Front. Optoelectron. 2016, 9(2): 270–276
DOI 10.1007/s12200-016-0607-2

RESEARCH ARTICLE

# Novel applications of space-division multiplexing

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**Abstract** Space-division multiplexing (SDM) using multi-core fibers (MCFs) and few-mode fibers (FMFs) was proposed as a solution to increase capacity and/or reduce the cost per bit of fiber-optic transmission. Advances in passive and active SDM devices as well as digital signal processing have led to impressive SDM transmission demonstrations in the laboratory. Although the perceived advantages in terms of capacity and cost per bit that SDM offers over parallel SMF bundles are not universally accepted, SDM is beginning to emerge as an indispensable solution in major network segments. The introduction of the spatial degree of freedom allows optical networks to overcome fundamental limitations such as fiber nonlinearity as well practical limitations such as power delivery. We describe these application scenarios that the optical communications industry has already began to explore. From a fundamental science point of view, concepts such as the principal modes, generalized Stokes space, and multi-component solitons discovered in SDM research will likely have a broad impact in other areas of science and engineering.

**Keywords** space-division multiplexing (SDM), few-mode fiber (FMF), multi-core fiber (MCF), wavelength-selective switch (WSS), passive optical network (PON)

## 1 Introduction

The capacity of a communication channel (for example, the optical fiber), is given by the Shannon capacity formula

$$\overset{\text{bits/s}}{C} = \underbrace{\overset{\text{Hz}}{W}}_{\text{bandwidth}} \times \overbrace{\log_2(1+\underbrace{S/N}_{\text{signal-to-noise ratio}})}^{\text{spectral efficiency bits/s/Hz}}, \tag{1}$$

where $W$ is the bandwidth and $S/N$ is the signal-to-noise ratio (SNR). The theoretical capacity limit of a single-mode fiber (SMF) occurs at the optimum transmission power dictated by the SMF nonlinearity, at which it is generally believed that a spectral efficiency of 5 bits/s/Hz can be achieved. The bandwidth of optical amplification is about 10 THz. Substituting those quantities into Eq. (1), and assuming polarization multiplexing, yields a 100 Tb/s transmission capacity limit of SMF, known as the nonlinear Shannon limit [1].

In the meantime, the international internet bandwidth usage was on the order of 200 Tb/s in 2014, and it grows by about 40%, or 2 dB, each year, according to the Global Bandwidth Research Service [2]. At this rate, the internet bandwidth demand in the next 10 years will be at least two orders of magnitude higher than the nonlinear Shannon capacity. The gap between the internet capacity demand and the nonlinear Shannon limit of the current SMF-based infrastructure has been referred to as the "capacity crunch".

In the past, multiplicative fiber capacity growth has been employed to satisfy exponential capacity demand. The most recent examples are wavelength-division multiplexing (WDM) and polarization-division multiplexing. With these techniques, all degrees of freedom of a SMF have been employed for the purpose of multiplexing. In recent years, much work has been done in the optical communications community on methods to overcome the impending "capacity crunch" [3]. Space-division multiplexing (SDM) has been proposed as a solution to the capacity crunch.

## 2 Space-division multiplexing

SDM of two different varieties can be employed to transmit independent information over different spatial channels within a single fiber thereby providing further multiplicative capacity growth. The first technique used in SDM is mode-division multiplexing (MDM), and involves transmitting independent information via the individual

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Received January 22, 2016; accepted February 18, 2016

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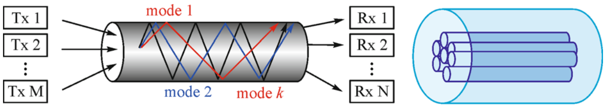
modes in a few-mode fiber (FMF) [2]. MDM can increase the capacity of a single fiber proportional to the number of modes used. The second technique used in SDM, called core multiplexing, necessitates that a single fiber be constructed that contains several high-index cores in the same cladding [4]. Independent information can be transmitted via each of the cores in such a multi-core fiber (MCF). The aforementioned techniques are illustrated in Figs. 1(a) and 1(b). Both of these techniques, if used properly, can increase the capacity of a single fiber beyond the nonlinear Shannon limit. In addition, these two methods can be combined to multiplicatively increase the capacity of a single fiber.



(a) (b)

**Fig. 1** An illustration of (a) MDM in a FMF and (b) a MCF for core multiplexing

Major advances have been made in the last few years as research interest and activities in SDM grow. From a fundamental science point of view, the concepts of the generalized Stokes space [5], principal modes [6] and multi-component solitons [7] have been established. Enabling components for SDM including SDM fibers [8,9], passive SDM devices (in particular mode multiplexers/demultiplexers [10]) and active SDM devices (in particular amplifiers [11–13] and switchers [14]) have made SDM transmission feasible. Record-breaking capacities have been demonstrated in SDM transmission [15,16]. For a review, please see Ref. [17].

Despite successful laboratory demonstrations of SDM transmission, the advantages and necessity of SDM have not been convincingly articulated. From a capacity standpoint, an alternative method of increasing network capacity is the use of multiple parallel WDM systems in a SMF bundle. In theory, fiber bundles should be capable of providing as much capacity as necessary. Even though SDM can increase per-fiber transmission capacity, the same capacity can be realized using multiple SMFs. A related argument for SDM is that it can decrease cost per bit for fiber transmission through integration. However, further analysis reveals that many of these integration techniques such as integrated transceivers are applicable in parallel WDM transmission. Therefore, the economics of SDM does not seem to offer overwhelming advantages over multiple SMF WDM systems as WDM did over multiple SMF time-division multiplexed (TDM) systems. Justifications for SDM from a transmission capacity or cost per bit point of view are not convincing. We argue in this paper that there are fundamental and practical limits, other than the nonlinear Shannon limit, that make SDM *indispensable*.

## 3 Application scenarios for SDM

The reason why SDM could become indispensable is because it can break fundamental and practical limits in optical transmission and networking. The various advantages of SDM can be realized in the different segments of optical fiber communications networks, including submarine, terrestrial, and access networks. The benefits SDM offers in each network segment vary due to the different nature of each segment. For example, submarine networks are very space sensitive and very power sensitive, terrestrial networks are cost sensitive and very space sensitive, while access networks are space sensitive and very price sensitive.

### 3.1 Submarine networks

In submarine networks, cable strength and flexibility requirements determine cable material choices and the largest cable diameter, therefore indirectly determining the number of fibers that can be embedded in a single cable. Modern technology has given rise to cables with diameters on the order of centimeters. Within this limited volume, only 8 to 16 fiber pairs occupying a space on the order of millimeters are possible; the rest of the space is occupied by strengthening members and power supply lines. The state-of-the-art submarine system can provide roughly +/− 6000 V on either end of the cable, yielding an overall potential difference of 12000 V. Of that 12000 V potential, 7500 V is lost to the cable itself (assuming a 10000 km cable length), 1000 V is used to compensate for the earth potential, and only 3500 V can be used for repeaters [18]. Therefore, capacity of future submarine systems will be limited practically by how much power a submarine cable can supply [17].

Under the constraint of power delivery, one can deduce the need for SDM as follows. The total per-cable transmission capacity when multiplexing with $M$ channels is

$$C = M \times W \times \log_2(1+S/N), \tag{2}$$

and the number of channels under the total power constraint $P$ is

$$\mathrm{M} = \frac{P}{S}, \tag{3}$$

where per channel power is $S$. Equations (2) and (3) can be combined to produce a singular expression for the per-cable transmission capacity that depends only on the total power available, the bandwidth, and power per channel.

$$C = \frac{P}{S} \times W \times \log_2(1+S/N) \approx P \times W \times \frac{\log_2(S)}{S}. \tag{4}$$

In Eq. (4), we have assumed that per channel SNR is much greater than unity. As is evident from Eq. (4), under rigorous power constraints such as those encountered in submarine networks, the best approach to achieving the largest transmission capacity per cable is to decrease the per channel power and increase the degree of multiplexing within the limited available space, rather than increasing spectral efficiency per channel. FMF and MCF can provide much larger channel density than a fiber bundle. This is the rationale for SDM in submarine networks. In fact, TE-subcom has begun ground work toward a high-channel count, low spectral efficiency per channel system by optimizing power efficiency per channel [19].

It is important to note that while future submarine optical fiber networks will eventually be limited by the practicality of power delivery, currently submarine capacity is still limited by fiber nonlinearity [20]. Therefore, an important near-term goal is to increase the capacity of submarine cables beyond the nonlinear Shannon limit of SMF. It turns out that this can most easily be achieved using technologies developed for SDM, namely by transmitting information in the fundamental mode of a FMF, as opposed to a SMF.

Figure 2 illustrates the concept behind increased capacity using FMF. The nonlinear Shannon limit is the direct result of the nonlinear refractive index of the fiber being proportional to the intensity within the core, which is, in turn, inversely proportional to the effective area of the fiber. Since FMF has a larger effective area, for the same launched power it will have a smaller internal intensity, allowing for more transmission capacity.

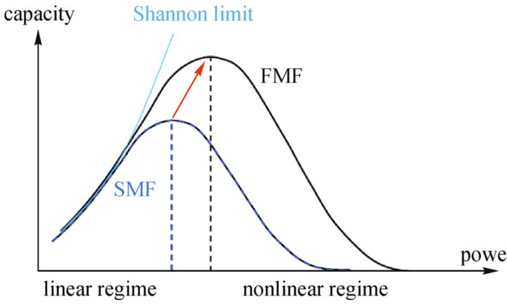


**Fig. 2** An illustration of the increased capacity that can be achieved by using FMF in place of SMF [4]

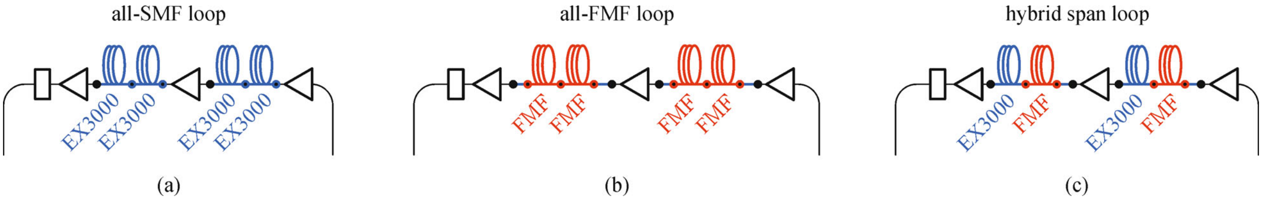
A recent experiment has been performed by NEC to compare the transmission capacity of SMF, FMF, and a hybrid setup involving both SMF and FMF, as shown in Fig. 3 [21].

In the hybrid setup, FMFs were implemented immediately following an amplifier, where the internal power is the highest, and was then connected to SMFs when the power had been sufficiently attenuated such that the SMF would be operating in the linear regime. Using the hybrid fiber setup, record-breaking transmission performances in spectral efficiency at 6.5 bits/s/Hz were demonstrated at a transmission distance of 6600 km with a baud rate of 32 GHz and a channel spacing of 33 GHz [21]. Figure 4 provides comparisons between all three experimental setups. Fundamental mode transmission in FMFs may represent the first commercial application of SDM.

It should be noted that the large effective area of FMF fibers can be exploited for analog transmission in which transmission performance metrics including the radio frequency (RF) gain, dynamic range and noise figure are all proportional to the power handling capability of the nonlinear fiber channel [22].

### 3.2 Terrestrial networks

Terrestrial networks are somewhat different than submarine networks in that power is readily available on land, there is no practical space limitation on terrestrial cables, and, more importantly, they are typically not point-to-point systems like their submarine counterparts. Instead, terrestrial networks involve frequent routing and switching in order to allow communication with multitudes of end users. In commercial terrestrial networks, the core network capacity is expected to reach 10 – 100 Pb/s. The nonlinear Shannon limit imposes a 500 Gb/s per-wavelength data rate restriction, meaning 20000 to 200000 independent channels would be necessary to carry the aforementioned network capacity. The per-fiber capacity of SMF is limited 100 Tb/s, necessitating 100 to 1000 fibers on the trunk lines to maintain that capacity. Therefore, as the internet capacity demand continues to increase so does the need for more and more switching. The current switching granularity of wavelength-selective switches (WSS) at the one-mode-per-wavelength level will lead to an unmanageable



(a) (b) (c)

**Fig. 3** Experimental setups designed to test the transmission capacity of network systems involving (a) entirely SMF, (b) entirely FMF, and (c) a hybrid system utilizing both SMF and FMF [21] number of connection states (any data channel from one fiber to another fiber) on the order of

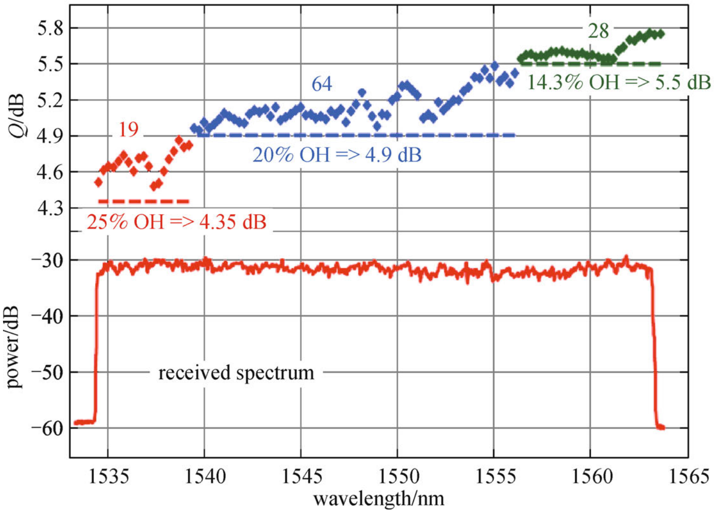
$$\begin{pmatrix} N_{\mathrm{F}} \\ N_{\mathrm{C}} \end{pmatrix} = \begin{pmatrix} 1000 \\ 200000 \end{pmatrix},$$

which is an astronomically large number. When a SDM-compatible WSS is used instead, all spatial modes carried on the same wavelength are bundled together and switched together, greatly simplifying switching architecture, and reducing the number of independent channels $N_{\mathrm{C}}$ and the number of trunk fibers $N_{\mathrm{F}}$ by the number of modes used for MDM.

SDM can be employed in terrestrial networks via two different methods: SDM-compatible components placed in both transmission and switching infrastructures, or implementation of SDM only in the switching architecture – aggregation of multiple single mode fibers into one FMF before switching occurs. Figure 5 provides a clear illustration of both types of SDM implementation into switching architecture. In either case, SDM provides a simplification of network and switching infrastructure that would allow telecommunications providers to keep up with an ever-increasing capacity demand. SDM-compatible networking elements such as WSSes and cross-connects has been demonstrated [23].

### 3.3 Access networks

Access networks can also benefit from SDM, as they are very price sensitive. The keys to a low-cost passive optical network (PON) are longer reaches and larger splitting ratios, thereby increasing equipment sharing and reducing the cost per customer. The splitters used in today's networks lead to an unavoidable upstream combining loss, as is to be expected under the constraints of power conservation. By eliminating the upstream combining loss, the power budget can be improved to allow for a PON with a greater reach and splitting ratio than those in use today. A previous proposal, illustrated in Fig. 6(a), included the use of a multi-mode combiner at the optical line termination (OLT) receiver, creating an entirely passive method of eliminating the upstream combining loss in a PON [24]. However, this method necessitates the use of multiple



| number of channels | FEC OH | spectral efficiency /(bits·s$^{-1}$·Hz$^{-1}$) | codeword length |
|---|---|---|---|
| 19 | 25% | 6.2 | 74985 |
| 64 | 20% | 6.46 | 13680 |
| 28 | 14.3% | 6.78 | 13680 |
| 111 | | 6.5 | |

[1]

**Fig. 4** A demonstration of 111 independent channels transmitted in the C-band achieving a spectral efficiency of 6.5 bits/s/Hz [21]

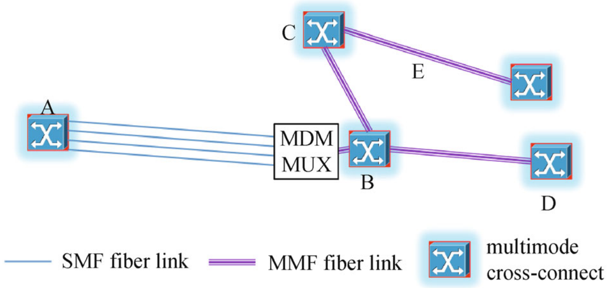
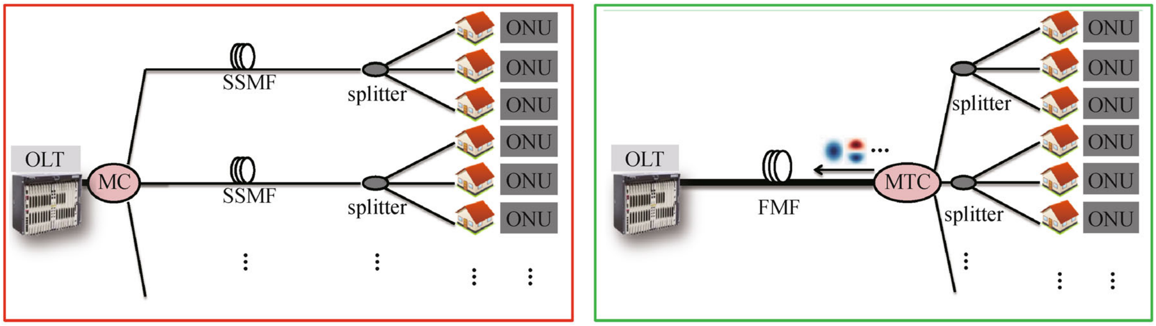


**Fig. 5** An illustration of the aggregation of multiple SMFs into one FMF (point A to point B), and of SDM-compatible components implemented throughout the entire network (points B through E)



(a) (b)

**Fig. 6** Illustrations of PON setups used to eliminate upstream combining loss, (a) demonstrates a proposal that requires the use of multiple SSMF lines and (b) demonstrates an SDM-based design using a MTC and FMF, eliminating the need for multiple fiber lines

feeder fibers, thereby increasing the cost. We proposed the use of a single FMF and a mode transforming coupler (MTC), which is essentially a mode-division multiplexer as shown in Fig. 6(b). This arrangement provides the same benefits as the aforementioned proposal, namely a fully passive method of eliminating the upstream combining loss, while simultaneously reducing the number of back-haul fibers [25]. Figure 6 illustrates the differences between these proposed solutions.

A mode-selective PON, like the one described in Fig. 6 (b), was successfully demonstrated recently. In that experiment, upstream TDM data was transmitted over 20 km of FMF. Commercially available GPON equipment, specifically OLTs and optical network units (ONUs), were used in the demonstration, and a reach extender was added to enable the detection of FMF modes. Figure 7 is the experimental setup used for this demonstration.

This network setup was tested extensively using three modes (LP01, LP11a, and LP11b), and achieved a bit-error rate (BER) of less than $10^{-9}$ for all three modes. However, the LP11a and LP11b modes experienced power penalties, greater than that of LP01, of 1.5 and 2.7 dB, respectively. Nevertheless, real traffic measurements using Ethernet testers showed no packet loss, even when tested for long periods of time – upwards of 16 h [6]. Figures 8(a) and 8(b) quantify the BER and packet loss of the mode-selective PON.

## 4 Conclusions

Advances in optical technology have made SDM technically feasible in a laboratory setting. In this article, we point out that SDM may become indispensable in three major segments of optical communication networks, namely submarine, terrestrial, and access networks. Utilization of a new degree of freedom, space, will help to increase transmission capacity of power-limited submarine systems, simplify routing and switching architectures in terrestrial networks that would otherwise have an impractical amount of connection states, and reduce the upstream combining loss and the cost of PONs. In addition, fundamental mode transmission in FMFs may represent the first commercial application of the SDM technology. From a fundamental science point of view, concepts such as the principal modes, generalized Stokes space, and multi-component solitons discovered in SDM research will likely have broad impact in other areas of

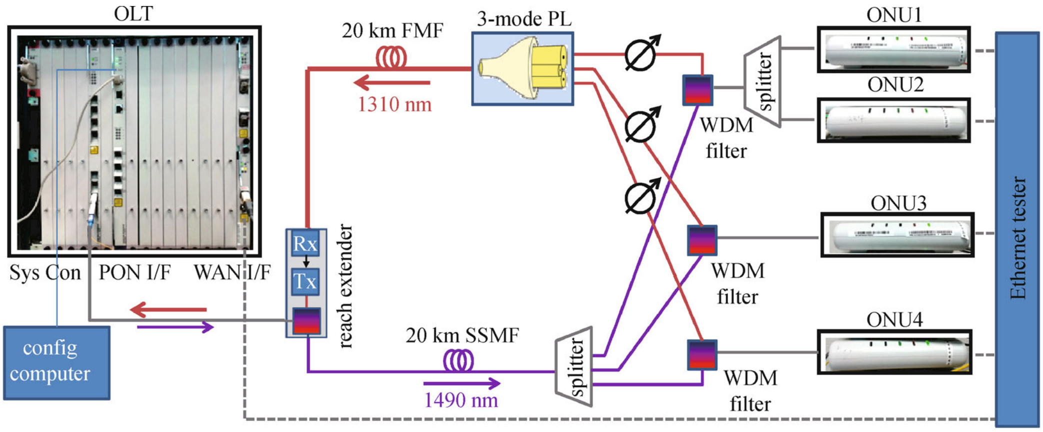
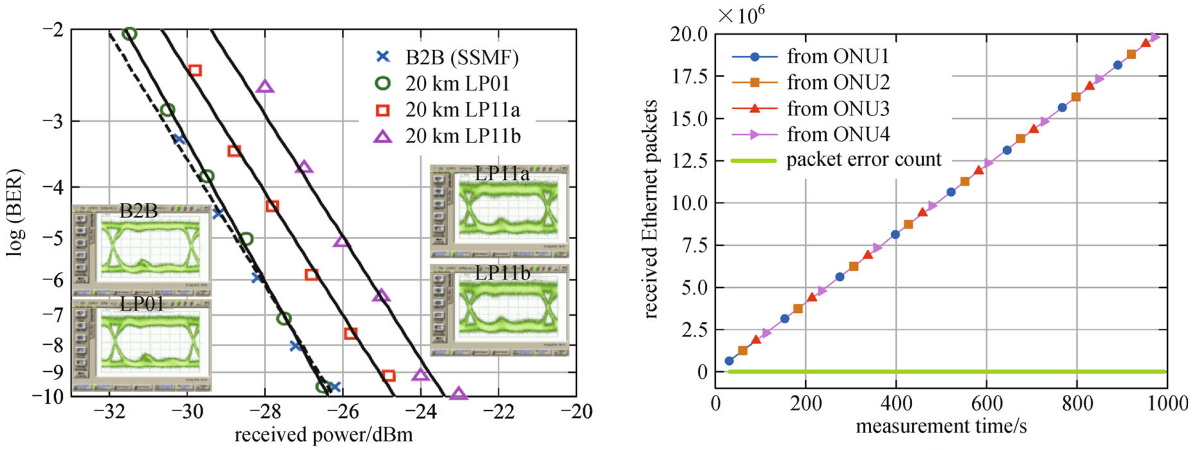


**Fig. 7** A diagram of the 20 km FMF demonstration using commercially available GPON equipment [6]



(a)

(b)

**Fig. 8** Plots of the data gathered pertaining to (a) BER vs. received power and (b) packet loss while testing the 20 km mode-selective PON

science and engineering from nonlinear dynamics to high power fiber delivery.

**Acknowledgements** This work has been supported in part by the National Basic Research Program of China (973) (No. 2014CB340104/1), the National Natural Science Foundation of China (NSFC) (Grant Nos. 61377076, 61307085 and 61431009).

## References

1. Richardson D J, Fini J M, Nelson L E. Space-division multiplexing in optical fibres. Nature Photonics, 2013, 7(5): 354–362
2. Ip E, Bai N, Huang Y K, Mateo E, Yaman F, Bickham S, Tam H Y, Lu C, Li M J, Ten S, Lau A P T, Tse V, Peng G D, Montero C, Prieto X, Li G. 88×3×112-Gb/s WDM transmission over 50-km of three-mode fiber with inline multimode fiber amplifier. In: Proceedings of 37th European Conference and Exposition on Optical Communications (Geneva). 2011, p.Th.13.C.12
3. Winzer P J. Optical networking beyond WDM. IEEE Photonics Journal, 2012, 4(2): 647–651
4. Zhu B, Liu X, Chandrasekhar S, Taunay T, Fishteyn M, Yan M, Fini J M, Monberg E, Dimarcello F. 112-Tb/s (7×160×107Gb/s) space-division multiplexed DWDM transmission over a 76.8-km multicore fiber. In: Proceedings of European Conference and Exposition on Optical Communications. 2011, p.Tu.5.B.5
5. Antonelli C, Mecozzi A, Shtaif M, Winzer P J. Stokes-space analysis of modal dispersion in fibers with multiple mode transmission. Optics Express, 2012, 20(11): 11718–11733
6. Fan S, Kahn J M. Principal modes in multimode waveguides. Optics Letters, 2005, 30(2): 135–137
7. Mecozzi A, Antonelli C, Shtaif M. Nonlinear propagation in multimode fibers in the strong coupling regime. Optics Express, 2012, 20 (11): 11673–11678
8. Grüner-Nielsen L, Sun Y, Jensen R V S, Nicholson J W, Lingle R. Recent advances in low DGD few-mode fibre design, fabrication, characterization and experiments. In: Proceedings of Optical Fiber Communication Conference. 2015, p.M2C.3
9. Takahashi H, Igarashi K, Tsuritani T. Long-haul transmission using multicore fibers. In: Proceedings of Optical Fiber Communication Conference (San Francisco, California). 2014, p. Tu2J.2
10. Leon-Saval S G, Fontaine N K, Salazar-Gil J R, Ercan B, Ryf R, Bland-Hawthorn J. Mode-selective photonic lanterns for space-division multiplexing. Optics Express, 2014, 22(1): 1036–1044
11. Bai N, Ip E, Wang T, Li G. Multimode fiber amplifier with tunable modal gain using a reconfigurable multimode pump. Optics Express, 2011, 19(17): 16601–16611
12. Abedin K S, Taunay T F, Fishteyn M, DiGiovanni D J, Supradeepa V R, Fini J M, Yan M F, Zhu B, Monberg E M, Dimarcello F V. Cladding-pumped erbium-doped multicore fiber amplifier. Optics Express, 2012, 20(18): 20191–20200
13. Jung Y, Lim E L, Kang Q, May-Smith T C, Wong N H, Standish R, Poletti F, Sahu J K, Alam S U, Richardson D J. Cladding pumped few-mode EDFA for mode division multiplexed transmission. Optics Express, 2014, 22(23): 29008–29013
14. Fontaine N K, Ryf R, Liu C, Ercan B, Salazar Gil J R, Leon-Saval S G, Bland-Hawthorn J, Neilson D T. Few-mode fiber wavelength selective switch with spatial-diversity and reduced-steering angle. In: Proceedings of Optical Fiber Communication Conference. 2014, p.Th4A.7
15. Takeshima K, Tsuritani T, Tsuchida Y, Maeda K, Watanabe K, Sasa T, Imamura K, Sugizaki R, Igarashi K, Morita I, Suzuki M. 51.1-Tbit/s MCF transmission over 2520 km using cladding pumped 7-core EDFAs. In: Proceedings of Optical Fiber Communications Conference and Exhibition. 2015, pp. W3G–1
16. Fontaine N K, Ryf R, Chen H, Benitez A V, Guan B, Scott R, Ercan B, Yoo S J B, Grüner-Nielsen L E, Sun Y, Lingle R, Antonio-Lopez E, Amezcua-Correa R. 30×30 MIMO transmission over 15 spatial modes. In: Proceedings of Optical Fiber Communication Conference Post Deadline Papers. 2015, p.Th5C.1
17. Li G, Bai N, Zhao N, Xia C. Space-division multiplexing: the next frontier in optical communication. Advances in Optics and Photonics, 2014, 6(4): 413–487
18. Bergano N. Undersea fiber optic cables – enabling a connected world. In: Proceedings of Optical Fiber Communications Conference. 2015, p.Tu1A.2

19. Zhang H, Turukhin A, Sinkin O V, Patterson W, Batshon H G, Sun Y, Davidson C R, Mazurczyk M, Mohs G, Foursa D G, Pilipetskii A. Power-efficient 100 Gb/s transmission over transoceanic distance using 8-dimensional coded modulation. In: Proceedings of 2015 European Conference on Optical Communication (ECOC). 2015, 1–3
20. Yaman F, Bai N, Zhu B, Wang T, Li G. Long distance transmission in few-mode fibers. Optics Express, 2010, 18(12): 13250–13257
21. Yaman F, Zhang S, Huang Y K, Ip E ,Downie J D, Wood W A, Zakharian A, Mishra S K, Hurley J E , Zhang Y, Djordjevic I B, Huang M F, Mateo E, Nakamura K, Inoue T , Inada Y, Ogata T. First quasi-single-mode transmission over transoceanic distance using few-mode fibers. In: Proceedings of Optical Fiber Communication Conference Post Deadline Papers (Los Angeles, California). 2015, p. Th5C.7
22. Wen H, Zheng H, Zhu B, Li G. Experimental demonstration of long-distance analog transmission over few-mode fibers. In: Proceedings of Optical Fiber Communication Conference (Los Angeles, California). 2015, p. M3E.2
23. Marom D M, Dunayevsky J, Sinefeld D, Blau M, Ryf R, Fontaine N K, Montoliu M, Randel S, Liu C, Ercan B, Esmaeelpour M, Chandrasekhar S, Gnauck A H, Leon-Saval S G, Bland-Hawthorn J, Salazar-Gil J R, Sun Y, Grüner-Nielsen L, Lingle R. Wavelength-selective switch with direct few mode fiber integration. Optics Express, 2015, 23(5): 5723–5737
24. Ning C, Zhenxing L, Effenberger F J. Large splitting and long reach passive optical networks with mode coupling receivers. In: Proceedings of 2010 36th European Conference and Exhibition on Optical Communication (ECOC). 2010, 1–3
25. Xia C, Chand N, Velázquez-Benítez A M, Yang Z, Liu X, Antonio-Lopez J E, Wen H, Zhu B, Zhao N, Effenberger F, Amezcua-Correa R, Li G. Time-division-multiplexed few-mode passive optical network. Optics Express, 2015, 23(2): 1151–1158

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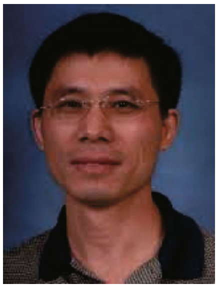

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