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Chapter Thirteen

Spatial multiplexing: technology

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Space division multiplexing (SDM) utilizing few-mode fibres or multicore fibres supporting multiple spatial channels, is currently under intense investigation as an efficient approach to overcome the current capacity limitations of high-speed long-haul transmission systems based on single mode optical fibres. In order to realize the potential energy and cost savings offered by SDM systems, the individual spatial channels should be simultaneously multiplexed, transmitted, amplified and switched with associated SDM components and subsystems. In this chapter, a review of recent progress on the implementation of various SDM technologies is provided and the latest strategies and trends are presented. In particular, integrated SDM amplifier technologies will be discussed in detail and the prospect of further scaling with respect to the number of spatial channels that can be amplified will be described.

13.1 INTRODUCTION

Over the past few decades, the demand for internet capacity has grown exponentially at an average rate of about 40-60% year-on-year and there are fears that future growth of the internet will be constrained due to fundamental capacity limits in optical fibres due to their intrinsic nonlinearity. To date operators have kept up with the increasing data traffic through a sequence of technical innovations (as labelled in Figure

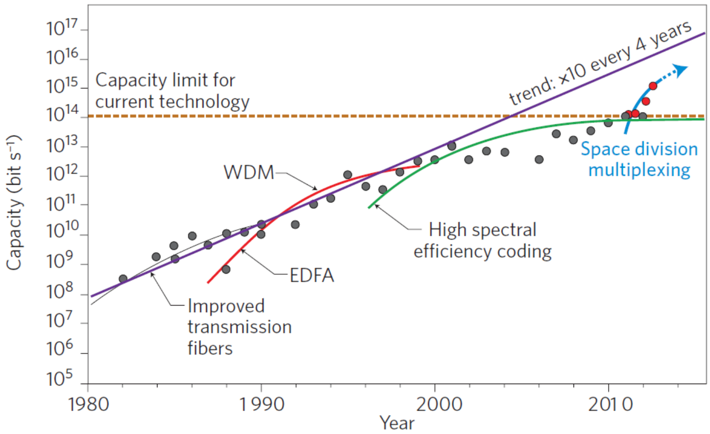


Figure 13.1. The historical evolution of transmission capacity in optical fibres [3, 5].

13.1) associated with ever better exploitation of the transmission capacity of single mode fibre (SMF) which has formed the essential physical fabric of our global communication systems for the past ~40 years**Error! Reference source not found.**. However, this situation is set to change: in the laboratory the fundamental limit to transmission capacity imposed by optical nonlinearity in SMF is rapidly being approached (the so-called "Nonlinear Shannon Limit" [1, 2] which constrains transmission capacity over 1000 km length scale to ~100 Tbit/s). Given the relentless growth in data traffic and the fact that 10 Tbit/s systems are already being installed, there are concerns of a future "Capacity Crunch" in the coming decade, where the need to install new fibres to take up additional traffic growth (at an effectively constant cost-per-bit as further capacity is added) threatens to constrain future internet growth. As a consequence radical innovation is now required to overcome this threat and this will almost certainly dictate the need to revisit our choice of transmission fibre and corresponding optical amplifiers. The only physical signaling dimension not fully exploited in current system is "space" and consequently Space Division Multiplexing (SDM) [3–5] has emerged as the most promising solution to the "capacity crunch" problem. In SDM transmission system, independent data streams can be transmitted in parallel spatial channels and various SDM fibre strategies have been proposed. In the following section, we first summarize the state-of-the-art for various SDM approaches under investigation, tabulating progress in the development of SDM transmission fibres, SDM multiplexers/ demultiplexers and the associated partner SDM amplifiers.

13.2 SDM TRANSMISSION FIBRES

Several different SDM transmission fibres have been proposed and investigated to overcome the capacity limit of SMFs and Figure 13.2 shows the classification of the primary SDM fibre types reported to date. There are two main SDM approaches for achieving multiple spatial channels within a single fibre: 1) multicore fibre (MCF) whereby multiple cores are incorporated in a single fibre cladding, and 2) few-mode fibre (FMF) that utilizes multiple spatial modes in a large core fibre to define the distinct spatial information channels. Both of these approaches are being

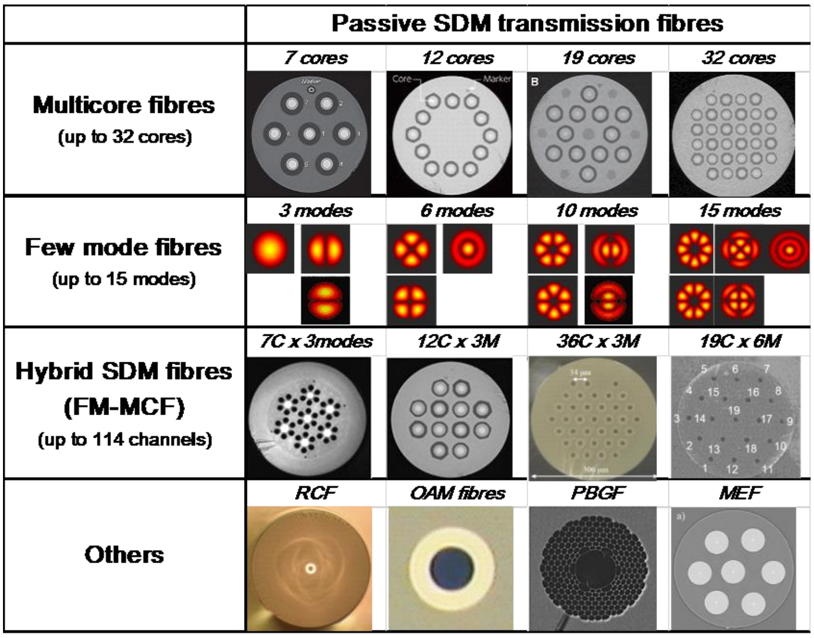


Figure 13.2. Different types of SDM transmission fibres reported so far; MCF [6, 7], FMF [8, 19, 36], FM-MCF [9, 10, 23] and others [11–14].

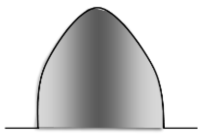
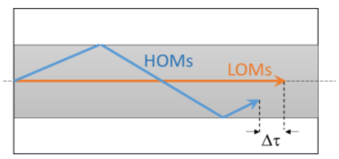
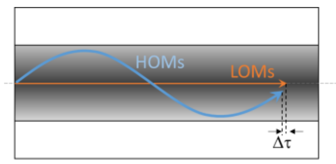
investigated intensively around the globe and an approximate 10-fold increase in overall fibre capacity (using a 12-core fibre) has already been achieved [6] in little more than 5 years. Moreover, at the most recent OFC'16 conference, MCFs with up to 32-cores have been demonstrated providing a high spatial core density and low crosstalk supporting transmission over distance in excess of 1000km [7] while a 15 spatial mode FMF has also been demonstrated [8], supporting 15 channel transmission over a distance of 22.8km. In order to further increase the fibre capacity for future SDM networks, the number of spatial channels needs to be further scaled and the introduction of a hybrid SDM fibre structure (e.g. few-mode multicore fibre, FM-MCF) can help further increase the capacity by combining the two basic spatial multiplexing schemes (FMF and MCF). At the OFC'15 conference, two state-of-the-art hybrid SDM fibres were presented one with 36 cores × 3 modes [9] and the other with 19 cores × 6 modes [10]. Initial hybrid SDM fibre transmission experiments in both fibres were presented highlighting the potential for 100-fold capacity increases with respect to standard single mode optical fibre. In addition, several other types of SDM transmission fibre have also been proposed offering spatial channels with interesting features. For example, single radial mode but azimuthally multi-mode transmission in ring-core fibres (RCFs) [11], orbital angular momentum (OAM) mode transmission in OAM fibres [12], low latency air-core guidance in hollow-core photonic bandgap fibres (HC-PBGFs) [13] and fibre bundle like multi-element fibres (MEFs) [14] that provide for easy access to the cores within the individual fibre elements. In the following sections, the detailed fibre design concepts of two mainstream of SDM fibres (i.e. FMFs and MCFs) will be provided.

13.2.1 *Few mode fibres*

A few mode fibre (FMF) is a multimode fibre that has been designed to support a limited but carefully controlled number of spatial modes. The normalized frequency parameter of FMFs (the so-called the V-number) needs to be greater than 2.405 (the cut-off value for SM fibre operation), which means that the fibre has either to have a larger core diameter (>10μm) and/or a larger refractive index differences (> 0.005) between core and cladding than in conventional telecom SMFs. Since the spatial modes are orthogonal, it is in principle possible to increase the transmission capacity in accordance with the number of modes supported by the FMFs. The distinguishable spatial data pathways required for SDM are defined either by the particular modes supported by the fibre, or alternatively orthogonal combinations of these fibre modes. Since all spatial modes in FMFs have significant spatial overlap, the data signals are prone to couple randomly between spatial channels during propagation. Thus it is generally necessary to employ multi-input multi-output (MIMO) digital signal processing (DSP) at the receiver end in order to mitigate the transmission impairments from mode coupling. To fully compensate for the effects of mode coupling using MIMO, the equalization filter length needs to be longer than the impulse response spread of an individual symbol. Therefore, the modal dispersion (i.e. differential group delay (DGD)) is one of the most important factors affecting the transmission performance in FMFs.

Currently two different primary types of refractive index profile have been considered for the design of FMFs as shown in Table 13. 1: high-DGD step-index FMFs and low-DGD graded-index FMFs [15, 16]. In the ray-optic analogy, light rays travelling down fibres with a step-index profile follow different optical paths along the axis of the fibre. Generally higher-order modes (HOMs) have larger propagation angles and therefore travel greater distances than the lower-order modes (LOMs), resulting in a significant amount of intermodal dispersion. The typical DGD value for a step-index FMF is a few ns/km and the number of taps required for MIMO processing (which is proportional to the DGD induced spread of a single data bit) becomes increasingly challenging for transmission distances much above 10km. Controlling the overall DGD in FMFs is therefore a primary design consideration and a large body of research work has been devoted to develop FMF designs providing substantially reduced DGD. Using a graded-index FMF design featuring an accurately parabolic refractive index profile, the DGD value can be efficiently reduced. As shown in Table 13. 1(right), the HOMs travelling in outer regions of the core (i.e. relatively low refractive index regions) will travel faster than the LOMs travelling in the central region of the core (i.e. high refractive index region). Therefore the transit time for both HOMs and LOMs can be similar and the DGD value (or modal dispersion) can be significantly reduced. The index profile of the graded-index FMF is commonly characterized by a power-law index profile (i.e. α-profile governing the shape of the graded-index core) and the optimum α-value (i.e. nearly parabolic profile, $\alpha \sim 2$) can be selected to get the lowest possible DGD between the mode groups. Typical DGD values in graded-index FMFs are around a few 10-100 ps/km, which is one or two orders of magnitudes smaller than those of step-index FMFs. However, it is very challenging to fabricate low DGD graded-index FMFs because the fibre DGD value is known to be very sensitive to small index profile variations during the fabrication process. Therefore, an alternative (or complementary) approach of DGD compensation has recently been demonstrated. DGD compensation is implemented by constructing transmission lines comprising lengths of FMFs with opposite signs (positive and negative) of DGD. Link averaged net values of DGD as low as approximately 5 ps/km have been achieved in this way. In addition, trench assisted index profiles (i.e. incorporation of a low index trench surrounding the core) can be added to FMF design, effectively improving light confinement within the core and thereby improving the macro-bend performance and optical loss of HOMs. With the trench assisted FMF design, the mode dependent loss (MDL) is almost negligible and it opens up the possibility of transmission over more than 1000km length scales when combined with the use of a suitable SDM optical amplifier.

Table 13. 1. Two different types of index profiles used in FMF design

	Step index FMFs	Graded index FMFs
Fibre refractive index profile		
Ray tracing		
DGD ($\Delta\tau$)	High (few ns/km)	Low (few 10-100 ps/km)
MIMO complexity	High	Low

13.2.2 *Multicore fibres*

A multicore fibre incorporates multiple cores in a single fibre cladding to provide multiple spatial channels within a single fibre. In a MCF-based SDM transmission, the inter-core crosstalk (XT) is one of the most important design considerations and sufficiently low XT MCF is crucial so that the individual cores can be considered as effectively independent information channels over the desired propagation distances and for the particular modulation formats used. Considerable research effort has been devoted to realize such fibres and different techniques have been used to minimize the XT for different MCF structures [17, 18], as summarized in Figure 13.3. The simplest MCF approach (referred to as homogeneous MCF) uses an identical design for each core (Figure 13.3(a)) and the core density is dominated by the core-to-core distance (i.e. core pitch, Λ). Since the phase velocity of each core is identical, coupling between adjacent cores is very strong and this can only be suppressed by keeping the cores relatively well separated (to minimize field overlap between neighboring cores). Typical core spacing in homogenous MCFs with standard SMF core designs are more than 45 μm and it is difficult to substantially increase the number of independent cores within practical fibres of this form beyond 7. However, using trench assisted index profiles (i.e. similar to those discussed above in relation to FMFs) can be used within homogeneous MCFs to enhance mode confinement and to help suppress inter-core XT. More than 20-30dB XT reduction can be readily achieved by engineering the trench volume. Due to the reduced XT, the core spacing can be reduced to 30-40 μm in trench-assisted homogeneous MCFs (Figure 13.3(b)) and impressively low XT levels (e.g. less than -90dB/km) have been demonstrated, thereby enabling independent parallel transmission over multi-1000 km length scales. Another common approach for reducing the XT of MCF is to employ a heterogeneous core arrangement with different types of cores, each having slightly different effective indices but similar effective mode areas. Due to the dissimilar phase matching conditions between neighboring cores, the XT can be significantly reduced using heterogeneous core arrangement (Fig. 13.3(c)), however does come at the expense of increased fibre fabrication complexity. Another MCF fibre design consideration is the cladding thickness and the outer diameter of the fibre. Generally, the outermost cores in MCFs experience additional attenuation caused by leakage of the light field into the polymer coating as the fibre cladding thickness is reduced. Typically the cladding thickness should be greater than 30μm due to micro-bend loss considerations. The choice of maximum fibre outer diameter is related to fibre failure probability (i.e. mechanical fibre reliability) and cladding diameters beyond approximately 250μm are not considered practical for MCF-based SDM transmission. The recent research to date seems to indicate that the maximum number of independent cores that one can practically envisage using for long-haul transmission lies somewhere in the range 12-19, although fibres with as many as 32 cores and impressively low levels of XT of less than -40dB over 100km have just recently been demonstrated exploiting heterogeneous core arrangements [7]. Note that the current frontier in SDM research is to combine multiple SDM approaches to achieve much higher levels of spatial channel count (referred to as channel multiplicity). For example, both MCF and FMF technologies can be combined together (e.g. few-mode multicore fibres) to support a total of M × N spatial channels. Excellent progress has been made and just recently data transmission at a record spectral efficiency of 345 bit/s/Hz was reported through a 9.8km few-

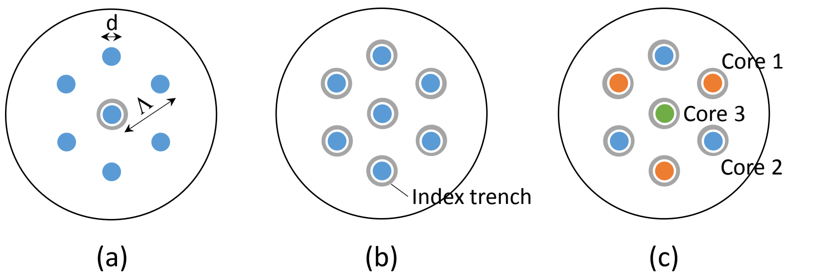


Figure 13.3. Different types of multicore fibres to reduce the inter-core crosstalk: (a) homogeneous MCFs, (b) trench-assisted homogeneous MCFs and (c) trench-assisted heterogeneous MCFs.

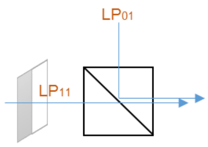
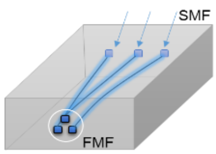
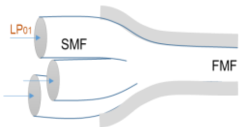
mode MCF containing 19 cores with each core supporting six spatial modes, providing a total of 114 distinguishable spatial channels [10].

13.3 SDM MULTIPLEXERS AND DEMULTIPLEXERS

Other key optical components for SDM system are an efficient and stable SDM multiplexers (MUXs) and demultiplexers (DEMUXs), which allow for individual spatial modes (or cores) to be accessed with minimal loss and crosstalk. A variety of technologies and approaches are being explored to combine and separate all spatial channels in SDM fibres. The following two subsections provide a brief summary of the most common techniques used for the two major classes of SDM fibre: 1) mode MUXs/DEMUXs for few-mode fibres and 2) fan-in/ fan-out devices for multicore fibres.

13.3.1 *Mode MUXs/DEMUXs for few-mode fibres*

Table 13. 2. The most commonly used mode multiplexers for FMFs

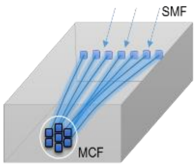
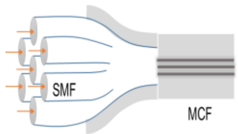
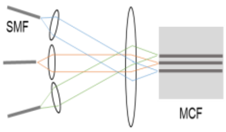
	Phase plates	3D waveguides	Photonic lanterns
Schematics			
Fabrication complexity	Simple	Moderate	Simple
Insertion loss	High	Moderate	Low
MDL	High	Moderate	Low
Scalability	Difficult	Good	Good
Footprint size	Large	Compact	Compact
Cost	Expensive	Moderate	Good

Mode MUXs can either couple light from multiple single mode fibres directly to specific guided modes of a FMF or couple light to a linear combination of modes. The options for mode MUXs depend on the coupling amongst the guided modes. For transmission systems relying on weak mode coupling, selective mode excitation methods such as phase plates, spatial light modulators or mode selective fibre couplers are commonly used. For transmission systems where mode mixing can be tolerated, photonic lanterns, 3D waveguides and multi-spot options are suitable. The most commonly used mode MUX options are summarized in Table 13. 2. The first example illustrates a phase plate based mode multiplexer. Binary bulk phase plates are placed between two free space collimators to modify the spatial phase distribution of the input Gaussian beams originating from SMFs in order to efficiently excite higher-order modes in FMF. It is one of the easiest ways to enable the desired higher-order mode excitation and modal purity is typically greater than 25dB [19]. However the MUX includes a number of 50/50 beam splitters to combine beams and the overall device is thus inherently bulk with a high insertion loss that scales badly with increased mode count. The second approach is a 3-dimensional (3D) waveguide based mode MUX. A tightly focused femtosecond laser beam is used to modify the refractive index of a transparent bulk glass sample to enable 3D waveguide geometries with subwavelength precision by direct laser writing [20]. In this type of mode MUX, the mode transformation is accomplished by transitioning from a 1D array of single mode waveguides into a 2D coupled-core arrangement of waveguides supporting super-modes that can then be coupled to the FMF. In principle, the approach relies upon the same concept as the multi-spot launcher [21] where each beam spot excites a linear combination of modes but a special geometrical spot arrangement is required to excite a near-orthogonal combination of modes. These spot launchers can scale to a large number of modes without a significant increase in insertion loss. The third example is a photonic lantern [22]. Here, a bundle of N separate single mode fibres is inserted into a low index glass capillary tube and tapered together to obtain a multimode fibre structure supporting N spatial modes. Due to the adiabatic nature of the taper transition, this device is theoretically lossless and can scale to a large number of modes with negligible MDL.

13.3.2 *Fan-in/fan-out devices for multi-core fibres*

Table 13. 3. The most commonly used fan-in/fan-out devices for MCFs

	3D waveguides	Fused taper	Free space optics

Schematics			
Fabrication complexity	Moderate	Simple	Complex
Insertion loss	Moderate	Low	Low
Crosstalk	Moderate	Moderate	Low
Scalability	Good	Good	Moderate
Footprint size	Compact	Compact	Moderate
Cost	Moderate	Good	Expensive

In the case of MCF, spatial multiplexers/demultiplexers are referred to as fan-in/fan-out (FIFO) devices and are used to efficiently couple light from individual SMFs to each core of the MCF and vice versa. Various configurations have been reported so far but three primary techniques are widely used as listed in Table 13. 3. Note that FIFO device fabrication processes are very similar to those of the mode MUX/DEMUX. A critical feature here is that at high core counts some level of cross-talk becomes inevitable and an effective means to achieve cross-talk reduction in FIFO devices is one of the most important factors limiting MCF transmission performance. Moreover, hybrid SDM multiplexer (e.g. few-mode multicore fibre) have also recently been reported to further increase spatial multiplicity by integrating both technologies [23].

13.4 SDM OPTICAL AMPLIIFERS

While various SDM transmission fibres have been demonstrated so far the question naturally arises as to what progress has been made in the suitable partner amplifiers required to enable long haul transmission? It is perhaps not surprising but fair to say that SDM amplifier research has lagged one step behind the advances in passive SDM transmission fibre technology as shown in Figure 13.4. – as soon as SDM amplifier research starts to address the particular optical amplification needs of one form of SDM fibre a new generation of high-density SDM transmission fibres appears on the horizon. In the case of multicore EDFAs (MC-EDFAs), both core-pumped and cladding-pumped 7-core EDFAs [24] have been demonstrated in 2011 and 2012, respectively. The core pumped MC-EDFA was then scaled to 19-cores in 2013 [25], which represents the highest core-density MC-EDFA to date. Improved sharing of the optical components and significant device integration was also demonstrated as required to obtain the anticipated cost reduction benefits of SDM. For example, a single free-space isolator was used to simultaneously prevent unwanted reflections from all 19 cores and a single dichroic mirror was used to couple pump beams into each individual active MCF core. In the case of few-mode erbium doped fibre amplifiers (FM-EDFAs), both core-pumped [26] and cladding-pumped 6-mode EDFAs [27] were demonstrated in 2014. More recently a cladding pumped 10-mode EDFA [28] was reported representing the highest mode count FM-EDFA reported so far. The cladding-pumped FM-EDFA, which was originally end-pumped using free space optics, has recently been upgraded to incorporate a fully

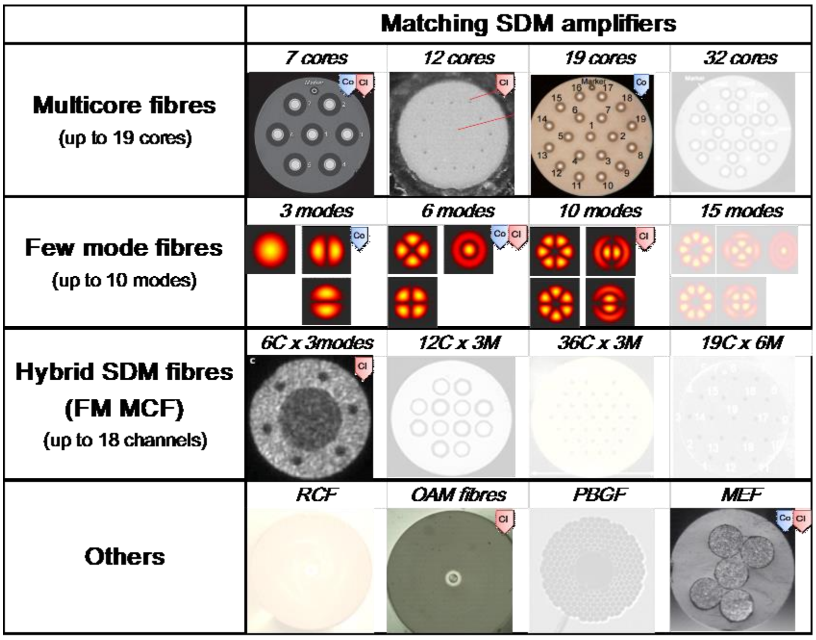


Figure 13.4. The corresponding SDM optical amplifiers. Faded images are used to indicate instances where suitable partner amplifier solutions have yet to be demonstrated.

fiberized side-pumping configuration and this functionality makes it possible to construct a fully integrated SDM amplifier capable of providing stable modal amplification without the need for free-space optics. In order to realize a high-capacity hybrid SDM system a hybrid SDM amplifier supporting few-mode multicore fibres represents an essential subsystem and a three-mode six-core SDM amplifier [29] was recently demonstrated supporting 18 spatial channels. Other interesting forms of SDM amplifiers, e.g. ring-core fibre amplifiers [30], OAM fibre amplifiers [31] and MEF amplifiers [14], have been introduced. Most interestingly, the ring-core fibre amplifiers can be designed to support single radial modes (i.e. LP_{1m} modes where *m* is an integer) and can provide exceptionally well equalized modal gain (nearly identical gain) for all guided signal modes. These amplifiers are very attractive as few-mode EDFAs in terms of Differential Modal Gain (DMG) mitigation but no experimental demonstrations has been reported to date. A fibre optic OAM amplifiers capable of robustly amplifying modes with a helical phase front has recently been demonstrated [31] and has attracted significant scientific interest not only in optical communications but also for optical trapping, laser material processing and quantum information processing. There is no report yet of matching optical amplifiers for HC-PBGFs due to the air-hole structure. Both core-pumped and cladding-pumped MEF amplifiers [14] have also been demonstrated with up to 7 fibre elements in a single assembly. In the following section, we will focus on the development of few-mode EDFAs offering low DMG between all supported modes. In FM-EDFAs, DMG directly affects the system outage probability and can limit system reach and we will discuss in detail methods to minimize it. We will concentrate in particular on the case of the 6-mode EDFA and will discuss DMG control for both core and cladding-pumped configurations. Finally, we review the results of a comprehensive theoretical study to show that it may be possible to achieve lower DMG over the full C-band of EDFAs supporting 10 spatial modes by optimizing the erbium dopant distribution of the active fibre in a cladding pumped configuration.

13.4.1 *Strategies to minimize differential modal gain in few-mode EDFA*

In FM-EDFAs, the most important factor is the DMG control required to

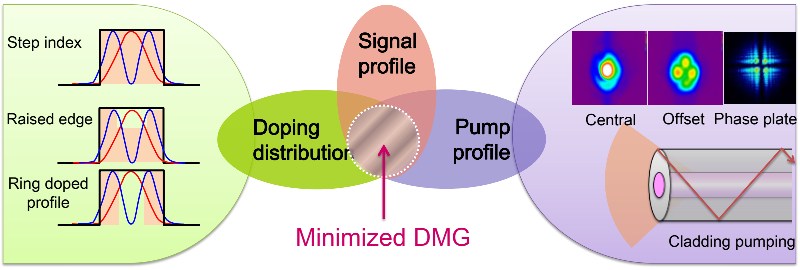


Figure 13.5. Strategies to minimize DMG in few-mode EDFAs. The DMG can be engineered by i) tailoring the radial erbium-doping concentration profile of the erbium doped fibre, ii) controlling the pump field intensity distribution and (iii) controlling the signal mode.

ensure that all spatial channels are equally amplified. As shown in Figure 13.5, the DMG is a function of the overlap integrals between the doping distribution, the pump mode profile and signal mode profile. If we assume that the input signal mode profiles are fixed (i.e. the refractive index profile of the fibre remains constant) then there are two main strategies to minimize the DMG: i) tailoring the radial erbium-doping concentration profile of the erbium doped fibre and ii) controlling the pump field intensity distribution [32, 33]. With respect to the approach of controlling the doping distribution within the active fibre, we begin by considering a simple uniformly-doped step-index EDF. Whilst such a fibre can amplify multiple modes it preferentially amplifies the LP_{01} mode compared to the HOMs. Indeed >10dB MDG has been reported for uniformly-doped step-index 3M-EDFAs [26, 34]. To address this both raised-edge and ring-doped erbium dopant profiles have been introduced as a means to reduce the overlap of the dopant with the field of the fundamental mode in the central core region. Confining the erbium ions to lie within a ring around the fibre axis can be particularly effective and can drastically enhance the HOM gain. Pump mode control can also be used to control the DMG. On axis, launching of pump light into the active fibre generally creates an LP_{01}-like pump intensity profile which also tends to result in preferential amplification of the LP_{01} signal mode. In contrast launching the pump offset from the fibre axis or launching the pump light into well-defined HOMs tends to result in preferential gain for HOMs. More recently, the cladding pumped configuration has been employed to minimize the impact of the pump mode profile and to offer a cost-effective alternative to core-pumped variants. Cladding pumping allows low cost, high power multimode pumps to be used, and offers performance improvements, scalability and simplicity to FM-EDFA design. In practice, a combination of both strategies (i.e. dopant distribution control and pump mode profile engineering) is generally required in the case of core-pumped FM-EDFAs. Dopant distribution control is the only possible option for controlling DMG in cladding-pumped FM-EDFAs.

13.4.2 *Core pumped 6-mode EDFA*

Figure 13.6(a) shows a schematic of a core-pumped 6-mode EDFA (6M-EDFA) [26] for simultaneous amplification of the six lowest order spatial modes (i.e. LP_{01}, $LP_{11a,b}$, $LP_{21a,b}$ and LP_{02}). Two dichroic mirrors are used for combining 980nm pump light with the 1550nm input signals and two polarization-insensitive free-space isolators are included to prevent unwanted parasitic lasing within the 6M-EDFA. In order to mitigate the

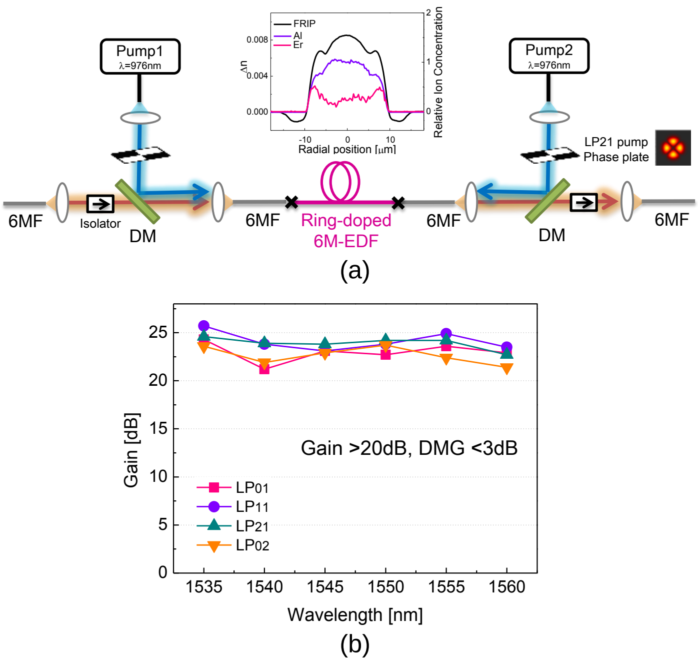


Figure 13.6. (a) The schematic of a core-pumped 6M-EDFA and (b) its gain performance.

DMG, a tailored ring-doped EDF was fabricated to provide dopant distribution control and bi-directional HOM pumping (e.g. LP_{21} pump mode in this particular experiment) was used to provide pump mode control. As shown in Figure 13.6(b), the amplifier provides more than 20dB signal gain for all six spatial modes with less than 3dB DMG across the full C-band. Note that the use of HOM pump profiles enables us to mitigate the DMG of the FM-EDFA. The pump coupling losses to the 6-mode fibre (6MF) depend on the particular pump mode under consideration with HOMs experiencing higher coupling loss. In our experiment an LP_{21} pump mode profile was used and a 3.5dB coupling loss was observed. Therefore a single pump LD with a maximum output power of 750 mW cannot provide enough gain for all the spatial modes meaning we need to use two pump LDs in a bidirectional pump configuration to get acceptable signal gain. As the number of spatial modes is further scaled up to 10 and beyond, it will become increasingly challenging to meet the associated pump power requirements with single-mode pump diodes. For this reason, a cladding-pumped scheme is attractive to address such issues.

13.4.3 *Cladding pumped 6-mode EDFA*

Figure 13.7(a) shows a schematic of our cladding-pumped 6M-EDFA [27]. A D-shaped double-clad 6M-EDF was fabricated and coated with a low index polymer such that it guides pump light in the glass cladding. A side-pumping scheme was adopted to realize a fully-fiberized integrated SDM amplifier. A multimode pump delivery fibre was tapered down to a central uniform waist of 10-20μm and this taper was then wound around a short stripped section of the active fibre with a slight tension to couple pump light efficiently into the glass cladding. A pump coupling efficiency of more than 70% can easily be achieved. A UV-curable low-index acrylate polymer was then applied to the tapered section to ensure robust stable optical contact within the pump combiner. Residual pump power at the output of the amplifier was removed by applying high-index polymer to a further section of stripped fibre and removing the associated heat generated. As shown in Figure 13.7(b), more than 20dB of average modal gain was successfully achieved across the C-band with a DMG of ~3dB amongst the mode groups and a corresponding noise figure of 6-7dB. The amplifier performance could be further improved by optimizing the core

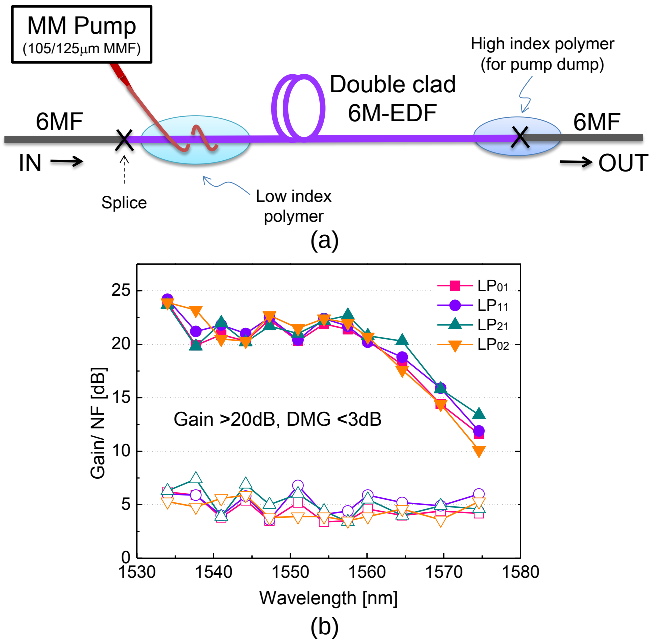


Figure 13.7. (a) The schematic of a cladding-pumped 6M-EDFA and (b) the associated gain performance.

dopant distribution and by reducing the core-to-clad area ratio. We consider this to be an important step in increasing the mode scalability of the few-mode EDFA, which offers cost effective and efficient amplification of a large number of spatial data channels in a single device.

13.4.4 *Future prospects to increase the number of spatial modes in FM-EDFAs*

Scalability to a larger number of modes is an essential feature for the penetration of SDM in next generation optical transmission systems. In this section, we present a cladding pumped FM-EDFA design supporting 10 spatial modes with a multi-layer ring-doped erbium profile [35]. A Genetic Algorithm was employed to minimize the DMG over all supported signal modes (at the same wavelength). The optimal EDFA designs found through the algorithm provided less than 1 dB DMG across the C-band (1530-1565 nm) whilst achieving more than 20 dB gain per mode. As shown in figure 13.8(a), the optimum 10M-EDF design exhibits a step-index fibre refractive index profile and a complex four-layer erbium dopant profile. For the purpose of reducing fabrication complexity, the number of erbium-doped ring layers should be minimized but we found that at least four-layer multiple ring structures are required in order to achieve a DMG of less than 1dB across the C-band. The diameter of the inner-cladding was chosen to be 70 μm, compatible with our preferred choice of pigtailed pump diode. As shown in figure 13.8(b), the averaged modal gain is well above 20dB and NFs are found to be less than 5dB. Note that FM-EDFA designs supporting more than 10 spatial modes will certainly become more complex and it will be very challenging to realize multiple ring-doped profiles with accurate radial control of the dopant distribution using conventional modified chemical vapor deposition and solution doping techniques. Also, dopant diffusion is another limiting factor in the fabrication of such a complex multi-layer structure because some degree of dopant diffusion is inevitable during the fibre fabrication process due to the heat treatment during tube collapsing and subsequent fibre drawing. In this respect, rather than targeting complex fibre doping profile with low DMG (<1dB), adopting a less complicated erbium doping profile offering moderate DMG (2-5dB) and using this in conjunction with a spatial modal filtering device offering controllable modal loss is perhaps a more realistic approach. The filter (fixed or preferably dynamic) could

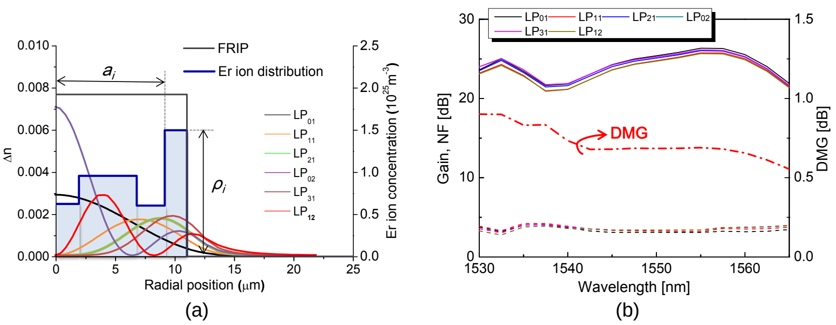


Figure 13.8. (a) Erbium doping distribution and refractive index profile of the cladding-pumped 10M-EDF and (b) the calculated gain and noise figure spectra.

be inserted in the middle of a dual-stage FM-EDFA and total DMG can effectively be improved without noticeable NF degradation in an analogous manner to the gain-flattening filters used in many current single mode amplifiers.

13.5 CONCLUSION

Over the last few years, major advances in SDM technology have been made in both few-mode and multicore fibres. Both of these approaches are being investigated around the globe and a 10-fold increase in overall fibre capacity has already been achieved over the past 5 years. Furthermore, a heterogeneous SDM fibre structure (e.g. few-mode multicore fibre) by combining both technologies has been introduced to further increase the spectral efficiency in a single fibre and has demonstrated up to 100-fold capacity increase. However, although these point-to-point transmission results are highly encouraging in order for SDM to be exploited commercially several key subsystems and optical components are still required to provide network functionality while component integration will be essential to provide practical, field-deployable devices.

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