

Chapter 1

Spatial Division Multiplexing

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Abstract Spatial division multiplexing (SDM) by employing few-mode fiber or multi-core fiber is expected to efficiently enhance the capacity of optical networks and overcome the anticipated ‘capacity crunch’ due to fast increasing capacity demand. This chapter first introduces the advantages and state-of-the-art of SDM. Second, different SDM technologies and key building blocks such as spatial multiplexer, optical amplifier, wavelength selective switch, splicer, connector and digital signal processing block are thoroughly analyzed. Third, commercialized SDM-related components are summarized and discussed.

1.1 Introduction

The exploitation of the spatial domain, which is regarded as the last unexplored physical dimension in optical communication [1, 2], has come into spotlight recently and the corresponding technologies are designated as spatial division multiplexing (SDM).¹ While the utilization of spatial channels in order to enhance system capacity is still considered as innovative in the optical world, “SDM” has already

¹“SDM” is spelled out in the literature both as “spatial” and as “space” division multiplexing. SDM comprises various realization concepts: (1) Transmission based upon multiple parallel fibers, each with a separate cladding comprising one or more cores, without coupling between the fibers is one straightforward SDM concept. (2) Multi-channel transmission using fibers with a single few-moded or highly multi-moded core inside a cladding is designated to the point as mode-division multiplexing (MDM) although the designation SDM is also found in the literature for this case. (3) Transmission based upon multiple cores inside a single cladding where (i) each core may be single-moded without coupling between cores, (ii) each core may be multi-moded without coupling between the cores, (iii) there may be coupling between the cores of a multi-core fiber resulting in supermodes, is typically designated as SDM although MDM may also be comprised.

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been widely applied in the electronic and wire-less worlds, which influences our life unconsciously. PCI (Peripheral Component Interconnect) which refers to multiple parallel digital signal ports is widely used as a local computer bus. It interconnects mother boards with external functioning cards for video, sound and network. HDMI (High-Definition Multimedia Interface) and DVI (Digital Visual Interface), both characterized by a 2-dimensional digital port structure, support the transmission of high-quality videos from players to screens. Moreover, Wi-Fi empowered by multiple-input-multiple-output (MIMO) technology based on multiple antennas [3] is inevitable in our daily life to provide mobile Internet access.

In the optical domain, besides arranging more parallel optical fibers together as a fiber bundle, multiple modes co-propagating over few-mode fiber (FMF) and parallel-signal transmission over coupled or uncoupled multi-core fiber (MCF) are currently regarded as new-emerging SDM technologies to be exploited in optical communication. However, the origin of the concept to employ MCF and multiple modes co-propagating can be traced back to 1979 [4] and 1982 [5], respectively. However, only limited attention was paid to these SDM technologies during the past decades because capacity requirements of optical networks could nicely be satisfied by other, more cost-efficient technologies such as low-loss single-mode fiber (SMF) [6], optical amplifiers such as erbium-doped fiber amplifiers (EDFA) [7], wavelength division multiplexing (WDM) [8], quadrature (and higher order) multi-level modulation [9] and polarization division multiplexing (PDM) [10]. Figure 1.1 shows the evolution of the record transmission capacity and capacity demand of optical networks [2, 11]. Due to the fast growth of capacity requirement of optical networks, it has been foreseen that future bandwidth demands will exceed the maximum achievable capacity of SMF-based networks due to fiber nonlinear effects [12, 13]. The ‘capacity crunch’ [14] has been anticipated to happen around 2018, when commercial systems are expected to offer capacity per fiber in excess of 80 Tbit/s [15], which is almost the cap of SMF-based networks. As the last unexplored physical dimension, space [16, 17], and correspondingly SDM, is proposed to

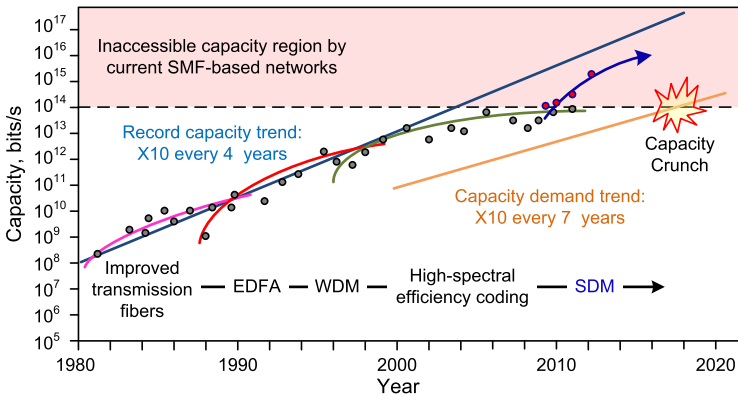


Fig. 1.1 The evolution of the record transmission capacity and capacity demand of optical networks

Table 1.1 System requirements for different optical networks

	Distance	Spectral efficiency	Component costs	Reliability
Submarine	<12.000 km	Highest	Highest	Highest
Long-haul	<4000 km	Higher	Higher	Higher
Regional	<1000 km	High	High	High
Metro	<200 km	High	High	High
Access	<100 km	Medium	Medium	Medium
Datacenter	<100 m	Low	Low	Low

bring a big leap forward in spectral efficiency per fiber so that the ‘capacity crunch’ is expected to be averted.

1.2 Why SDM?

The later 1970s witnessed the upspring of optical fiber based links and more recently copper cables have been rapidly replaced by optical fibers which offer a significant advantage in bandwidth distance product. The optical network development moved from long-haul to metro, access and nowadays to datacenter networks. Although datacenters have been the last where optical technologies have been introduced, SDM technologies have already been deployed in servers and super-computer interconnected networks due to their short distances, e.g. <100 m and strict requirements for low installation and maintenance costs. Vertical cavity surface emitting lasers (VCSELs), which are much cheaper than edge-emitting lasers and can be arranged as 2D arrays in a single wafer, along with low-cost PIN photodiodes have become key enabling components for the deployment of SDM in datacenters. SDM fibers such as MMF ribbons [18, 19] and MCFs with multi-mode cores [20–22] have been commercialized for datacenter and other short-reach applications in order to achieve high alignment tolerance, lower cabling costs and increasing cable density. 70 Gbit/s transmission over 100 m multi-mode 7-core UMCF was demonstrated by employing low-cost VCSELs [23]. A compact fiber link composed of a VCSEL array, MCF and a photodiode array can be a low cost and low power consumption solution for optical interconnects.

Datacenter development is mainly driven by cost, but in general any technology has to prove its reliability [24, 25] before its implementation starts in telecommunication networks ranging from access to submarine links as listed in Table 1.1. Moreover, the introduction of new technologies needs to be a smooth transition based upon existing infrastructure. For SDM technologies, the latter expectation cannot be fully satisfied since SMF links cannot be reused and new SDM fibers have to be deployed. Therefore the chance of SDM is expected to be primarily in new and upgraded optical networks for which new or more fibers have to be placed in order to meet the capacity demand. Under these circumstances, submarine networks can

be the first opportunity for SDM deployment since these networks are mostly influenced by fiber nonlinear effects due to the ultra-long length and will be confronted with a capacity crunch in the first position. Note that submarine networks also have the highest requirements on reliability, which means that the performance of SDM links has to be comparable to that of commercial SMF links. For the practical implementation, new-emerging SDM fibers such as FMF and MCF need to be verified with respect to their advantages in terms of cost-efficiency and energy-efficiency compared to simply arranging a number of parallel SMFs as a fiber bundle.

1.2.1 Cost-Efficiency

The development of SDM fibers such as MCF or FMF integrating multiple spatial channels over one fiber can be regarded as an extension of the integration trend in optical communication. Photonic integration enables fabrication of powerful photonic integrated circuits (PICs) composed of a large number of optical elements. Densely-integrated optical transmitters [26–28] and receivers [29, 30] have been demonstrated in support of WDM signals. The cost-efficiency of PICs through wafer-scale mass-production is more advantageous compared to the solutions employing discrete components, as the total number of components is getting larger. This is exactly the demand for SDM compatible optical transponders whose components' number is proportional to the spatial-channel number. Besides, SDM opens the possibility to integrate other key optical modules such as optical amplifiers [31, 32] and wavelength selective switch (WSS) based optical reconfigurable add/drop multiplexers (ROADMs) [33, 34]. SDM solutions provide the feasibility for network integration and therefore are able to lower the network cost per bit. Economic aspects of SDM are treated in more detail in the [Appendix \(Sect. 1.7\)](#).

1.2.2 Energy-Efficiency

It was pointed out [35, 36] that the energy efficiency of optical networks has been improving with a rate of about 15% annually, which can hardly be expected to be followed by simply deploying more SMFs. Considering a majority of power consumption comes from system management overheads [36], SDM which provides higher spectral efficiency is able to improve overall energy efficiency. For example, (1) a single cooling system can be used for a densely-integrated SDM transponder; (2) a cladding-pumped multi-mode EDFA by employing one multi-mode laser diode [31, 32] can amplify all spatial channels together with no need for a temperature controlling system (see also Chap. 12); (3) since spatially multiplexed signals over one specific wavelength are amplified and switched together, signals over one SDM fiber will experience common impairments which enables joint digital signal processing (DSP) to compensate the same impairments, e.g., frequency offset and

Table 1.2 Potential applications of SDM technologies and key components for different telecommunication networks and datacenters

	FMF or CMCF	UMCF	SDM amplifier	SDM ROADM
Submarine	✓	✓	✓	
Long-haul	✓	✓	✓	✓
Regional	✓	✓	✓	✓
Metro	✓	✓		
Access	✓	✓		
Datacenter		✓		

✓: high potential, applications without mark: less promising

phase distortions in coherent detection [37, 38]. Compared to independent multiple SMFs, power consumption at the receivers can be reduced due to lower computational complexity; (4) one overhead including routing and management information is enough for all spatially multiplexed signals and can be added into one spatial channel. In this case, the other channels can directly send data information. After a proof-point in submarine links has been reached, SDM can be passed down to terrestrial networks due to the aforementioned advantages in cost- and energy-efficiency. Table 1.2 gives expected potential applications of SDM technologies and key components for different telecommunication networks and datacenters. Transmission of multiple modes over FMF or coupled MCF (CMCF) and independent signal co-propagation over different cores of uncoupled MCF (UMCF) have their advantages and disadvantages, respectively, which also strongly depend on the development of related components, and fibers along with electronics in the future.

1.3 State-of-the-Art

In the past few years, a series of successful experiments employing SDM has been carried out in telecommunication networks. High capacity SDM, combined with WDM transmission trials are listed in Table 1.3 with an increasing transmission distance. 140.7 Tbit/s transmission [39] over a 7-core MCF of 7326 km length is a record SDM transmission distance. All state-of-the-art SDM system trials listed in the top half of the table have been realized by MDM over either FMF or multi-mode fiber (MMF). The highest achieved spectral efficiency per fiber core for MDM is 32 bit/s/Hz [40], almost 3 times larger than the maximum capacity that can be provided by an SMF over the same distance. The MDM demonstration over a conventional MMF [41] further enhances the possibility for practical applications of SDM since already deployed MMFs can be reused. By the end of December 2014, combined SDM and WDM trials with a transmission distance longer than 1000 km were only demonstrated with MCFs, listed in the bottom part of Table 1.3. Components for MCF based networks such as multi-core EDFA [42], MCF compatible reconfigurable optical add/drop (ROADM) [33] and MCF loop [43] were demonstrated through directly upgrading the existing SMF based ones. On the contrary to

Table 1.3 High capacity SDM combined with MDM transmission trials (SMUXs will be treated in detail below, see Sect. 1.4.2)

	Distance (km)	Capacity (Tbit/s)	Spectral efficiency (bit/s/Hz)	Fiber type	SMUX solution
[44]	119	73.7	12	3-mode FMF	Phase plate
[50]	120	7.68	9.6	3-mode FMF	Spot coupler
[40]	177	24.6	32	6-mode FMF	Photonic lantern
[51]	305	18	9	MMF	Photonic lantern
[52]	500	30	3.6	3-mode FMF	Phase plate
[49]	900	9.6	3	3-mode FMF	Photonic lantern
[52]	1000	3.5	1.8	3-mode FMF	Phase plate
[53]	1500	2×344	36.8	12-core MCF	Fiber bundle
[54]	1705	17.82	18	6-core CMCF	Photonic lantern
[55]	2688	7.5	15	7-core MCF	Fiber bundle
[56]	4200	1.2	4.8	3-core CMCF	Spot coupler
[42]	6160	28.8	14.4	7-core MCF	Fiber bundle
[43]	7326	140.7	28	7-core MCF	Fiber bundle

the MCF trials, although few-mode EDFA [44–46], few-mode re-circulation loop [47, 48] and low-loss mode coupler [49] were verified successfully, non-negligible mode-dependent loss (MDL) and coupler insertion loss (CIL) still exist in these components, which limit the distance, especially in an accumulated case such as loop measurements.

1.4 SDM Components

1.4.1 SDM Fiber

Figure 1.2 illustrates different optical fibers.

(1) SMF, see Fig. 1.2(a), is operating below the cut off frequency and guides the fundamental LP_{01} mode only. Therefore, SMF provides one spatial channel with two orthogonal polarization states.

(2) FMFs have a slightly bigger core, as shown in Fig. 1.2(b) which enables guiding a few fiber modes. Linearly polarized (LP) modes are well known and usually used to represent fiber modes. However, in SDM, especially MDM, spatial modes are used more often since the number of spatial modes is exactly that of the spatial channels, each of which has two orthogonal polarization states. For spatial modes, degenerate LP modes are considered as two different modes, in other words, two spatial channels. For example, the LP_{11} mode in LP mode definition is degenerate and has two spatial modes LP_{11a} and LP_{11b} . One rotated by 90 degrees with respect to the other, see Fig. 1.3(a).

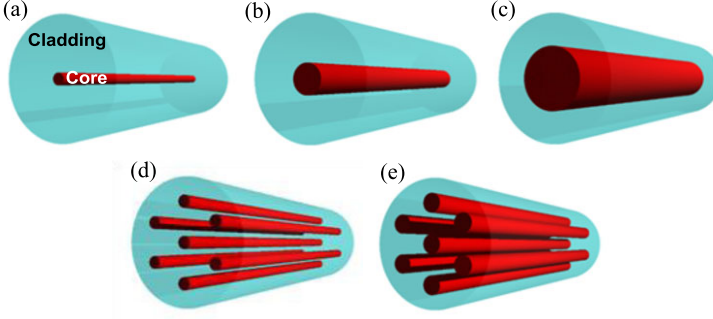


Fig. 1.2 Illustrations of different optical fibers: (a) SMF; (b) FMF; (c) MMF; (d) MCF and (e) multi-core FMF

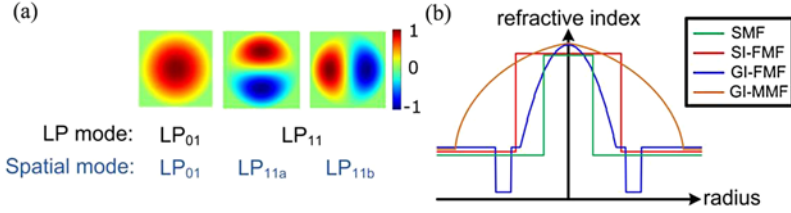
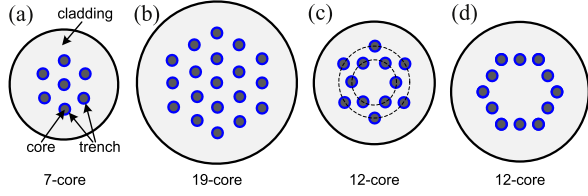


Fig. 1.3 (a) Relation between LP and spatial modes, and (b) index profiles for different fiber types. Color indicates relative phase of isolated modes

Both, step-index (SI) and graded-index (GI) FMFs, see Fig. 1.3(b), can be used in MDM transmission. The SI index profile enables to minimize mode coupling and achieve weakly-coupled FMFs [57, 58]. The differences of propagation velocities between different modes in SI-FMF are quite large, which makes it difficult to achieve a small modal differential group delay (MDGD) over long distance transmission, i.e., <20 ps/km. If there is negligible modal crosstalk and each mode can be individually detected, the complexity of multiple-input-multiple-output based receivers can be significantly reduced and MDGD is not an issue anymore. The practical application of this type of FMF requires precise fiber splicing along the fiber link and excellent FMF components such as spatial multiplexers (SMUXs) to selectively launch and detect each mode. The GI-FMF is generally designed with an index trench [58, 59] in order to minimize fiber bend loss, see Fig. 1.3(b). Low MDGMs within ps/km can be achieved by a well-designed GI index profile. Moreover, through combining FMF spools with positive and negative delays, the cascaded MDGDs can be fully compensated [50], which is beneficial for reducing the size of the MIMO equalizer in the receiver. The additional advantage is that no mode-selective SMUXs are required. Conventional MMFs are generally fabricated with a core size of $50\ \mu\text{m}$ or $62.5\ \mu\text{m}$ in a $125\ \mu\text{m}$ cladding. A $50\ \mu\text{m}$ GI-MMF, see Fig. 1.3(b), supports around 50 spatial modes in the wavelength regime around $1550\ \text{nm}$ and has a maximum MDGD around $2\ \text{ns/km}$. Due to the modal disper-

Fig. 1.4 UMCF integrating (a) 7, (b) 19, (c, d) 12 cores in a single cladding



sion, MMF is mostly used for short-distance communication. Particular attention has been paid to explore the SDM possibilities of MMFs as an already installed fiber which supports MDM. It has been demonstrated that low order modes can be selectively launched and detected [41, 51] and >300 km MDM transmission over MMF is possible.

(3) Multi-core fiber is another type of SDM fiber, which integrates multiple cores in one cladding. MCF can be categorized into two groups depending on whether cores are coupled with each other or not: coupled-MCF (CMCF) and uncoupled-MCF (UMCF), respectively.

Each core of the UMCF can be regarded as an individual spatial channel. For long-distance (i.e., >10 km) optical networks, large capacity transmission over 7-core [39, 55, 60], 12-core [53, 61] and 19-core [62, 63] has been demonstrated. The 7-core, see Fig. 1.4(a) and 19-core, see Fig. 1.4(b) UMCFs are both based on a hexagonal close-packed structure (HCPS). In order to reduce the crosstalk between cores, trench-assisted [64] and hole-assisted [65, 66] structures have been proposed. The trenches and holes around cores have a smaller index which confines the electric field distribution in each core. Two kinds of 12-core MCFs, based on a two-pitch structure (TPS) [53] and a one-ring structure (ORS) [61], respectively, have also been demonstrated, see Fig. 1.4(c) and (d). The significant advantage of UMCF is that commercial polarization-diversity coherent receivers can be directly used for signal recovery. To support long-haul transmission, UMCF needs to achieve low fiber loss, a large effective area (A_{eff}) to reduce fiber nonlinear effects, small inter-core crosstalk, and a reasonable cladding diameter to guarantee mechanical reliability. Another remaining issue for its practical application is scalability. The 19-core UMCF has a cladding diameter around 200 μm , which is already quite sensitive to fiber bending with a small radius [67]. If the cladding has to be enlarged in order to integrate more cores with negligible inter-core crosstalk, the fiber's mechanical reliability will be a serious issue.

Coupled MCF is the other type of MCF which can have strongly- or weakly-coupled cores [68]. For CMCFs, supermodes are generated at the coupled-core region where each supermode can be regarded as one spatial channel. Figures 1.5 and 1.6 show the schematics and simulated supermode profiles for a 3-core and 6-core CMCF, respectively. It is worthwhile to note that the phases of the isolated modes, the superposition of which results in the supermodes, are not always the same. This is indicated in Figs. 1.5 and 1.6 by the different colors which indicate the relative phases of the constituent isolated modes. In simulations, the index contrast and core diameter d for both fibers are 3×10^{-3} and 12 μm , respectively. The circle radii, r , where cores are located, are 17 μm and 28 μm , respectively. Compared to

Fig. 1.5 (a) Schematic of a 3-core CMCF and (b) simulated supermode profiles. *Color* indicates relative phase of isolated modes

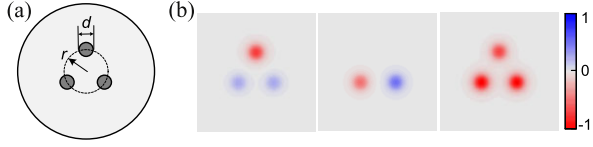


Fig. 1.6 (a) Schematic of a 6-core CMCF and (b) simulated supermode profiles. *Color* indicates relative phase of isolated modes

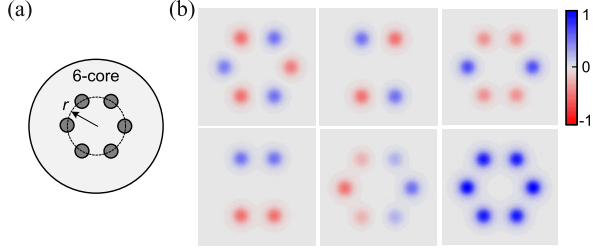


Table 1.4 Comparison between FMF and two types of MCFs

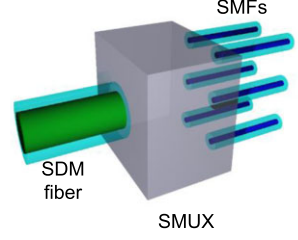
	Spatial utilization efficiency	DSP complexity	Nonlinearity tolerance [72]	Scalability
FMF/MMF	High	High	Medium	High
CMCF	Medium	Medium	Medium/High	Medium
UMCF	Low	Low ($\approx$ SMF)	Low ($\approx$ SMF)	Low

FMF, CMCF can be designed with larger A_{eff} and is therefore more tolerant to fiber nonlinearities [69, 70]. 4200 km and 1705 km combined SDM and WDM transmission have been achieved by 3-core and 6-core CMCF, respectively [54, 71], which is much longer than the maximum distance reached by 3-mode and 6-mode FMF. Moreover, the MDGD of CMCF increases in proportion to the square root of the fiber length [69, 70] instead of linearly as encountered in FMF. Similar to transmission over FMF, MIMO-based DSP is needed for CMCF to fully recover signals but with reduced computational complexity due to the smaller MDGD. Compared to UMCF, CMCF has a higher spatial utilization efficiency and can nicely fit into a standard 125 μm cladding. Table 1.4 gives the comparison between FMF and two types of MCFs. Chapter 2 gives a more detailed description of optical fibers.

1.4.2 Spatial Multiplexers (SMUX)

Figure 1.7 is a schematic diagram of an SMUX, whose basic functionality is to convert optical power from a bundle of SMFs into modes or separate cores of an SDM fiber [73]. SMUXs have evolved from bulky optics with large footprint to recent photonic integrated, 3-dimensional waveguide (3DW) and fiber-bundle based compact solutions. In principle, these solutions can be categorized into two groups.

Fig. 1.7 Schematic diagram of SMUX



One is based on multiple spots, which are generally Gaussian-distributed optical beams from SMFs or single-mode waveguides. In this chapter, these solutions are designated as spot-based SMUXs, which enable efficient coupling not only to MCF but to FMF as well. The second group is mode-selective based on creating similar mode profiles to FMF and therefore only suitable to realize MDM. In the following sections, different SMUX solutions such as bulk optics, photonic integration, fiber bundle and 3DW are discussed subsequently. The performance of SMUXs can be judged in terms of mode or core dependent loss (MDL or CDL) and coupler insertion loss (CIL). MDL is the loss difference between the best and worst modes and CDL is the counterpart for separate cores. CIL represents the average insertion loss for all spatial channels which can be modes or cores.

In order to simplify the model, matrices are utilized to represent the SMUX, as shown below:

$$\underbrace{\begin{bmatrix} M_1 \\ M_2 \\ \vdots \\ M_N \end{bmatrix}}_{M: \text{spatial channel field}} = \underbrace{\begin{bmatrix} \gamma_{1,1} & \gamma_{1,2} & \cdots & \gamma_{1,N} \\ \gamma_{2,1} & \gamma_{2,2} & \cdots & \gamma_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_{N,1} & \gamma_{N,2} & \cdots & \gamma_{N,N} \end{bmatrix}}_{\Gamma: \text{SMUX transfer matrix}} \underbrace{\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{bmatrix}}_{I: \text{launch field}} \quad (1.1)$$

where the components of the vector I represent the launch fields from input SMFs, M is an array of the fields of spatial channels and N is the number of spatial channels in the SDM fiber. Γ is the transfer matrix of the SMUX, which can be quantified with an overlap integral at the SDM fiber facet. The overlap integral is calculated as:

$$\gamma_{i,j} = \frac{\int E_{\text{launch},i}^* \cdot H_{\text{spatial},j} dA}{\sqrt{\int E_{\text{launch},i}^* \cdot H_{\text{spatial},i} dA} \sqrt{\int E_{\text{mode},j}^* \cdot H_{\text{spatial},j} dA}} \leq 1 \quad (1.2)$$

where $E_{\text{launch},i}$ and $H_{\text{spatial},j}$ are the transverse electric field of the i th launch field at the SDM fiber facet and the transverse magnetic field of the j th spatial channel, respectively. A is the fiber cross-sectional area. The notation $*$ indicates the complex conjugate.

For MCF with uncoupled cores, (1.1) can be rewritten as a diagonal matrix Γ . CDL and CIL can be calculated immediately with the diagonal entries of Γ , which

are identical to singular values.

$$\begin{bmatrix} M_1 \\ M_2 \\ \vdots \\ M_N \end{bmatrix} = \begin{bmatrix} \gamma_{1,1} & 0 & \cdots & 0 \\ 0 & \gamma_{2,2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \gamma_{N,N} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{bmatrix} \quad (1.3)$$

$$CDL = \max(\gamma_{n,n}^2) / \min(\gamma_{n,n}^2) \quad (1.4)$$

$$CIL = \sum (\gamma_{n,n}^2) / N \quad (1.5)$$

For FMF with spatial modes, Γ is diagonal only in the case of mode selective excitation. Singular value decomposition (SVD) is arranged for Γ to get N singular values λ_n ($n = 1$ to N). MDL and CIL can be calculated by:

$$MDL = \max(\lambda_n^2) / \min(\lambda_n^2) \quad (1.6)$$

$$CIL = \sum (\lambda_n^2) / N \quad (1.7)$$

1.4.2.1 Bulk Optics

(1) Spot-Based Excitation

For free space spot-based SMUXs, prisms [50, 74–76] and sharp-edge mirrors [56] have been applied to relocate multiple collimated optical beams closer to each other in a certain spot arrangement. Additional imaging optics is generally chosen to optimize the size of the parallel optical beams to match the SDM fiber. Due to optical reversibility, the same setup can also be used for demultiplexing. It is straightforward to design spot-based SMUXs for MCFs. In order to achieve decent coupling performance for FMFs which have a single core, specific spot arrangements are required as analyzed in [77, 78] (see Fig. 1.8) for unitary mode transitions.

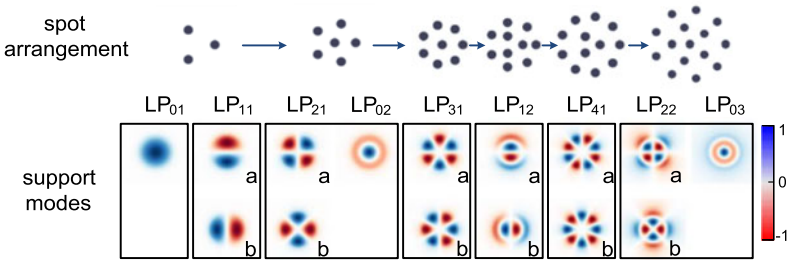


Fig. 1.8 Spot arrangements for supporting different spatial modes. *Color* indicates relative phase of isolated modes

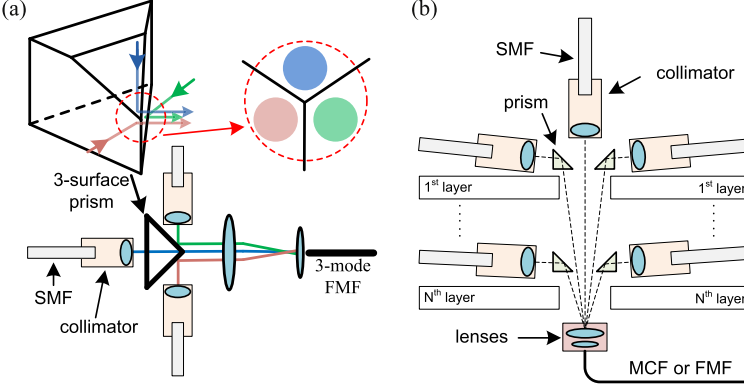


Fig. 1.9 (a) 3-spot SMUX for 3-mode FMF based on a single prism [50]; (b) scalable spot-based SMUX, designed for a 19-core UMCF [74]

Three spots located at the vertices of an equilateral triangle provide efficient mode multiplexing for the spatial LP_{01} , LP_{11a} and LP_{11b} modes, which was demonstrated by a 3-surface prism with small bevels in free space [50]. As shown in Fig. 1.9(a), two vertical surfaces of the prism are perpendicular to each other and the top surface is inclined by 45° with respect to the vertical. In order to ensure the optimal injection with optical beams along the optical axis, a telecentric lens setup is utilized to image spots into a 3-mode FMF. An ideal 3-spot SMUX can be approximated [77] by the equation given below with spot-profile optimization [79].

$$\begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & e^{j2\pi/3} & e^{-j2\pi/3} \\ 1 & e^{-j2\pi/3} & e^{j2\pi/3} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} \quad (1.8)$$

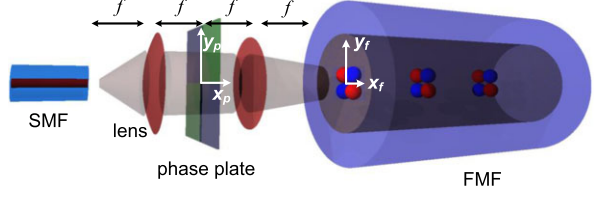
where M_1 , M_2 and M_3 represent the field profiles for the LP_{01} , LP_{11a} and LP_{11b} modes, respectively. The transfer matrix Γ is unitary, which means that both, MDL and CIL are zero.

The schematics of a scalable spot-based SMUX in free space is illustrated in Fig. 1.9(b) which was designed for coupling to a 19-core UMCF [74]. Fiber collimators and prisms are circularly arranged around the SMUX's central axis and more layers can be added as the number of spots increases.

(2) Mode-Selective Excitation

For the excitation of one specific spatial mode, the optical launch field should have the same field distribution as the mode of interest, which can be realized through spatially tailoring the collimated optical beam. Binary phase plates [44, 47, 80, 81], and spatial light modulators (SLM) [57, 82, 83] have been demonstrated for selectively exciting modes. SLMs are usually based on polarization-sensitive liquid

Fig. 1.10 Mode-selective excitation of LP_{21} mode



crystals. To support polarization multiplexed light, extra polarization separation and conversion setups are required [84, 85]. Phase plates can be made of glass and supporting both polarization states. A $4f$ setup is usually applied for mode-selective excitation. An example of LP_{21} mode excitation is illustrated in Fig. 1.10, where a phase plate is placed at the Fourier plane. x_p, y_p and x_f, y_f are spatial coordinates of the Fourier and the FMF input plane, respectively. At the Fourier plane, the collimated optical beam from the SMF is written as $I_P(x_p, y_p)$, and the transmittance of the phase plate is given by $t_P(x_p, y_p)$. The launch field at the back focal point of the 2nd lens can be described as the Fourier transform of the product of $t_P(x_p, x_p)$ and $I_P(x_p, x_p)$ [86, 87]:

$$U_F(x_f, y_f) = \mathcal{F}[I_P(x_p, y_p) \cdot t_P(x_p, y_p)] \quad (1.9)$$

where $\mathcal{F}$ denotes the Fourier transform. Figure 1.11(a) gives the theoretical mode profiles (left to right: LP_{11a} , LP_{21a} and LP_{02} mode) of a 6-mode fiber. Figure 1.11(b) shows the schematics of binary phase plates which are employed to excite each spatial mode. The simulated launch field profiles at the FMF input plane corresponding to different phase plates are also given, which are simulated for the case that a Gaussian-distributed LP_{01} mode is the input beam. With a 90° rotation of the phase plate, the LP_{11b} mode can be excited. For the LP_{21b} mode, the phase plate needs to be rotated by 45° . Figure 1.12 gives the vertical cross-sections of the theoretical mode profiles of a 6-mode SI-FMF with a core diameter of $24.7 \mu\text{m}$ by the blue curves and the simulated launch field profiles are shown by the red curves. It can be seen that binary phase plates are able to create a similar optical field at the focal point to match the corresponding fiber mode [84].

In order to (de)multiplex N spatial modes, $N - 1$ lossy beam combiners need to be used, see Fig. 1.13. Assuming that each spatial mode is efficiently excited through an ideal phase plate and beam splitters with different splitting ratios are used to balance the insertion loss for different ports since different launch fields go through different numbers of beam splitters, the CIL is given by:

$$CIL = -1/N \quad (1.10)$$

CIL will be 10 dB for 10 spatial modes. The increasing CIL limits the scalability of phase-plate based SMUXs.

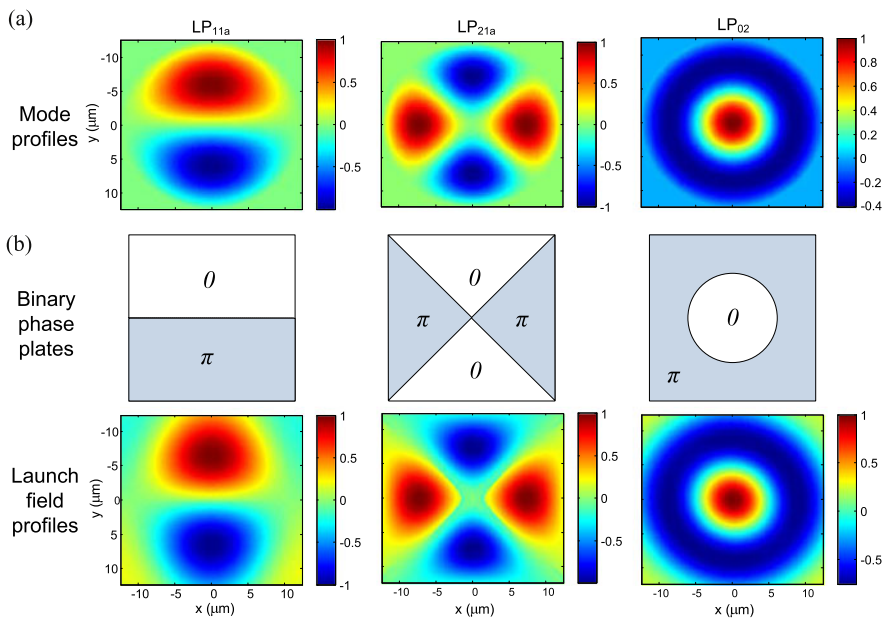


Fig. 1.11 (a) Theoretical mode profiles and (b) simulated launch field profiles of phase plates for LP_{11} , LP_{21} and LP_{02} modes. *Color* indicates relative phase of isolated modes

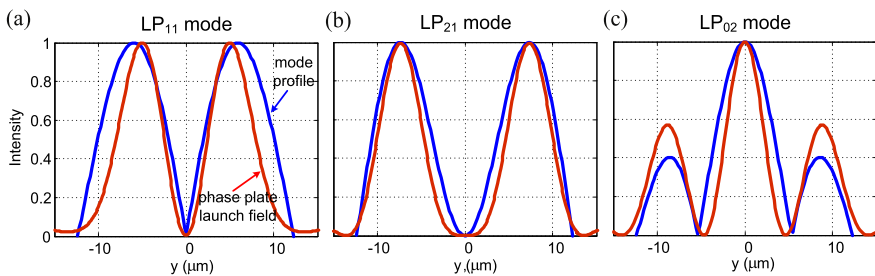
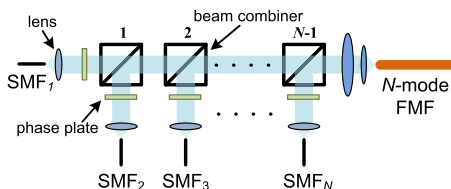


Fig. 1.12 Vertical cross-section of theoretical mode profiles (*blue curves*) and simulated launch field profiles of phase plates (*red curves*) for (a) LP_{11} , (b) LP_{21} and (c) LP_{02} mode

Fig. 1.13 Phase-plate based mode-selective SMUX



1.4.2.2 Photonic Integration

Photonic integration technology based on the silicon-on-insulator (SOI) [88, 89] and indium phosphide (InP) [90, 91] platforms enables the integration of passive and active optical functionalities on a single chip, which is more compact, reliable and potentially cheaper than the solution with discrete optical components. The SOI and InP platforms generally offer planar photonic integrated circuits (PICs), and fiber-chip coupling can be realized by edge coupling through spot-size converters [92], lensed or tapered fibers and top-coupling through grating couplers [93–96] or vertical mirrors [97, 98]. It is challenging for edge coupling to stack multiple waveguide layers together with a small spacing to realize 2D coupling for SDM, especially for coupling into FMFs, where 2D patterns need to be positioned with micron accuracy. Top coupling provides more freedom for vertical emitters in 2D arrangements. Figure 1.14(a) illustrates the schematics of a spot-based SMUX by employing three 1D grating couplers to couple to a 3-core MCF. Photonic integrated MCF transceivers were demonstrated in [22] where eight SOI-based grating couplers were employed for coupling to a 2×4 linear UMCF. A silicon photonic 7-core UMCF receiver was demonstrated in [99]. It has been demonstrated that 1.25 dB coupling loss to an SMF can be achieved for a 1D grating coupler which couples one polarization state into or out of the fiber [100]. The coupling loss increases to 3.2 dB for a 2D grating coupler which supports dual polarization states. As illustrated in Fig. 1.14(b), two orthogonal polarization states x and y are combined by a single 2D grating coupler, and three 2D grating couplers were employed to couple to a 3-mode FMF as a 3-spot SMUX [101].

Mode-selective excitation can also be achieved by 2D top-coupling. For instance, in order to create a bipolar field for exciting the LP_{11} mode, two grating couplers are driven in a push-pull configuration with a π phase difference [102–104], as illustrated in Fig. 1.15. By further extending this concept, a full 6-channel integrated mode-selective SMUX was demonstrated in [105], where one 2D grating coupler is placed at the center for launching or detecting the LP_{01} mode, and four grating couplers are distributed in an outer ring for the LP_{11a} and LP_{11b} modes. A scanning

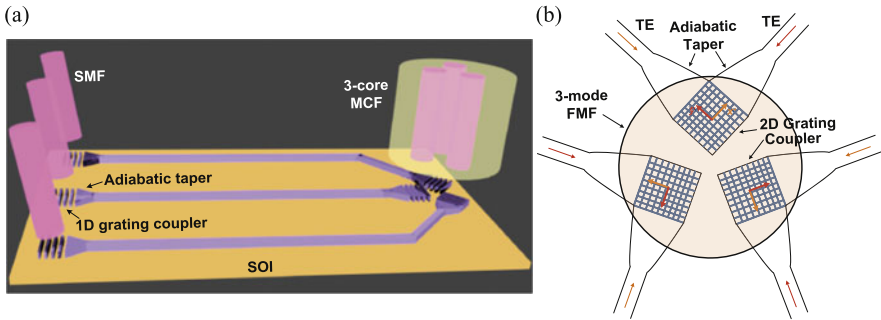


Fig. 1.14 (a) Schematics of spot-based SMUX employing 1D grating couplers, and (b) top-view of a 3-spot SMUX based on three 2D grating couplers coupling to a 3-mode FMF [101]

Fig. 1.15 Schematics of a push-pull based LP_{11} mode excitation scheme

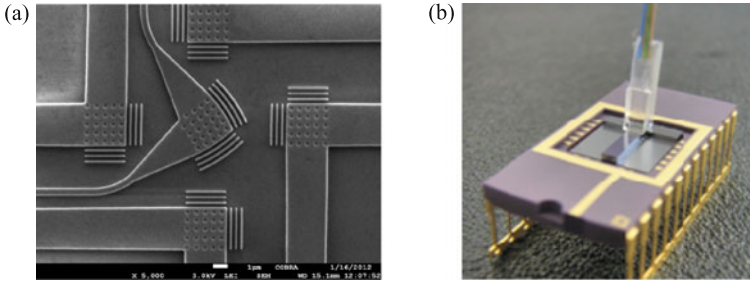
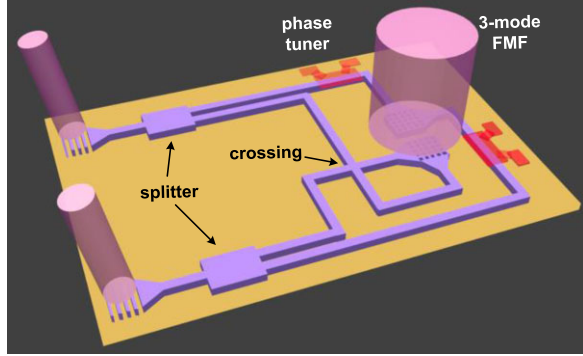


Fig. 1.16 (a) SEM image of region with five grating couplers and (b) image of packaged SOI-based SMUX

electron microscope (SEM) image of the region with all five grating couplers is given in Fig. 1.16(a). The integrated SMUX has been packaged with an SMF array for six SMF ports and wire-bonded to an electronic circuit for controlling the phases for selectively exciting the LP_{11} modes, see Fig. 1.16(b).

1.4.2.3 Fiber Bundle

A fiber bundle is an assembly of many optical fibers. Based on fiber bundles, both spot-based and mode-selective SMUXs have been demonstrated. It is straightforward to employ fiber bundles for coupling to MCFs. Figure 1.17(a) shows a design of a fiber-bundle SMUX for a UMCF [106, 107], where seven thin-cladding fibers are inserted into a glass capillary, stacked by curing adhesive and then polished mechanically. The cladding diameter of each fiber is around $45\ \mu\text{m}$, which is similar to the pitch of the 7-core UMCF. For fibers with larger cladding diameters, a tapering process can be applied to downsize the fiber bundle to match the size of the MCF, see Fig. 1.17(b) [108]. The SMUX for MCF is also designated as a fan-in/fan-out (FI/FO) device in some articles.

In order to selectively excite fiber modes, a fiber bundle is further down-tapered in such a way that a few-mode end guiding multiple supermodes is created, see

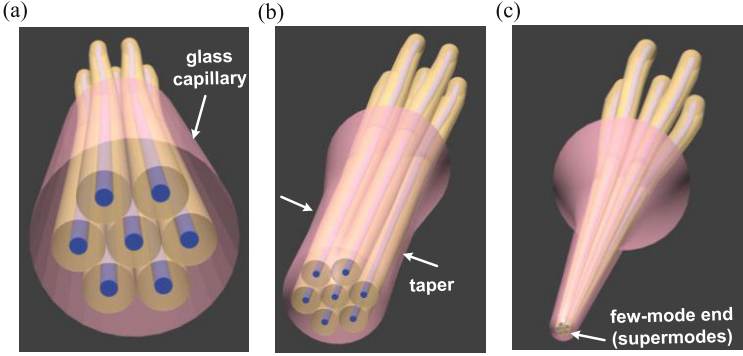


Fig. 1.17 Fiber bundle (a) without and (b) with down-tapering; (c) mode-selective SMUX based on tapered fiber bundle

Fig. 1.18 Image of 6-core photonic lantern coupling to a 50/125 μm GI-MMF [41]

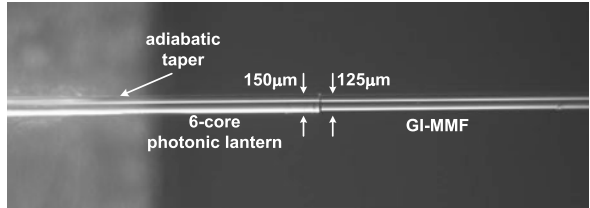


Fig. 1.17(c). This type of SMUX is also designated as a photonic lantern, which was originally proposed for applications in astrophotonics [109–111]. Figure 1.17(c) gives an example of a 6-mode mode-selective SMUX. Unlike the arrangement of fiber cores in a 7-core MCF, six fibers are positioned in the glass capillary according to the structure shown in Fig. 1.8 (see the arrangement of six spots for interfacing with LP_{01} , $\text{LP}_{11a/b}$, $\text{LP}_{21a/b}$ and LP_{02} modes) in order to support the six spatial modes [78]. In [49] and [112], respectively, 3-mode and 6-mode photonic-lantern SMUXs have been experimentally verified. It should be noted that if all fibers are identical, the photonic lantern cannot excite each spatial mode but creates supermodes which are the unitary combinations of the spatial modes [78]. In this chapter, this kind of SMUX is also classified as mode-selective since only desired spatial modes get excited. For instance, six fully mixed spatial modes were experimentally excited over a conventional 50/125 μm GI-MMF which guides more than 35 spatial modes by the fiber-bundle SMUX [41] and mode mixing was compensated by DSP. Figure 1.18 gives the image of a 6-core photonic lantern coupling to the 50/125 μm GI-MMF.

In order to selectively launch each spatial mode, dissimilar fibers are used to introduce degeneracy into the cores and create an asymmetric few-mode end. In this case, spatial modes can be individually excited through corresponding isolated input fibers [113–116].

1.4.2.4 3-Dimensional Waveguide (3DW)

The fabrication of 3-dimensional waveguide devices is enabled by femto-second laser pulses, which are focused inside a fused silica substrate. Both, the core and the cladding of the waveguides are made out of pure fused silica. This concept enables to locally modify the refractive index of a glass so that waveguides in 3D are created. Figure 1.19 gives a sketch of a 3DW SMUX for coupling to a 7-core MCF. The 3DW SMUX has seven single-mode waveguides arranged in a line at the one end, which enables the efficient connection to a standard SMF array with a pitch of 127 μm or 250 μm . Figure 1.20 shows the 3DW SMUX for coupling to a 6-mode FMF. Single-mode and few-mode waveguides can be written by multi-scan techniques [117, 118].

Laser-inscribed waveguides were investigated as early as 1996 [119]. More recently, laser-inscribed single-mode waveguides with small propagation loss around 0.3 dB/cm at 1550 nm [120] and low coupling loss to an SMF have been realized. However, refractive index changes induced by the laser inscription are constrained to a small volume. Higher index contrast, i.e., $\Delta n > 6 \times 10^{-3}$, has been achieved through an additional fabrication process [121, 122], but the uniformity and the scattering of the waveguides have not been thoroughly discussed/investigated. 3DW devices with low Δn can work properly for MCF coupling due to the single-mode operation, whereas for FMF, larger Δn is required for direct coupling between a 3DW SMUX and an FMF, especially in cases with a large number of modes [123]. As a means to overcome the design constraints of 3DW devices due to the limited

Fig. 1.19 3DW SMUX for coupling to 7-core MCF

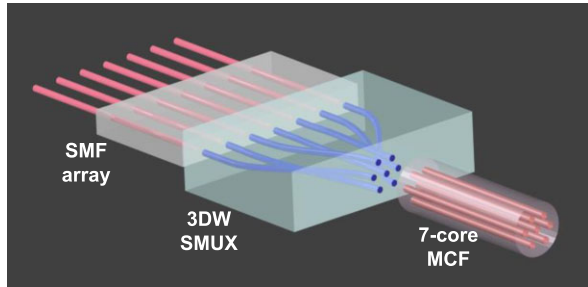


Fig. 1.20 3DW SMUX for coupling to 6-mode FMF

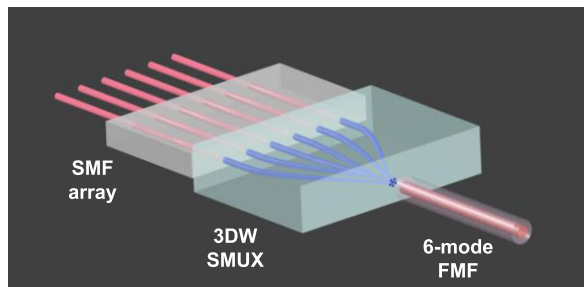
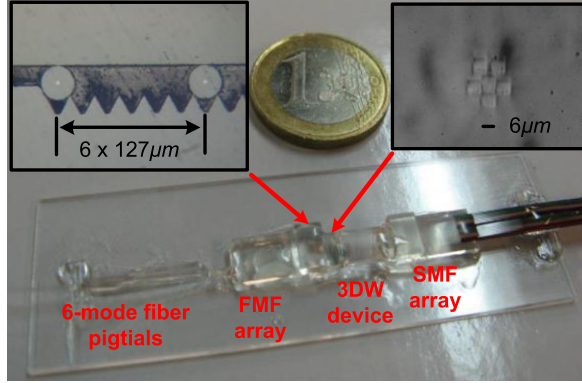


Fig. 1.21 Picture of packaged dual-channel 6-mode 3DW device with up-tapered 6-mode FMF array [123]



Δn , the employment of imaging optics [124] or up-tapering [123] has been proposed.

A dual-channel 6-mode 3DW device with two photonic-lantern SMUXs has been demonstrated as illustrated in Fig. 1.21 [123]. Two SMUXs can be used as mode multiplexer and demultiplexer, respectively. The left inset in Fig. 1.21 gives the microscope image of the FMF array facet where two adiabatically up-tapered 6-mode FMFs with a cladding of $175\text{ }\mu\text{m}$ diameter are positioned and assembled in a standard V-groove with a pitch of $127\text{ }\mu\text{m}$. The right inset in Fig. 1.21 gives the microscope image of the 3DW 6-core photonic-lantern structure. The SMF array, 3DW device, and FMF array are glued together using UV curing epoxy. Figure 1.21 shows the packaged 3DW device, which has a link CIL less than 8 dB and a double-pass MDL around 7 dB. Large capacity six spatial-mode multiplexed transmission demonstrations based on the fully packaged 3DW device have been published in [125].

1.4.2.5 Summary

Tables 1.5 and 1.6 list the measured results of a larger number of experimentally demonstrated SMUXs for coupling to different kinds of MCF and FMF/MMF, respectively. Decent performance of MCF SMUXs in terms of CIL and CDL is achieved by most of the applied technologies due to single-mode operation. For MDM applications, as shown in Table 1.6, spot-based and mode-selective solutions have both been shown to enable smooth mode transitions from multiple single modes to a group of spatial modes. Photonic lantern technology [78] based on fiber bundle or 3DW devices is the most promising solution to achieve efficient mode (de)multiplexing with low CIL and MDL. Moreover, photonic-lantern based 3DW SMUXs have also been exploited for few-mode MCFs [126, 127], which further demonstrates the photonic lantern's flexibility and robustness in 2D optical coupling.

Table 1.5 Experimentally demonstrated SMUXs for MCF

	Fiber type	Technology	CIL (dB)	CDL (dB)
[128]	7-core UMCF	Tapered fiber bundle	1.48	2.3
[107]	7-core UMCF	Thin-cladding fiber bundle	0.2	0.3
[129]	7-core UMCF	Stacked polymer waveguide	6	6
[75]	7-core UMCF	Prism based bulk optics	0.4	0.4
[130]	12-core UMCF	Ferrule with a hexagonal hole	0.64	1
[74]	19-core UMCF	Prism based bulk optics	1.22	0.4
[54]	6-core CMCF	3DW	4.5	

Table 1.6 Experimentally demonstrated SMUXs for MDM

	Fiber type	Technology	CIL (dB)	MDL (dB)
[80, 131]	3-mode FMF	Phase plate based bulk optics ^a	9	2.3
[132]	3-mode FMF	Sharp-edge mirror based bulk optics	3.8	<2
[50]	3-mode FMF	3-surface prism based bulk optics	3.5	<2
[102, 105]	3-mode FMF	Silicon integrated grating coupler ^a	22	5
[49]	3-mode FMF	Fiber based photonic lantern	<2	<1
[133]	3-mode FMF	Stacked polymer waveguide ^a	8	10
[134, 135]	6-mode FMF	Trench-assisted PLC ^a	5	9
[73, 123]	6-mode FMF	3DW	<4	<3.5
[136]	6-mode FMF	Multi-plane light conversion [137] ^a	3.6	1
[41]	50 μ m GI-MMF	Fiber based photonic lantern	2.5	4.5

^aMode selective excitation

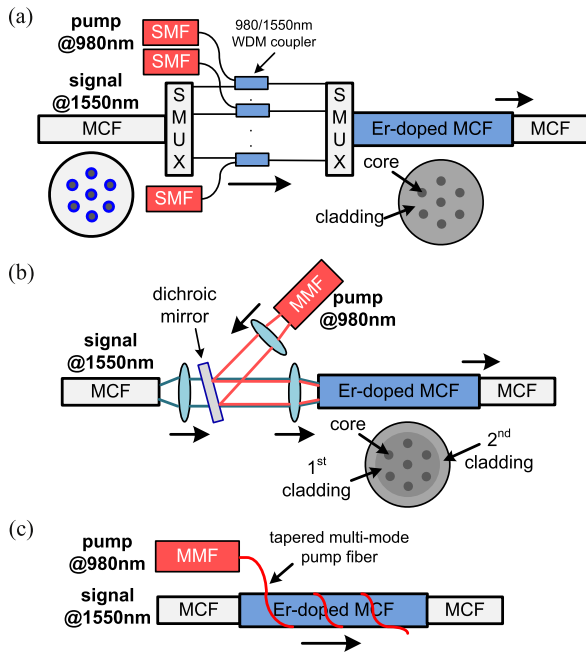
1.4.3 Optical Amplifiers

Although optical fibers nowadays can be manufactured with low attenuation loss around 0.2 dB/km, optical amplifiers such as erbium-doped fiber amplifiers and distributed Raman amplifiers are still inevitable to compensate connector and fiber losses of optical networks, especially for those with distances larger than 100 km.

1.4.3.1 MCF

A hybrid amplification scheme by employing both DRAs and EDFAs was demonstrated in [138], where 9–12 dB DRA gain and less than 1 dB noise figure (NF) were realized over a 75 km 7-core MCF. Extra SMF EDFAs were used to fully compensate the fiber loss. In order to achieve enough amplification gain, core-

Fig. 1.22 (a) Schematic of core-pumped EDFA with external WDM couplers; (b) cladding-pumped EDFA with multi-mode laser diode by end-coupling and (c) side-coupling



pumped and cladding-pumped EDFAs are both under investigation for MCF applications.

A schematic illustration of a core-pumped MCF EDFA [139–141] with external WDM couplers to combine the signal and pump is shown in Fig. 1.22(a) where the number of pump lasers and couplers is proportional to that of the core channels. It has been demonstrated that the performance of the core-pumped MCF amplifiers are comparable to that of conventional SMF EDFAs with 25 dB amplification gain and less than 4 dB NF [139, 142]. In order to lower the power consumption and downsize the optical amplifier, cladding-pumped MCF amplifiers have become more attractive and are under current investigation [143–146]. Instead of using discrete pump sources, it was demonstrated that a single multi-mode laser diode launched into the center core can be applied to pump all outer six cores in a 7-core MCF [143]. Cladding pumping enables the use of all cores as transmission channels, and a corresponding solution is illustrated in Fig. 1.22(b), where a dichroic mirror acts as a free space WDM coupler for end-coupling and combining signal and pump light. In order to confine the pump better, Er-doped MCFs are generally designed and fabricated with double claddings. Due to the small overlap between the cores and the pump light, double-cladding Er-doped MCFs operate over longer distances [144, 147] in order to increase pump absorption and pump all cores simultaneously. However, the long Er-doped MCFs result in a low gain spectrum and large NFs in the short wavelength regime of the C-band, e.g., 1530 nm [142, 148, 149], which limits the full C-band (1530–1565 nm) operation of cladding-pumped MCF amplifiers. In order to further minimize internal loss from free space coupling and downsize opti-

Table 1.7 Experimentally demonstrated MCF EDFAs

	MCF type	Pumping type	Length (m)	Gain (dB)	NF (dB)	Crosstalk (dB)
[139]	7-core (Er)	Core	15	25	4	< −25
[140]	7-core (Er)	Core	16	20	< 7	< −40
[141]	Bundled 7-core (Er)	Core	7.3	23	5.1	< −48.5
[143]	7-core (Er)	Cladding	50	20	6	
[144]	7-core (Er) ^a	Cladding	10	> 14	< 9	< −32.7
[147]	7-core (Er) ^a	Cladding	100	> 15	< 5.5	< −30
[146]	19-core (Er)	Cladding	7	< 23.3	< 7	
[145]	12-core (Er/Yb) ^a	Cladding	5	< 18.3	< 13	< −33
[32]	7-core (Er) ^b	Cladding	34	> 20	< 8	< −45

^aDouble-cladding^bSide-coupling

cal amplifiers, a side-coupled MCF EDFA has been proposed, see Fig. 1.22(c). All cores were pumped simultaneously by a side-coupled tapered multimode fiber [32], and more than 25 dB was obtained in each core over the full C-band. Besides gain and NF, core-to-core crosstalk is also essential and determines the maximum transmission length and capacity. A comprehensive list of demonstrated MCF EDFAs is given in Table 1.7.

1.4.3.2 FMF

Both DRAs and EDFAs for FMF applications have been experimentally demonstrated. Similar to the MCF case, an FMF DRA was applied together with SMF EDFAs due to the low DRA gain [150]. This hybrid FMF amplification scheme realized 5–8 dB DRA gain and <2 dB NF covering the full C-band for three spatial modes propagating over a 137 km FMF. Unlike the FMF DRA, an FMF EDFA is able to offer large amplification gain to fully compensate the fiber loss [151]. The FMF EDFA can be analyzed as a two-level model with total erbium ion concentration ρ . The power of the i th spatial mode at position z along the erbium-doped fiber can be calculated by:

$$\frac{dP_{s,i}(v_s, z)}{dz} = P_{s,i}(v_s, z)[\gamma_{e,i}(v_s, z) - \gamma_{a,i}(v_s, z)] \quad (1.11)$$

where v_s is the signal frequency, and $\gamma_{e,i}$ and $\gamma_{a,i}$ are the emission and absorption factors for the i th spatial mode, respectively.

$$\gamma_{e,i}(v_s, z) \propto \int n_2(z) I_{s,i}(z) dA \quad (1.12)$$

$$\gamma_{a,i}(\nu_s, z) \propto \int n_1(z) I_{s,i}(z) dA \quad (1.13)$$

where A is the fiber cross-sectional area and n_1 and n_2 are the erbium ion populations at the upper and lower energy level, respectively, and obeying the relation $n_1 + n_2 = \rho$. Note that amplified spontaneous emission (ASE) and mode mixing are omitted.

The factors $\gamma_{e,i}$ and $\gamma_{a,i}$ are determined by the overlap integrals between the i th spatial mode and the erbium ion populations.

In a steady state, n_1 and n_2 along the active fiber are fully determined by the intensity profiles of M pump modes $I_{p,j}$ ($j = 1$ to M) and N signal modes $I_{s,i}$ ($i = 1$ to N). Therefore, the erbium ion distribution and the intensity profiles of the pump and signal modes all play crucial roles in determining the gain of each spatial mode. A good FMF amplifier should offer a large average gain, small differential modal gain (DMG) and low NF. Assuming that the transmission FMF and the Er-doped active FMF have the same guided modes, a signal mode whose profile has a better match to the profiles of the pump intensity and the Er-doping will experience a larger gain. The DMG at the frequency ν_s can be calculated by:

$$DMG = \max[P_{s,i}(\nu_s, L)] / \min[P_{s,i}(\nu_s, L)] \quad (1.14)$$

where L is the length of the erbium-doped fiber.

In order to balance the DMG, different schemes for optimizing the pump and Er-doped FMF have been investigated. Active FMFs with different Er-doping profiles result in different gain for each mode. It has been demonstrated that through concatenating two active FMFs with different Er-doping profiles, it is possible to achieve DMG < 6 dB for all six spatial modes over the full C-band using a single-mode pump [152, 153], see Fig. 1.23(a). Besides optimizing the Er-doping profiles, it is also beneficial to modify the transverse profile of the pump for achieving a lower DMG. Using a few-mode EDFA supporting five [154] or six [155] spatial modes and pumping a higher order mode, e.g. LP₂₁, DMG < 2.5 dB has been demonstrated. As shown in Fig. 1.23(b), the LP₂₁ mode has been excited by employing phase plates in combination with bi-directional pumping. More details of these investigations, including various FMF EDFAs reported so far, are compiled in Table 1.8.

As the number of modes is scaled up, more pump power will be required to keep the same gain and NF for all modes, which means multiple single-mode pumps need to be combined and used together. Due to the availability of high-power multi-mode laser diodes, a cladding-pumped FMF EDFA has been proposed for simultaneous amplification of all modes in a more cost-efficient and simple way [31], see Fig. 1.23(c). A recent theoretical analysis aiming at minimizing the maximum DMG over all supported signal modes of cladding-pumped four-mode and six-mode-group EDFAs has shown that more than 20 dB gain per mode and less than 1 dB DMG across the whole C-band (1530–1565 nm) can be achieved for up to 10 spatial modes. The corresponding optimum EDFA design had a step index profile with up to four different doping levels in a circular arrangement [156]. Such active FMFs with ring-shaped doping (see Fig. 1.23(c)) have turned out to be advantageous in

Fig. 1.23 Schematics of different FMF EDFA concepts: (a) concatenated active FMFs to balance DMG, (b) bi-directional pumping with high-order pump mode, (c) cladding-coupling and ring-doped active FMF

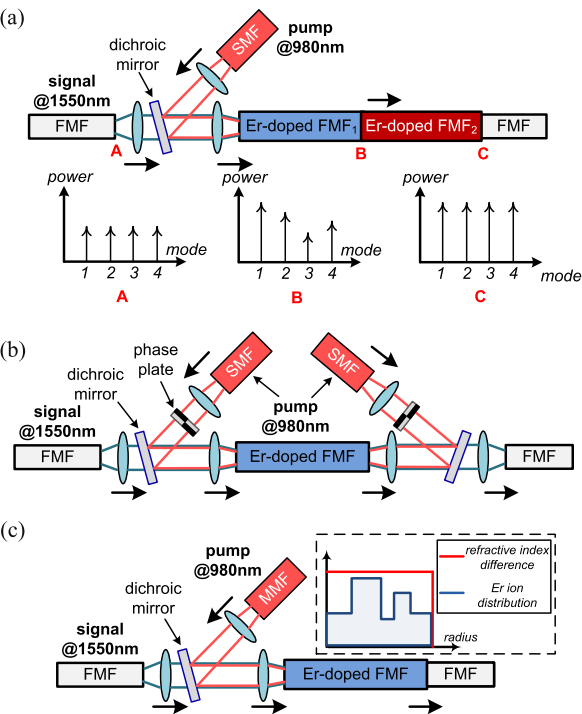


Table 1.8 Experimentally demonstrated FMF EDFAs

	FMF type	Pumping scheme	Gain (dB)	DMG (dB)	NF (dB)
[46]	3-mode	Core (offset pump)	>20	<5	
[152]	6-mode (concatenated)	Core (LP ₀₁ mode pump)	>18	<6	<7
[154]	5-mode (ring-doped)	Core (LP ₂₁ mode pump) ^a	>20	<2.5	
[155]	6-mode (ring-doped)	Core (LP ₂₁ mode pump) ^a	>20	<2	
[31]	6-mode (double-cladding)	Cladding (multi-mode pump)	>20	<4	

^aBi-directional pump

balancing the DMG [157, 158] and reducing performance degradation in macro-bending [159]. However, with conventional fiber fabrication processes such as modified chemical vapor decomposition (MCVD), the designed Er-doping profiles are hard to achieve mainly due to Er ion diffusion [160, 161]. It has been observed in [155, 160] that each doped section is more like Gaussian-shaped. In order to overcome this unwanted effect, a micro-structured core, which can be manufactured by the stack-and-draw process, has been proposed to approximate the ring geometry with moderate fabrication complexity [160].

1.4.4 Wavelength Selective Switches (WSS)

A wavelength selective switch (WSS) is a $1 \times N$ optical device which receives multiple wavelengths at one common input port and enables dynamic routing of any wavelength channel to any of N output ports (see also Chap. 10, Sect. 10.1.4). Its functionality can be used reversely to combine the wavelength channels. WSSs constitute a key component in reconfigurable optical add/drop multiplexers [162]. The schematic of an SMF WSS is illustrated in Fig. 1.24, which essentially consists of (1) a fiber and a micro-lens array as input/output section, (2) a diffraction grating which angularly disperses wavelength channels in a horizontal plane (the x - y plane in Fig. 1.24), (3) a Fourier lens which converts the angular shifts as beam displacements on a beam steering element, and (4) the beam steering element which can be a micro-electro-mechanical system (MEMS) [163, 164] or a liquid crystal-on-silicon (LCoS) [165] for vertical beam steering. Note that a polarization-diversity section and a beam expansion section have been omitted in Fig. 1.24.

In a conventional SMF WSS, each wavelength channel can be switched individually. Investigations trying to transfer this concept to SDM by switching spatial channels individually have shown that this approach is apparently limited due to crosstalk induced by mode mixing [166]. Moreover, it has been pointed out that MDM and WDM are two fundamentally different concepts [24]: crosstalk in WDM can be negligible while MDM exhibits severe linear crosstalk among parallel modes. With respect to performance requirements such as negligible crosstalk and high spectral resolution, all spatial channels at one wavelength should be regarded as one entity to be switched and should therefore jointly be routed over SDM compatible WSSs similar to the SMF case.

Fig. 1.24 Schematic of an SMF WSS

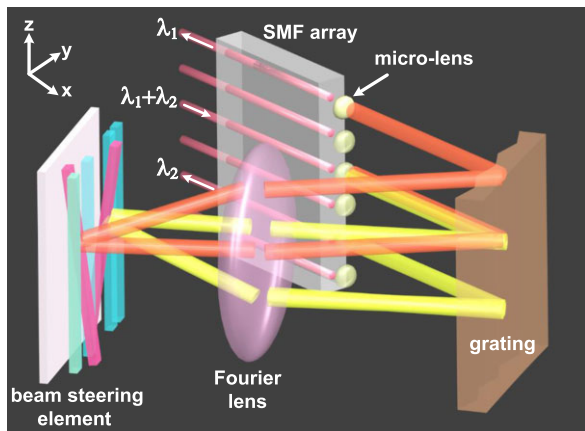


Table 1.9 Experimentally demonstrated SDM WSSs

	SDM type	SDM ports	SMUX usage	Remapping	Steering element
[33]	7-core MCF	1×2	Yes	No	MEMS
[167]	7-core MCF	1×2	Yes	Yes	MEMS
[34]	3-mode FMF	1×9	No	No	LCoS
[168]	3-mode FMF	1×2	No	No	LCoS
[169]	3-mode FMF	1×2	Yes	Yes	LCoS
[170]	3-mode FMF	1×11	Yes	No	LCoS

^aDouble-cladding^bSide-coupling

1.4.4.1 MCF WSS

In [33, 167] 7-core MCF WSSs have been demonstrated, where an SMUX is used to demultiplex a spatially-multiplexed signal into seven parallel ones over seven SMFs. The seven parallel signals are fed into a commercial WSS with more than 21 SMF ports ($7 \text{ cores} \times (1 \text{ common port} + 2 \text{ output ports})$), jointly steered to seven output SMF ports, which are multiplexed by another SMUX to a 7-core MCF. In order to minimize beam steering angle and crosstalk [171], it was proposed to add a remapping block between the SMUXs and the SMF input/output section which interleaves the signals from different spatial channels into neighboring single-mode ports [167]. A compilation of experimentally demonstrated SDM WSSs is presented in Table 1.9.

1.4.4.2 FMF WSS

Since spatial modes propagate together in one fiber core, it is feasible to replace the SMF array as shown in Fig. 1.24 directly by an FMF array to realize an FMF compatible WSS, as demonstrated in [34, 168] for three spatial modes. In contrast to the conversion of mode-multiplexed signals into single-mode operation by SMUXs [170], the port count of a WSS is not affected by the direct replacement [172]. However, due to different modal characteristics such as mode field diameter (MFD) [173, 174] and mode field profile, different modes exhibit mode-dependent spectral responses. Figure 1.25 gives the simulated 3×3 amplitude responses for 3 spatial modes versus the normalized wavelength. Different amplitude roll-offs can be observed at the passband edges in the diagonal plots (blue curves), which are for the case that the excitation and launch modes are the same. In the other plots (red curves), strong mode coupling can be found. Based on the 3×3 amplitude responses, Fig. 1.26 gives the simulated transmission and MDL as a function of normalized wavelength. It can be seen that the MDL curve is narrower than the transmission curve due to varying spectral responses of modes, which results in a narrower spectral passband [175, 176]. Therefore, this type of FMF WSS requires

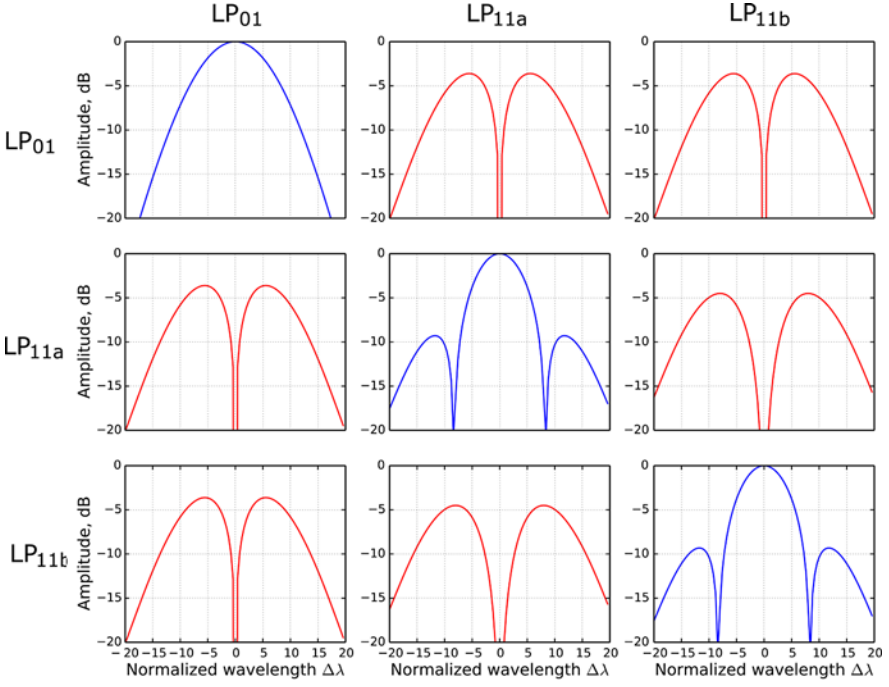
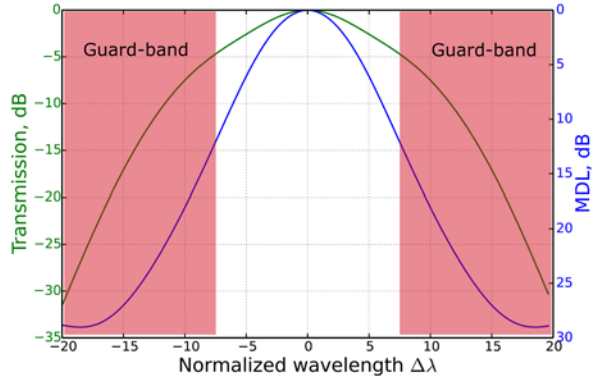


Fig. 1.25 Amplitude responses of FMF WSS for three spatial modes as a function of normalized wavelength

Fig. 1.26 Transmission and MDL of FMF WSS versus normalized wavelength



larger spectral guard-bands compared to the conventional SMF ones. Removal of the mode-dependencies, which at the same time minimizes the guard bands, has recently been demonstrated by employing a spatial-diversity scheme with an SMUX for demultiplexing the spatial modes into identical Gaussian beams and a remapping network for the proper arrangement and reshuffling of these beams [169].

1.4.5 Fiber Splicers and Connectors

Fiber splicers are used to join two fibers permanently through locally heating the fiber ends to melt and fuse them together. The functionality of fiber splicers is indispensable for the maintenance and installation of optical networks. Therefore, whether high-quality splicing for SDM fibers can be realized in an efficient way is a critical criterion to judge whether SDM will eventually become a practical solution. Since FMF and MMF have one single core inside a standard 125 μm cladding, conventional fiber fusion splicers empowered by either core or cladding alignment and fusion splice techniques using electric arcs or carbon dioxide (CO_2) lasers can still do the job with some fusion parameters optimization for specific FMFs or MMFs. The most popular fiber splicers based on electric arcs have shown decent performance in FMF [50, 177] and MMF [41] splicing. In terms of core-to-core misalignment induced splice losses, FMFs and MMFs for supporting MDM have higher requirements compared to the SMF case. Core-to-core misalignment does only cause power attenuation in SMF, but in fibers for MDM applications, MDL is also induced which limits transmission length and capacity. Numerical analyses show that the quality of fiber splicing determines the maximum reach of MDM systems [178], which is also valid for FMF mechanical connectors.

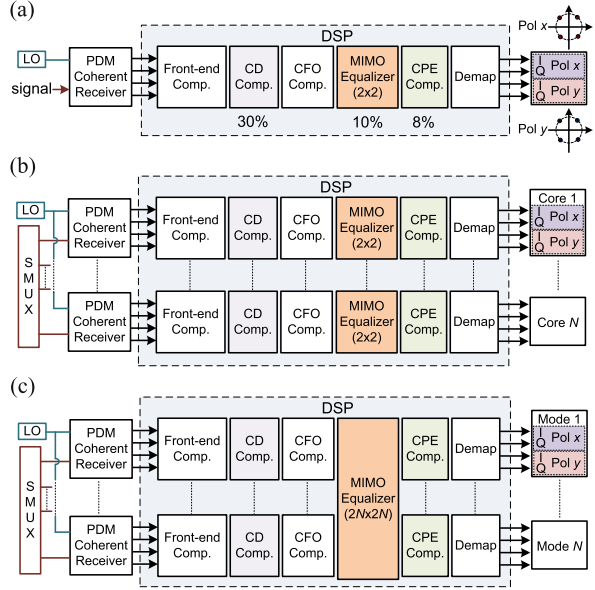
In order to align all fiber cores of MCFs simultaneously, MCF compatible splicers need to be capable of rotational alignment in addition to lateral alignment. It was demonstrated that both fiber side view [179] and end view [180] observation can enable rotational alignment. For side view observation, hollow-hole markers with large refractive index contrast have been added into a 7-core MCF to enhance visibility [179]. For end view observation, a camera has been used to monitor the two fiber ends, detect core positions and align corresponding cores [180], which is equivalent to the process for alignment of polarization maintaining fibers. Since MCFs generally have a larger cladding size, traditional fusion splice techniques cannot guarantee uniform heat distribution along the radial direction, which results in non-identical splice losses for different cores [181]. To create a sufficiently uniform discharge, a swing-electrode based fusion technique has been proposed to splice large cladding fibers such as MCFs.

A 7-core MCF connector with 0.13 dB average attenuation and < -45 dB average reflection has been developed by using a floating mechanism to eliminate the influence of deformation and physical contact to reduce the return loss [182]. The performance of the MCF connector is comparable to that of corresponding SMFs.

1.5 Digital Signal Processing

One important enabling factor of high capacity SDM systems especially with coupled spatial channels and essentially realized so far in lab trials only, is the tremendous development in electronics and DSP. For almost all demonstrations, optical coherent receivers and high-speed real-time oscilloscopes have been utilized for

Fig. 1.27 Schematics of optical receiver empowered by DSP for (a) SMF with DSP power dissipation distribution, (b) UMCF with N cores, and (c) CMCF or FMF guiding N spatial modes with a $2N \times 2N$ MIMO equalizer (LO: local oscillator)



detecting and sampling the received signals. The schematics of optical receivers supporting SMF, UMCF with N cores and CMCF or FMF supporting N spatial modes are all illustrated in Fig. 1.27. The optical receiver consists of optical polarization division multiplexing (PDM) coherent receivers and DSP blocks. In the digital domain, front-end impairments, chromatic dispersion (CD), timing offsets and carrier frequency offset (CFO) are compensated by DSP [183, 184]. Carrier phase estimation (CPE) is implemented after the time or frequency domain MIMO equalizer. For UMCF applications, as shown in Fig. 1.27(b), the DSP block for SMF can be duplicated to individually unravel the mixed PDM signals for each core. However, due to mode mixing, an MIMO equalizer with a larger matrix dimension is required for both, the CMCF and FMF cases, see Fig. 1.27(c).

The computational complexity of each digital module increases linearly with the number of spatial channels except for the bigger MIMO equalizers in the CMCF and FMF cases. Since all spatial channels at one wavelength are routed together, common-mode impairments can be expected and therefore joint signal recovery can be exploited. The joint CPE compensation has been demonstrated in both uncoupled [37] and coupled [38] spatial channels due to the phase fluctuations being correlated. Instead of employing N separate CPE compensation modules, one joint CPE scheme is sufficient.

One argument for coupled SDM applications is that the MIMO equalizer has to be applied to redo the coupling for recovering the signals, which results in higher computational complexity. Moreover, the size of the MIMO equalizer exhibits a quadratic growth with the number of spatial channels. For example, six spatial modes require a 12×12 MIMO equalizer which is 36-fold and 6-fold larger than

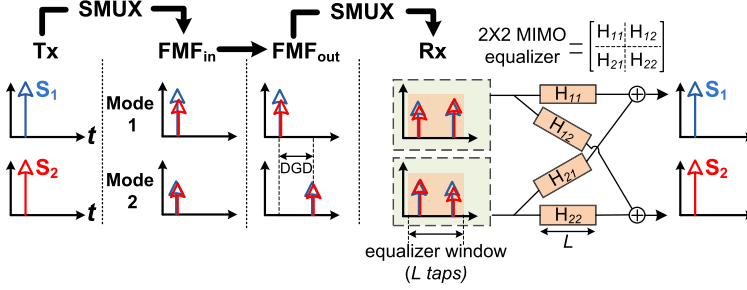


Fig. 1.28 Schematic of mode mixing and MDGD after FMF transmission (the MIMO equalizer has a wide equalizer window to handle MDGD)

the one for SMF and 10-core UCMF, respectively. Modal differential group delay (MDGD) is another effect which adds pressure on the DSP. Figure 1.28 shows a schematic diagram of mode mixing and MDGD after transmission of two spatial modes with one polarization. The MDGD is caused by the different propagation constants of the different modes. S_1 and S_2 in Fig. 1.28 represent two transmitted signals, and it is assumed that mode mixing occurs only in the multiplexing/demultiplexing stages. After transmission, the separation of two modes due to MDGD can be observed in the time domain. A 2×2 MIMO equalizer with a finite-impulse-response (FIR) filter in a butterfly structure can recover the mixed spatial channels. In order to cover the time delay between two modes, the equalizer window (in other words, the number of taps L) needs to be wider than the delay.

In early MDM demonstrations [44, 80], the time-domain data-aided (DA) least-mean-square (LMS) algorithm has been used for initializing the taps of the MIMO equalizer, and after convergence, decision-directed (DD) LMS or constant modulus algorithms (CMA) have been employed. To recover the optical PDM signals over N spatial modes, the MIMO equalizer requires a $2N \times 2N \times L$ FIR filter. Through applying frequency domain equalizers (FDE) [185, 186] with block-by-block processing and Fast Fourier Transform (FFT) implementation, a tremendous reduction in computational complexity [187] of MIMO processing for the handling of large MDGD has been demonstrated with the complexity becoming less dependent on MDGD [188]. Moreover, strong mode mixing shows its benefits in the reduction of DSP complexity [189]. In Fig. 1.27(a), the distribution of power dissipation for the different modules in the digital core of a 100 Gbit/s line card is given [190], where the CD compensation module consumes 30% power and the power dissipation of the MIMO equalizer consumes only 10% [187]. Therefore, the total DSP complexity of a coupled SDM system with six spatial channels, which can be a 6-mode FMF or a 6-core CMCF, only doubles compared to that of an uncoupled SDM system, which scales sublinearly with the SDM channel count.

1.6 Commercialization

SDM has not only received attention by academia, but by industry as well. SDM components such as corresponding fiber, SMUXs, optical amplifiers and splicers have been released into the market quickly following the research activities. Table 1.10 lists commercialized SDM components. It can be expected that more and more SDM components will be available from the shelf in the near future. In addition to the components, technical standards with respect to parameter definitions and component requirements, as well as standardized test procedures are also crucial for the further development of SDM technologies.

Table 1.10 Commercially available SDM components

SDM component	Manufacturer	Technology
FMF	OFS [191]	GI-FMF with depressed cladding [59]
MCF	OFS [192]	
MCF	YOFC [193]	
SMUX (FMF)	CAILabs [194]	Multi-plane light conversion [136, 137]
SMUX (MCF)	Chiral Photonics [195]	Fiber bundle [196, 197]
SMUX (FMF)	Kylia [198]	Free space optics [199]
SMUX (FMF)	Optoscribe [200]	3D waveguide [201]
SMUX (MCF)	Optoscribe [202]	3D waveguide [201]
Mode converter	Phoenix Photonics [203]	Mechanical grating [204, 205]
FMF EDFA	Phoenix Photonics [203]	
Fiber splicer	Fujikura [206]	Swing electrode [181]

Appendix

1.7.1 Economic Aspects of Mode Division Multiplexed Links

Next to the technical aspects of mode division multiplexed (MDM) systems, their economic aspects are also of major importance when deciding on the installation of new transmission links. An analysis has been made of the capital expenditure (CapEx) needed to install an MDM transmission link versus the CapEx for a traditional fiber division multiplexed (FDM¹) link, i.e. a link using a number of single-mode fiber links in parallel.

¹In electrical engineering the acronym FDM typically denotes frequency division multiplexing, i.e. multiplexing of frequency bands in the spectral domain. Here we use FDM to denote the multiplexing of fibers in the spatial domain.

Fiber Division Multiplexing

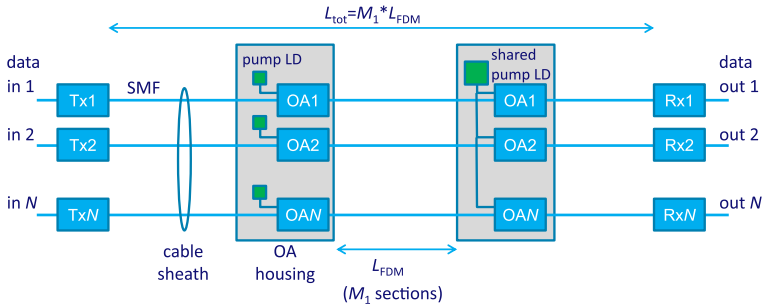


Fig. 1.29 Fiber division multiplexed transmission link using N single-mode fibers in parallel carrying N data channels

Mode Division Multiplexing

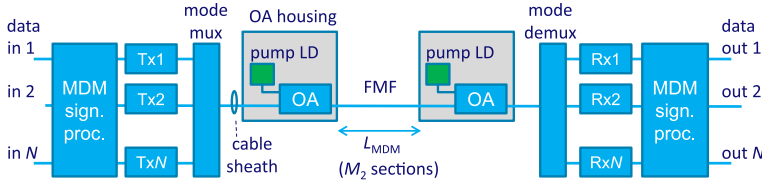


Fig. 1.30 Mode division multiplexed transmission link using a single few-mode fiber carrying N data channels

1.7.1.1 Cost Modeling

The system models used for this comparison are shown in Figs. 1.29 and 1.30.

The transmission link has to carry N data channels over a link total length L_{tot} which consists of M_1 single-mode fiber sections having a length L_{FDM} (or M_2 few-mode fiber sections of length L_{MDM}) with optical amplifiers (OAs) in between them. The N digital data channels are transmitted by N transmitters Tx_i ($i = 1..N$), and received by N receivers Rx_i ($i = 1..N$).

In the SDM link, the N data channels are carried over N single-mode fibers. N separate OAs are needed at each coupling between two sections; they may use N pump lasers or one shared powerful pump laser. The N OAs can be accommodated in a single housing. $(M_1 - 1)$ of these OA-sets are needed, where M_1 is the number of link sections. The N fibers are hosted in a single protective cable sheath, which is buried in a duct.

In the MDM link, the N data channels are carried over N mode channels in a single few-mode fiber. These mode channels are amplified together by a single multimode OA; $(M_2 - 1)$ of these OAs are needed, where M_2 is the number of link sections. The FMF is put in a protective cable sheath, which is buried in a duct. At the transmitter end of the link, a mode multiplexer couples the optical output signals of the N transmitters into the N mode channels of the FMF. At the receiver

end, a mode demultiplexer separates the N mode channels into the N receivers. Both at the transmitter end and at the receiver end digital signal processing is used for pre-conditioning the signals and counteracting the crosstalk incurred between them.

Based on these system models, the link CapEx costs for an FDM link, C_{FDM} , can be expressed as

$$C_{FDM} = N \cdot Tx + cable_{FDM} + (M_1 - 1)(N \cdot OA_{FDM} + housing_{OA}) + mode\ mux + mode\ demux + N \cdot Rx + 2 \cdot signal\ proc \quad (1.15)$$

where

$$cable_{FDM} = L_{FDM}(sheath + duct + N \cdot fibre_{FDM}) \quad (1.16)$$

and Tx , Rx , OA_{FDM} are the cost for a transmitter, a receiver, and an optical amplifier, respectively, $fibre_{FDM}$, $cable_{FDM}$, $sheath$, and $duct$ are the FDM fiber, FDM cable, sheath and duct cost per unit length, and $housing_{OA}$, $mode\ mux$, $mode\ demux$, and $signal\ proc$ are the unit cost for an OA housing, a mode multiplexer or mode demultiplexer, and signal processing, respectively.

In a similar way, the link CapEx costs for an MDM link, C_{MDM} , are

$$C_{MDM} = N \cdot Tx + cable_{MDM} + (M_2 - 1)(OA_{MDM} + housing_{OA}) + mode\ mux + mode\ demux + N \cdot Rx + 2 \cdot signal\ proc \quad (1.17)$$

where

$$cable_{MDM} = L_{MDM}(sheath + duct + fiber_{MDM}) \quad (1.18)$$

and all other quantities are defined for MDM fibers, devices, etc. corresponding to those in (1.15) and (1.16).

1.7.1.2 Assumptions

Table 1.11 shows preliminary cost assumptions for the three fiber types considered: standard SMF for the FDM case, and solid-core FMF (SC-FMF) and photonic bandgap FMF for the MDM case. Note that these numbers are approximative ones, taken for the sake of enabling a relative cost comparison of an MDM versus an FDM system.

Due to differential mode losses in the SC-FMF, the maximum section length in the MDM/SC-FMF case has been assumed to be somewhat smaller than for the FDM/SMF case. Due to the (expected) much lower losses in the photonic bandgap (PBG)-FMF, the maximum section length in the MDM/PBG-FMF case is considerably larger than in the other two cases. Because of the larger complexity (amongst others to achieve gain flatness among the modes) and the possibility of pump sharing among multiple OAs in the FDM case, the costs of a multimode OA needed in the MDM cases are assumed to be higher than for the FDM cases. The cable

Table 1.11 Cost assumptions for system elements

	Fiber cable (€/km)			Max. section length (km)	Optical Amplifier unit		Tx (€)	Rx (€)	Mode		Sign. proc. (€)
	Sheath	Duct instal.	Fiber		OA (€)	Housing (€)			mux (€)	demux (€)	
SMF	2000	1000	10	100	7000	10000	25000	35000			
SC-FMF	2000	1000	30	75	15000	10000	25000	35000	25000	25000	20000
PBG-FMF	2000	1000	50	250	15000	10000	25000	35000	25000	25000	20000

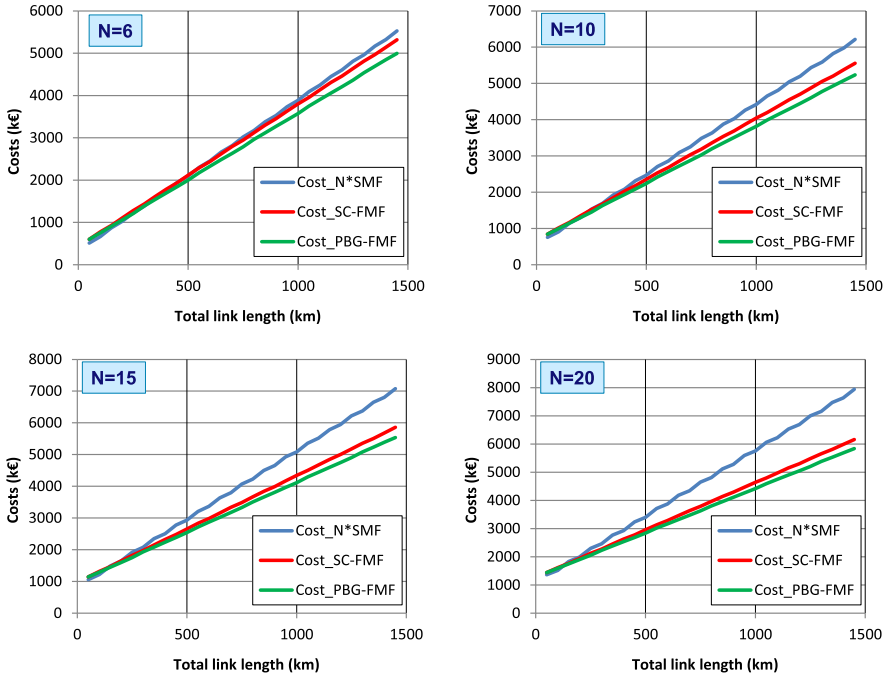


Fig. 1.31 Cost comparison between FDM case (N SMFs in parallel) and two MDM cases (solid core FMF, and photonic bandgap FMF), versus total link length and for different numbers N of multiplexed data channels

sheath, duct installation, OA housing, transmitter and receiver costs are expected to be (nearly) the same for the various cases.

1.7.1.3 Results

Figure 1.31 shows the costs calculated for the FDM case using N parallel SMFs and the two MDM cases using a single solid-core FMF using photonic bandgap FMF, respectively. The results indicate that MDM offers increasing cost advantages when the total link length grows, and when the number N of multiplexed data channels grows. Figure 1.32 indicates how the various cost items contribute to the total system costs for a total link length $L_{tot} = 1000$ km. The cost benefits of MDM are clearly due to the reduced OA costs, which outweigh the additional costs for the mode multiplexers and the signal processing. The contribution by the OA costs is reduced due to OA sharing in the MDM cases, and costs are further reduced due to the use of PBG-FMF because the section length increases and thus the number of OAs needed decreases.

Figure 1.33 summarizes the relative cost differences between MDM and FDM for the two MDM cases. It again shows that MDM offers cost advantages above

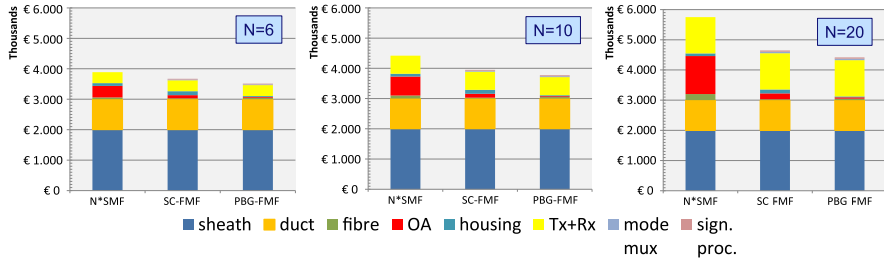


Fig. 1.32 Cost items for the FDM case (N SMFs in parallel) and two MDM cases (solid core FMF, and photonic bandgap FMF), for total link length $L_{tot} = 1000$ km and for different numbers N of multiplexed data channels

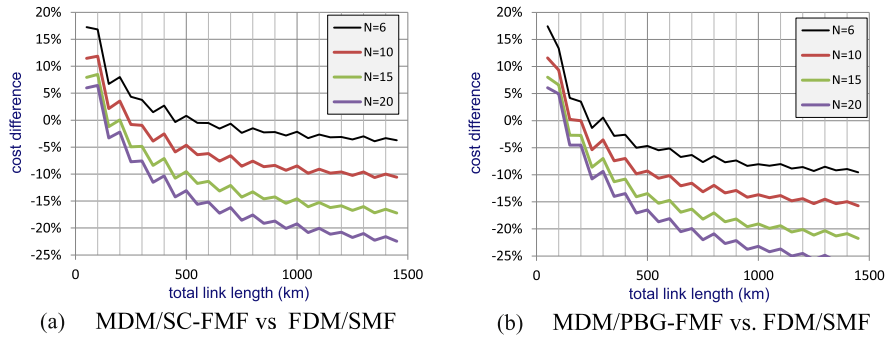


Fig. 1.33 Relative cost differences between MDM and FDM when using (a) solid-core FMF and (b) photonic bandgap FMF

FDM beyond a certain total link length. This break-even total link length decreases when the number of multiplexed data channels is increased, and when PBG-FMF is used instead of SC-FMF. For example, when using $N = 10$ channels MDM is advantageous beyond $L_{tot} = 250$ km for SC-FMF, and already beyond $L_{tot} = 150$ km for PBG-FMF. And for a link length $L_{tot} = 1000$ km, MDM with SC-FMF offers a cost reduction of 2.1% for $N = 6$ channels to 19.2% for $N = 20$ channels, and with PBG-FMF even a cost reduction of 8.1% for $N = 6$ to 23.2% for $N = 20$.

1.7.2 Conclusions

MDM offers clear CapEx cost reductions with respect to FDM for long link lengths where the total link length is sufficiently large (i.e. beyond 300 to 500 km), and when the number of multiplexed channels is large (i.e. beyond 10).

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