by adjusting the pump modes' power [58]. Varying the powers of the separate amplified modal signals was achieved by placing an SLM immediately after the amplifier to equalise the differential gain. Using higher-order mode pumping to minimise the differential gain has also been investigated experimentally. A 2-mode group amplifier (LP_{01} and two degenerates of LP_{11}) was demonstrated by adopting a step-index fibre consisting of a doped profile core region [59]. Furthermore, an investigation of all-fibre type MM-EDFA and control DMG using LPG was reported [60]. It was demonstrated that the DMG can be altered in between the range of -7 dB to 5 dB. The differential gain control was achieved by adjusting the LP_{01} to LP_{11} pump mode-ratio.

The second technique that minimises DMG is by controlling the doping level of erbium ions to the modes power distribution by, for example, ring-dope the ions. An investigation of the four-mode amplifier has been demonstrated [61] which engages the use of a fibre design constituted by two sections of distinct-doping levels. It demonstrates a low gain of less than 1 dB in the 4-mode EDFA that uses simple pumping configuration by adopting the LP_{01p} and LP_{41p} as the pump modes. Moreover, a five-mode amplifier using a ring-doped profile has achieved a gain greater than 13 dB at DMG of less than 5.7 dB [62]. Similarly, a 6-mode EDFA with circular ring-structured profiles was initially used on Er^{3+}-doped for the gain equalisation that employs a conventional fibre fabrication procedure [63]. Nevertheless, gain equalisation through this technique is difficult to realise experimentally. Thus, a new approach based on a "pixelated" Er^{3+}-doped core was implemented to achieve gain beyond the initial limit. In addition, a six-spatial mode optical amplifier with a reconfigurable DMG control was demonstrated using a bi-directional pumping technique in association with the Erbium doped amplifier [64]. A specially tailored doped-profile leads to achieving a gain greater than 20 dB for the LP-modes, demonstrating DMG of less than 2 dB. The photonic lantern was used to achieve mode selective amplification in a large mode area cladding-pumped Yb-doped fibre [65]. This reported signal gains of around 19 dB and output power greater than 1 W. In another report, a gain control six-mode EDFA was demonstrated by adopting MSPL for the pump light control. The device shows the ability to amplify the six modes separately with DMG value of less than 1 dB and a signal gain of around 16.17 dB [66]. An DMG can be reduced using ring-core EDFA (RC-EDFA) as reported in Ref. [67], a ring core and conventional step index EDFA are compared in terms of DMG. It was found that the RC-EDFA demonstrates a lower DMG of 1.6 and 1.8 dB for LP_{01} and LP_{11}, respectively. While 9.2 dB and 6.1 dB are respectively determined for the LP_{01} and LP_{11} using a conventional step-index EDFA.

Multicore EDFA (MC-EDFA) is also considered as a key element for the integration of MCF SDM-based network. A cladding pump approach was reported for an SDM-EDFA to realise 18 channels (comprising 6-cores by three-modes) [68] which utilises a common pump diode that exhibits similar complexity of a single mode EDFA (SM-EDFA). The amplification delivered a total power of greater than 20 dB m per core and NF of less than 7 dB over the C-band. This SDM-EDFA can combine SDM-WDM over a parallel MMF span. In addition, a ring-shaped index profile adapted to MC-FM-EDFA, Fig. 5(a) depicts a cross-section of the fabricated MC-FM-EDF [69] which consists of 7-cores all laid close to each other in hexagonal form. The core pitch of 40.3 μm housed by a cladding of 153 μm in diameter was employed. The core in each of the FMF supported 2-modes (LP_{01} and LP_{11}), cutting-off the LP_{21} mode at 1470 nm wavelength.

The MC-FM-EDFA connection was made to a WDM coupler modules (using free-space coupling), which comprises optical isolators and changeable binary phase plates to pump the light to achieve mode conversion [70] with the help of FI/FO device. Both the gain and the noise characteristics of the MC-FM-EDFA are calculated core by core. The amplification gain and the NF values are shown in Fig. 5(b) [69]. Table 3 summarises the recent progress in SDM/MDM-EDFA technology. It includes the method applied in the amplification process, the NM involved, and the average gain (AG) obtained. Also included in Tables 2–3 are the DMG, NF, and the pump power (PP). Other abbreviation used in the table includes nondominated sorting genetic algorithms ((NSGA-II), intensity and field model (IFM), intensity model (IM), field model (FM), cladding-pump (CP), few-mode distributed Raman amplifier (FM-DRA), and ring-core erbium-doped fiber (RC-EDFA). Also, overlap integral (OI), mode-selective bidirectional pumping (M-SBP), extra annulus doping (EAD) and semiconductor optical amplifiers (SOA) are used.

Beside EDFA, another type of optical amplifiers can be employed to enhance performance in an MDM system. For example, semiconductor optical amplifiers (SOAs) such as the one reported in Ref. [78], And RAs [79] can be engaged for the MDM communication. The SOAs are not frequently used today in the long-haul communication because of their drawbacks such as high noise, polarisation dependence, and nonlinear effect or fast gain response.

Figure 6(a)–(c) compares the relative intensity noise, relative noise frequency, input output power, EDFA pump power and SOA deriving currents [78]. The SOA indicates a greater noise level than EDFA, which is because of higher involvement in ASE, higher optical

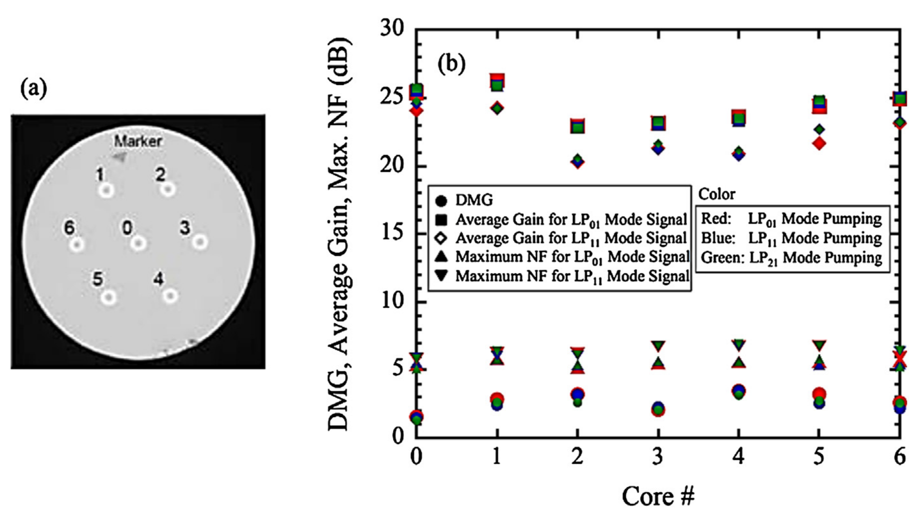


Fig. 5. (a) depicts a cross-section of the multicore few-mode-EDFA, (b) average gain; max. Noise figure (NA) for multicore few-mode-EDFA.

Table 3
Recent progress in SDM/MDM optical amplifiers.

Opt. Amp	Method	NMs	AG(dB)	DMG (dB)	NF (dB)	PP (mW)	Ref.
FM-EDFA	NSGA-II	12 (7-group)	22.2	3.3	Not reported	300	[71]
6-modes FM-EDFA	IFM	6	17.1	7.1-15(IM) 0.3-0.8(FM)	Not reported	600 (300 for each vector mode)	[72]
RC-MC-FM-EDFA	CP	18	>20	Not reported	<7	15×10^3 (6-cores × 3 modes)	[68]
FM-DRA	SOA	2	15.46	< 0.4	1.2 (LP_{01}) 1.1 (LP_{11})	30-260	[73]
Elliptical-core FMEDF	Not reported	5	17.5	7	4.3-15.1 (all modes)	100	[74]
RC-EDF	OI	2	17	1	<5.2 (LP_{01}) <5.8 (LP_{11})	Not reported	[70]
FM-EDFA	EAD	22 (6-group)	>20	< 0.9	Not reported	≥220	[75]
6M-EDFA	M-SBF	6	>20	<4 (all modes)	Not reported	338.8	[64]
FM-EDFA	CP	6	>20	$\tilde{3}$	6-7	1300-3100	[76]
TM-TDFA	CP	2 (group)	17-18.3	Not reported	7-8	3200	[77]

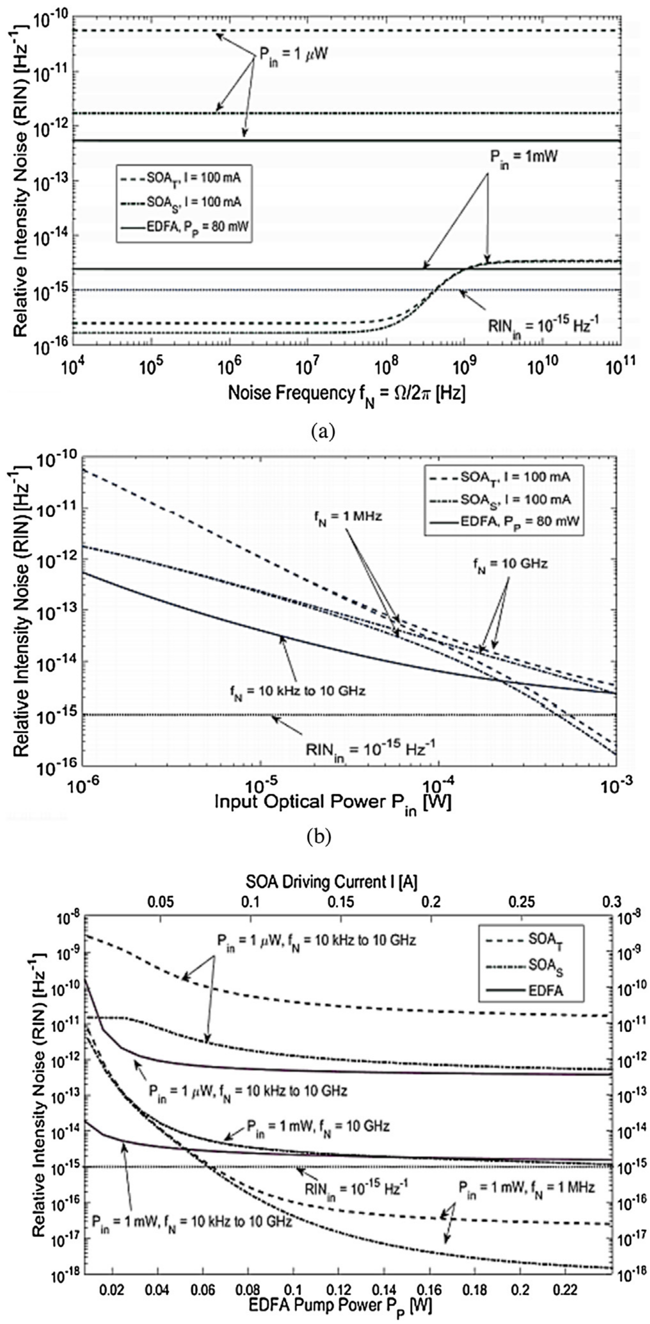


Fig. 6. Relative intensity noise (RIN) properties of the output light (a) frequency, (b) input optical power, and (c) pump level dependency *vs*. Noise [78].

absorption, and higher instability in the electron density injected. However, the OSA has a peculiar feature that helps in reducing the RIN of the light at the output below the input intensity level under some conditions. The line-width spectrum is very difficult to increase in the case of both SOAs and the EDFAs in linear operation. The noise effect in SOA was reported in Ref. [80] and is caused due to the counter phase fluctuation in the electron density, which was associated with optical power [81]. This is not observed in the case of EDFA, because of the low atomic density instability [82]. However, a four-mode OSA was recently demonstrated, which aimed to suppress equalise gain issue in EDFA for an MDM, and has demonstrated the potential of providing an equalised-gain for multiple input signal mode channels without introducing additional complexity and economically more affordable than EDFA [83]. Moreover, RAs are hardly used in the current commercial system. This is because of their complexities and requirements for a high pumping power. One of the advantages of RA over EDFA and SOA is that it gives room for achieving distributed amplification [73] which in turn reduces noise generation. Therefore, combining EDFA and RA technologies can allow extending transmission distance more than adopting only EDFA.

5. Use of FMF in MDM

The concept of using FMF for MDM is to restrict the number of spatial modes propagation in a fibre to avoid mode division (MD). This is because the higher the number of propagating modes the more severe the MD and the less bandwidth available [11]. Significant progress has been made to minimise the MD. For example, recently two novel high dispersion fibres with equalised MDs were reported [84]. Spatial modes transmitted through a single core and modes in a FMF are assumed orthogonal with respect to each other. Theoretically, each of the independent signal channels can be modulated onto each spatial mode, transport them through the same fibre and retrieve the signal at the output with minimum or no loss of information [85]. The data capacity per fibre is multiplied proportionally to the number of spatial modes transported by such fibres. This is in analogy to MCFs where the increase in system capacity is multiplied by the number of cores or number of fibres itself [86].

Figure 7 depicts the basic of the most commonly adopted approaches in MDM, it consists of two techniques, one uses linearly polarised modes as the independent channels [Fig. 7(a)], and the other includes each degenerate as a separate signal channel [Fig. 7(b)].

Figure 7(a) is restricted to using four distinctive modes (LP_{01}, LP_{11}, LP_{21} and LP_{02}) each representing a signal channel rather than going down to each degenerate, this is easier to deal with during mode (de) multiplexing. In Fig. 7(b), the degenerate modes (LP_{01}, LP_{11^x}, LP_{11^y}, LP_{21^x}, LP_{21^y}, and LP_{02}) under each spatial mode are considered as one channel, this adds more capacity to the system. X-pol and Y-pol are costlier and more complicated to de-multiplex at the receiving part of the network. This is because it is difficult to perform PDM for SDM network. The technicality of the implementation is challenging for both experiment and numerical investigation.

5.1. *Strong and weakly coupled approach in FMF*

FMFs have so far demonstrated higher potentials compared to its counter MCF. The main challenge is how to reduce DMGD and MCP among propagating modes. Two approaches are now under intensive research: weakly and strongly coupled approaches.

Weakly–coupled approach [87,88] targets at reducing coupling effect between the propagating modes so that each LP mode can separately serve as an independent channel and can be detected separately using simple MIMO technique irrespective of the number of LP modes involved. To achieve this, the FMF must carefully be designed in such a way that MCP is drastically mitigated to an acceptable level. Compatibility of the step index fibre (SI-fibre) with existing SSMF technology makes it promising and proven to be the most effective to utilise under this regime [89]. It is worth mentioning that such approach contributes very high DMGD. However, looking at the simplicity it offers in design and manufacturing processes, it is considered as a good alternative. To design an FMF under this regime, the highest normalise frequency value (V) is chosen, which allows N number of modes to propagate in the fibre, cutting off the next remaining high order modes. The core index is optimised after knowing the value of V. The core diame-

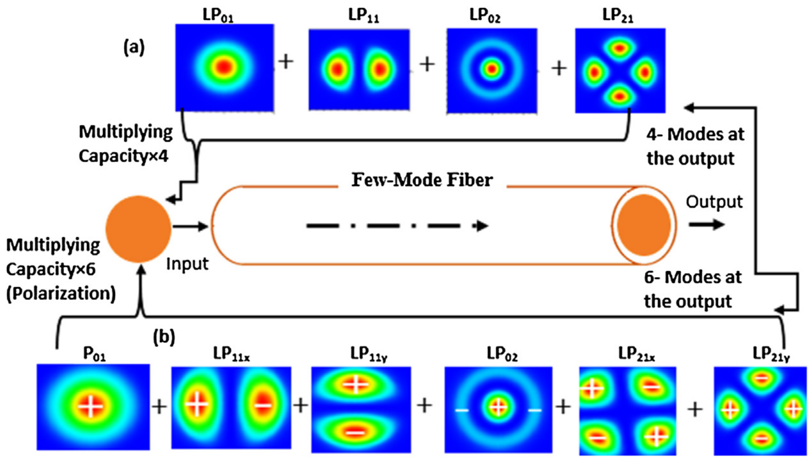


Fig. 7. Schematic of the basic concept of an MDM using FMF (a) constituted by an LP mode only, resulting in four-mode operation (b) Both spatial and polarization modes are included, which results in a six-mode fiber operation.

ter is obtained from the V-parameter relation, which is given by $V = 2\pi a/\lambda.(n_{cr}^2 - n_{cl}^2)^{1/2}$, and "$a$", the core radius, n_{cr} is the core index, n_{cl}, the cladding index, and λ represents the operating wavelength. Setting the index spacing ($\triangle n_{eff}$) > 1.0×10^{-3} for any two adjacent LP modes can reduce coupling effect [90,91]. Bending losses must be reduced to a minimum value (at a radius of 32 mm) to ensure robustness for all LP modes within the intended value of V parameter. Effective mode area (A_{eff}) is expected to be >100 μm^2 to suppress intra-model non-linearity along the fibre [89].

The strongly coupled approach aims at mitigating the DMGD so that the LP modes are simultaneously detected using complex MIMO technique [92,93]. In this approach, the coupling is not viewed as issue, but the fibre requires a careful design strategy to minimise DMGD. A fibre with the graded index profile (GI profile) is prepared for high-bandwidth FMF targeting low DMGD. Such type of fibres is capable of demonstrating DMGD of as low as 0.1 ps/m at a wavelength of 850 nm with the expectation of high bending losses [94]. This configuration is nevertheless well adapted to strongly coupled fibre for MDM systems [95,96], for which the DMGD has to be drastically reduced. The same modeling procedure as in the weakly coupled fibre can be adopted for the V selection. In addition, the exponent value that predicts the index shape may slightly differ from 2 to reduce DMGD [95]. The optimisation became more difficult as the number of transporting modes increases, most especially when good mode robustness (low bending loss per turn at a specified bending radius at 1550 nm) is targeted. DMGD can increase to a value higher than 0.1 ps/m as the mode count in the propagating fibre is greater than or equal to four. However, introducing a trenched cladding can minimise the bending sensitivity [97], and help improve a trade-off in DMGD and the bending losses [98]. It has been reported that DMGDs of below 0.025 ps/m was achieved for trench-assisted GI supporting six-LP-modes [99]. This fibre design has a sensitivity to small profile variations which occurs while manufacturing. A better way to minimise DMGD is to adopt DMGD-compensation technique for FMF links [100]. This approach was implemented long ago in MMFs [101] and seems to work perfectly well with FMF.

5.2. *Challenges of FMF in the MDM*

5.2.1. *Distributed mode coupling*

As discussed in Section 5.1 under the weakly coupled regime, it is significantly important for the FMF to have minimum MCP between the supporting modes. This reduces crosstalk between the multiplexed data streams (channels) [97]. The guided modes field in an ideal fibre most satisfy orthogonality and hence, energy remains uncoupled among the transporting modes. This orthogonality can suffer breakage in a real fibre due to the imperfections, which includes inhomogeneity in the fibre index or deformations in a core size and non-circularly core shape. These effects can give rise to energy coupling between the modes. In addition, imperfections in the channel path or coupling points can cause excessive power exchange among the optical modes. As demonstrated in some reports [102,103], such issue can be dealt with by implementing MIMO signal processing, but for the sake of understanding of the rationale behind FMF characteristics, one must have a proper view of the potential and effects of MCP. Note that MCP between degenerates (modes with the identical phase constants) is stronger, which means a substantial amount of optical power would be transferred between the modes within a close range of distance [104]. In the case of other modes with reasonable differences in propagation constant, e.g., between LP_{11} and LP_{01}, the coupling can be much weaker. Thus, the optical signal may cover up to tens of kilometers without significant coupling among the modes. Theoretically, for imperfect optical waveguides, the energy will couple between modes when the perturbations have a longitudinal frequency component, which could be introduced from the difference in longitudinal propagation constants ($\Delta\beta$) of the modes. The strength of coupling between two modes is a function of $\Delta\beta$ [105,106]. It was also reported that the coupling between modes of adjacent mode groups is proportional to:

$$(\Delta\beta)^{-(4+2q)}. \quad (1)$$

Where q characterises the power spectrum of the changes and typically carries values between 0 and 2, depending on the nature of the external perturbations. Thus, the best way to reduce MCP is to increase the value of $\Delta\beta$ between the modes.

5.2.2. *Differential group delay (DGD)*

Modes group velocities that carry independent MDM data stream are different. Thus, pulses can be launched simultaneously into the various modes of the optical fibre which propagate and arrive at the receiver at different times. MCP and DMGD may both be present and could lead to crosstalk that spread across multiple bit periods. The MIMO signal processing components that suppress signal channel crosstalk become complex due to the accumulated

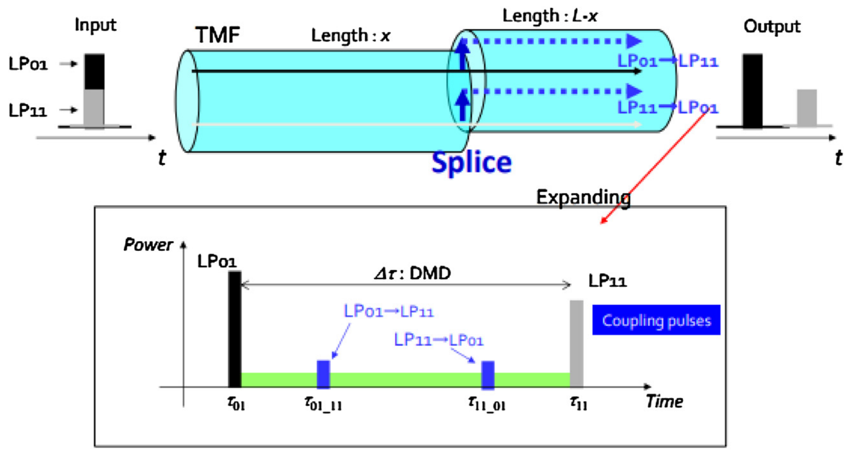


Fig. 8. Diagram depicting an impulse response at a point of splicing [108].

DGD between the individual modes and the crosstalk induces over many bit periods [107]. The DGD is expressed as:

$$DGD = \frac{\left(n_{eff}^{lm} - n_{eff}^{l'm'}\right)}{c}. \tag{2}$$

This effect would be more severe for a long haul SDM transmission [85]; hence, it is crucial to develop means to minimise the DGD. It is also extremely challenging to reduce both the DGD and MCP simultaneously.

5.2.3. DMGD accumulation with transmission distance

DMGD accumulation is proportional to the transmission distance, as well as to the magnitude of Δβ. Mode coupling effect depends on the issues related to fibre deployment. Moreover, cabling and splicing effects need to be considered thoroughly. Cabling stress increases the distributed MCP by inducing some additional source of perturbations in the fibre. Additionally, splices and connectors also bring some discrete MCP [108]. Even by taking into account small and random MCP, it can be proven that the DGD grow linearly with increasing length [109]. When a short signal pulse is launched simultaneously in each mode, the variation in arrival times of the pulse is given as a function of the fibre length, L [110]:

$$\left\langle (T - \langle T \rangle)^2{}_{av} \right\rangle = \frac{\mathrm{DMGD}^2 l_c L}{4}\left[1 - \frac{l_c}{2L}\left(1 - e^{-(2L/l_c)}\right)\right] \tag{3}$$

$$lim_{L/l_{c\rightarrow\infty}} \frac{\mathrm{DMGD}^2 l_c L}{4}, \tag{4}$$

where l_c represents the correlation length, $T$is the time-of-flight through the fibre length. Note that from Eqn (2-4), the spread in signal arrival time normally scales up with the product of square root of the correlation length and the fibre length (l_cL). This scaling law can similarly be adopted for any guides irrespective of the number of modes involved [111,112].

5.2.4. Measurement of impulse response

The method of launching light pulse at the same time in the various modes has been in practice for a long time. DGD in FMFs is relatively large to quantify by a mere comparison of the difference in arrival time of the light pulses that were launched simultaneously into different modes. It is the same approach that has been adopted in DGD measurement in MMF [113]. The difference in arrival time of the modes at the end of fibre allows determination of the DGD. To determine the sign of the DGD, it is crucial to figure out which mode corresponds to which pulse at the receiver. This can be achieved by demultiplexing the mode at the receiving end or by varying its launching properties (relative power in the two modes). Figure 8 shows an example of an impulse response schematic splicing at a point, on two-mode fibre (TMF), which adopts an overfilled launch condition. The LP_{01} converters to an LP_{11} mode at the splicing point. The additional pulses (coupling pulses) are caused by coupling initiated at a splicing point

5.2.5. Differential mode attenuation (DMA)

One of the key issues in FMF transmissions is the attenuation of individual mode as it propagates along the fibre length. The major challenge is the fact that MIMO processing technique is unable to compensate for DMA effects. It has been reported in Ref. [114] that the signal degradation does not depend on the DMA over the entire end-to-end optical link. For example, a 20 dB DMA results in a loss of system capacity of approximately 20%. This 20 dB is equivalent to 0.02 dB/km of DMA for a 1000 km link, 0.05 dB/ km for a 400 km link, 0.1 dB/km for a 200 km link, and 0.2 dB/km over a 100 km link. Hence, it is inevitable to device a means of limiting DMA to a lower value to support backbone signal propagation over traditional distances. An indirect way of assessing DMA effects is by optimising channel performance, which can be done by optimising the power launch into each mode, the difference in the required power between modes is due to DMA [11].

6. Spatial division multiplexing (SDM)

A practical SDM system realisation can be comprehensively understood by clear identification of the four main approaches illustrated in Fig. 9(a)–(d). The key difference is based on the employed fibre category, which determines the type of system to deal with. It is crucial to have unanimity between the individual spatial signal channels to minimise the required space needed of the SDM system. This can reduce the overall cost of both system operation and deployment.

The unanimity anticipated across the system includes the entire fibre length, optical amplifiers, and transceivers as illustrated in Fig. 10(a)–(c). Another important issue is reducing performance-limiting interactions in spatial channels and transmitting signals. Considering the mentioned criteria, each of the proposed approaches has specific potentials and challenges in MIMO complexity [Fig. 9(d)]. In the following section, each of the four approaches would briefly be reviewed.

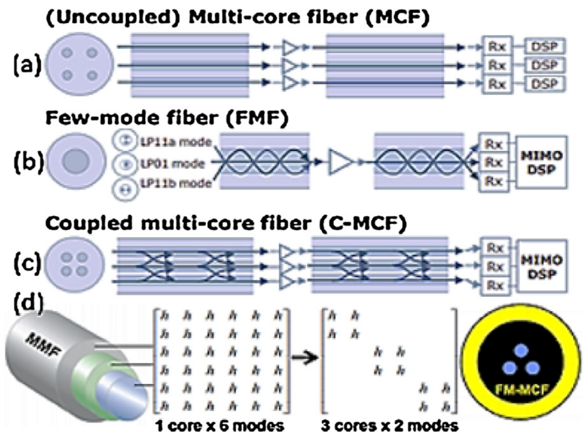


Fig. 9. Common SDM fibers and corresponding transmission systems (a) uncouple multicore, (b) few-mode fiber, (c) coupled multicore, (d) example of a DSP complexity table suitable for a six-mode multimode fiber and a three-core two-mode FM-MCF. The symbol h indicates complexity. In both cases, the solution results in an SDM factor of 6 and shows reduced complexity in the total MIMO calculation in the second case [11].

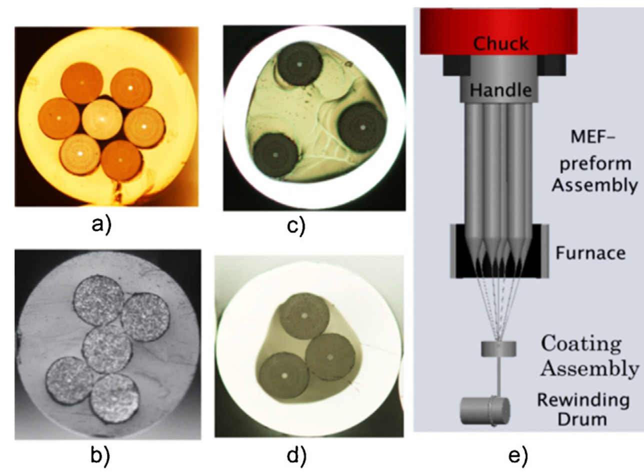


Fig. 11. Cross-section of multi-element fiber fabrication (a) demonstrating core-pumping optical amplification, (b) using the cladding-pumping technique, (c) and (d) transporting fiber, (e) diagram depicting seven multi-element preforms on the draw tower [4,9].

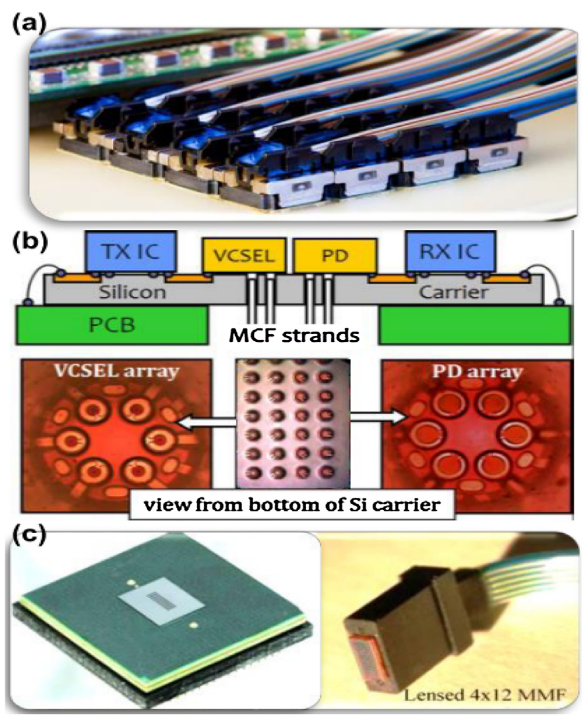


Fig. 10. Different SDM transceivers (a) Avago Minipod^{TM} adopting 12-single mode ribbon [115], (b) multicore fiber photonic transceiver chip [116], (c) VCSCEL/PD (4 × 12), which interfaces a multimode fiber bundle opto-chip that support a 480 Gbps transreceiver [117].

6.1. Multi-element fiber (fiber-bundle)

The data capacity over a conventional SMF has become insufficient to match with the demands of the current optical systems. One of the approaches considered to increase communication bandwidth is to deploy multiple numbers of SMF in parallel. Theoretically, this approach is visualised as one form of the SDM [118]. Unlike in multiple packed coaxial copper cables, optical fibres demonstrate no crosstalk between the associated fibres in a bundle when putting them as multiple elements. Deploying a single mode fibre-bundle (SMF-B) demonstrates no additional propagation impairments compared to SMF-based network [118]. The first demonstration of SMF-B was reported using a core-pumped spatial amplifier [4], a 3-SMF-B and a 7-SMF-B with no crosstalk was demonstrated. Figure 11(a) shows the schematic cross-section of a 7-SMF-B core-pumped fibre. The major drawback with this approach is the higher cost of production because of using a single diode assign to each core. The cladding-pumped that implements a single common pump diode was developed.

The launching into the cladding pump was achieved using a delivery fibre element that finally coupled the pumping light to the fibre element. Figure 11(c) and (d) illustrates the extension of the SMF-B in the fabrication of the passive MDM fibre for data propagation. Also showing in Fig. 11(e) is an extract of the 7-SMF-B assembled preform on the draw tower.

Another key issue for realising fibre bundle is the connecting device such as FI/FO component. It aligns and couples each of the single core (de)multiplexer coupling individual FM with the parallel SMFs. The requirement is either to combine FI/FO device to a few modes-multicore fibres (FM-MC) and arrange them in an array of mode (de)multiplexers for the individual FMF or integrate them in a similar way as in FI/FO integrated photonic lantern, with fabrication achieved using ultra-fast laser inscription [119]. The model of the FI/FO so far reported mainly targeted single mode multicore fibres, including multi-element type [120], a fused taper [121], and the one applicable to a free space optics [122]. Recently, a FI-FO device with improved alignment aimed to achieve low loss, low MDL (less than 2 dB) at connection terminals was reported. The report described in detail the design processes and fabrication procedure of the FI/FO device, which can be a good candidate in the fibre bundle for FM-MCFs. As shown in Fig. 12, the configuration of this device comprises two ferrules and a split sleeve. A cladding of 246 μm was used, and the FM-MCF insertion was made to couple into the micro-holes, which fit into the ferrules. In addition, the single core FMFs was made to fit the hexagonal micro-hole of the ferrule [123].

Single fibre bundle technology can be considered a candidate to burst data capacity through SDM implementation in optical fibre communication. It provides a crosstalk free platform between the spatial mode channels and can splice using conventional splicing procedure.

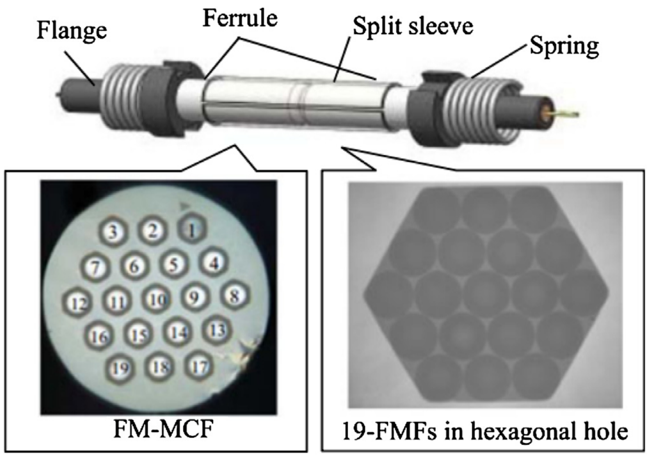


Fig. 12. Diagram of a fabricated multi-elements type pluggable FI-FO device [122].

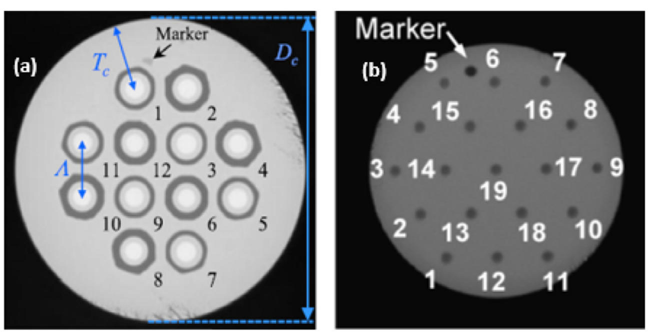


Fig. 13. (a) Cross-sectional diagram of the fabricated multi-step three-mode twelve-core uncoupled fiber consisting of a square-lattice configuration. The separations between two cores are denoted by odd, and even numbers respectively. *Λ*, *Tc*, represents core pitch, and the outer cladding thicknesses respectively, and *Dc* represents cladding [13]. (b) Cross-section of 6-mode 19-core uncoupled fibers [124].

6.2. Coupled and uncoupled MCF

Uncoupled approach adopts transmission of independent signals through distinct cores of the same or similar fibres. The promising advantage of this approach is that it demonstrates no significant crosstalk, this is realised through employing high integration in the inline fibre. Although crosstalk is not much anticipated, the cores must have enough separation distance from each other [122]. As shown in Fig. 13(a–b), a different approach can be employed to design uncoupled-multi core fibre (U-MCF), for example, design a MCF with heterogeneous core arrangement consisting of two distinct cores to reduce inter-core crosstalk (IC-XT) using the multistep index as reported in Ref. [13]. Adopting this core profile reduces and controls DMD without trade-off to intermodal crosstalk.

Furthermore, a square lattice structure permits the inclusion of twelve cores in the cladding of 230 µm diameter. This fibre demonstrates inter core-cross talk (IC-XT) and low DMD. Moreover, homogeneous core fibres can be employed for the U-MCF. Recently, an ultra-dense SDM optical transmission over six-mode nineteen-core fibres (6-mode-19-core fibre) was achieved [124]. The cross-section of the fibre is shown in Fig. 13(b). Here, the fabrication of the six-mode, 19-CF was processed in such a way to minimise crosstalk between the associated cores, as well as the MCP, which results in a large cladding with a diameter greater than 300 µm and Δ greater than 1%. A system of 4.5 THz bandwidth capacity at C-band, ($19 \times 114 \times 2.05$ pbit/s) was demonstrated [124]. This experimental demonstration is the highest recently reported aggregate spectral efficiency of 456 bit/s/Hz.

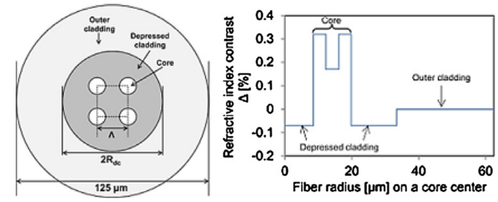


Fig. 14. Cross-section and refractive index profile of the couple core multicore fiber (C-MCF) with a radial line on a core center [127].

6.2.1. Coupled core fibers

The core adopted to C-MCFs is closer to one another compared to that in U-MCFs. The cores closeness initiates coupling between the signal mode channels propagating through the multicores. Due to the formation of supermodes, C-MCFs imposes minimum constraints in terms of fibre design and productions. This is at the expanse of complex MIMO-DSP at the receiver for decoupling the supermodes. Quite reasonable progress has been reported on experiment using supermodes to achieve transmission. For example, a distance of 1200 km and 4200 km [125,126] was achieved, and the work was presented during the post-deadline conference (ECOC2011, OFC2012). The modulation at 20 GBound was implemented and the supermodes were successfully decoupled by employing a 6×6 MIMO including two polarisations in each mode. Recently, a C-MCF consisting of four-core that demonstrate low MD (3.14 ± 0.17 ps/$\sqrt{\text{km}}$) operating in the C-band is realised [127]. The design recorded ultra-low mode attenuation (0.158 dB/km); these are the lowest reported dispersion and attenuation in the optical fibre that utilises couple multicore approach. It was achieved based on employing the index profile of ultra-low-pure silica core single mode fibre shown in Fig. 14 with a larger A_{eff} of 112 μm^2.

A recent comparison between the commercially available ultra-low losses SMF (ULA-SMF) [128] and a four-core C-MCF [129] that are virtually of the same core configuration was carried out. The two fibres employed are of the same length of 110 km using the same optical equipment. The result indicates that the four-core C-MCF can demonstrate a 0.7 Q-factor higher than that of the ULA-SMF. The maximum launch power targeted a distance range between 500 km to 10,000 km using both QPSK and 16-QAM. This was determined using a combination of the WDM-SDM on 30 Gb and a 33.33 GHz channel spacing (15-WDM channels); a 1,115,200 bit/s/Hz record of spectral efficiency distance product was achieved for the SDM transmission [129].

7. Conclusions

A review was presented on the recent achievements in the optical fibre devices, which are paramount to the successful realisation of an SDM system. Different mode conversion techniques were discussed and it has shown that more effort is needed for the higher order mode conversions as most of the recent reported work centred on LP_{01} mode conversion. Moreover, the recent finding in different mode multiplexed schemes were discussed, including the one exhibiting the highest demonstrated LP-mode selectivity in a ten-mode multiplexer with the average crosstalk of -26 dB, reporting higher coupling efficiency (low IL less than 4 dB when coupled to the MMF) and very low MDL (average 1.2 dB) over the entire C and L band. In addition, the recent advancement of various schemes to minimising DMG in FM-EDFAs and MC-FM-EDFAs is being studied. It also highlights the advantages of RAs over EDFA and SOA which includes achieving distributed amplification and reducing noise generation. Combining the two technologies EDFA and RA allows extending transmission distance than adopting only EDFA. Finally, recent work on the SDM system was reviewed. It is crucial to have unanimity between the individual spatial signal channels to minimise the require space needed of an SDM system. This can reduce the overall cost for both system operation and deployment.

Authors' statement

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