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# Recent Progress in Space-Division Multiplexed Transmission Technologies

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**Abstract:** Recent development of transmission technologies based on space-division multiplexing is described with future perspectives including a recent achievement of one Pb/s transmission in a single strand of fiber.

**OCIS codes:** (060.2330) Fiber optics communications; (060.2360) Fiber optics links and subsystems

## 1. Introduction

The data traffic continues to increase with ever-increasing computing powers, memory capacity as well as large user applications, greatly assisted by rapidly-increasing wired/wireless access speeds. Optical fiber communication technologies will certainly be a basis to accommodate this increase both in the terrestrial and undersea systems for the coming decades. As we look back, the last three decades since 80's have seen various great inventions such as low-noise semiconductor lasers, EDFAs/WDM technologies, and digital coherent technologies as shown in Fig. 1. Indeed, we have tried to make full use of the ultra-wide bandwidth of single-mode fibers with these technologies, achieving a capacity increase of 60 dB from 100 Mb/s up to 100 Tb/s (2dB/year), and for the next three decades we may need the similar scalability. However, recent ultra-high capacity experiments and theoretical prediction strongly suggest that we are approaching fundamental limits in capacity due to fiber nonlinearities, optical amplifier bandwidth, and fiber fuse. Space-division multiplexing (SDM) to utilize the last degree of freedom of "space", initially proposed more than three decades ago [1,2], has been intensively investigated recently as a means to substantially increase the transmission capacity beyond the limit of single-mode fiber [3-8] in a cost-effective and energy-efficient way [9]. In [5], in particular, what is called "3M technologies (multi-level modulation, multi-core fiber, and multi-mode control)" have been identified to achieve 1000 times capacity by SDM [10].

In addition to increasing capacity per a single fiber, we also need to consider "space" as a limited resource and to utilize the space occupied by the optical fibers and optical amplifiers most efficiently. The Space Utilization Efficiency (SUE), naturally defined by the transmission capacity per unit area of transmission medium or capacity per unit volume of optical amplifiers will eventually a limiting factor of the future systems. In fact, only 1/5000 area of most-dense 1,000 optical cables are utilized for transmission in the present system. The SUE can be regarded as a product of capacity per core and the number of cores per unit area, each of which can be increased by multiple modes in a core and multiple cores in a fiber cross section as mentioned below.

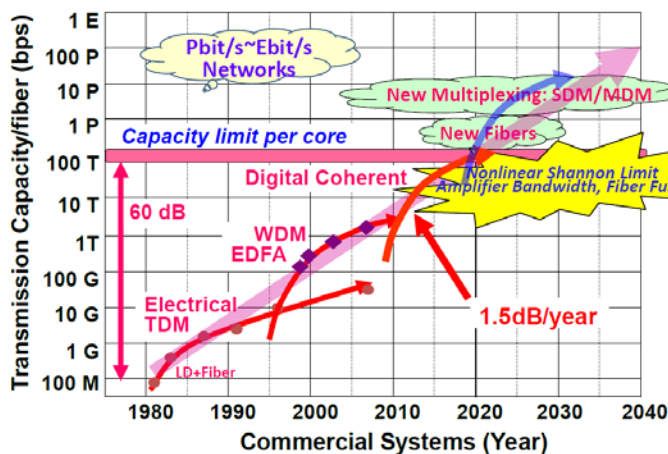


Fig. 1. Evolution of transmission technologies.

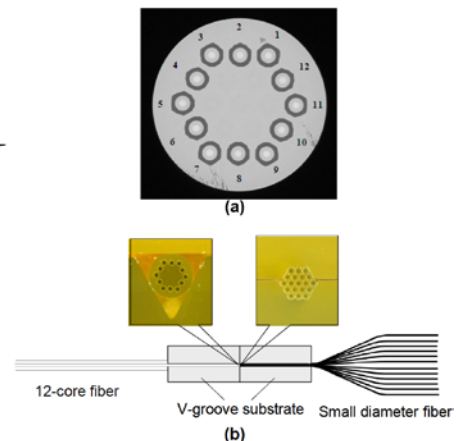


Fig. 2. 12-core fiber (a) and FI/FO (b) for Pb/s transmission [38].

## 2. Recent development on space-division multiplexing

There have been two major schemes depending on whether multi-core fibers (MCFs) [11-16] or multi-mode (few-mode) fibers (MMFs or FMFs) [17-21] are used. When multiple independent modes are used as an independent

channel, the scheme is also called mode-division multiplexing (MDM). More recently, even multi-core few-mode fibers (MC-FMFs) have been studied as a combination of the two fibers to further increase the transmission capacity [22, 23]. The major new components for SDM are space-multiplexer (S-MUX) to couple light from different cores or different modes into SDM fibers, SDM fibers, SDM optical amplifiers to amplify SDM signals, space-demultiplexer (S-DEMUX), optical connectors, and mode exciters (generators) in the case of MDM. Major important characteristics of the passive components are naturally low insertion loss, low core/mode dependent loss, low crosstalk among modes/cores and wide bandwidth to support WDM/SDM signals. Optical amplifiers designed for SDM transmission are also a challenge where low core/mode/wavelength dependent, wide bandwidth amplification characteristics with high gain and low noise figures (NFs) are desirable.

There has been much progress in MDM transmission experiments since 2011, employing well designed FMFs or coupled MCFs either with or without multiple-input multiple-output (MIMO) processing [24], where a transmission distance up to 4,200 km or 57.6 Tb/s net capacity over 119 km have been achieved [25-31]. MDM transmission employing orbital angular momentum (OAM) modes [32] has also demonstrated where 400 Gb/s QPSK data was transmitted recently over 1.1 km [33]. SDM transmission utilizing MCFs with low crosstalk, on the other hand, have also seen many experimental demonstrations on high-capacity transmission of 100 Tb/s, 300 Tb/s up to 1 Pb/s, employing uncoupled 7-core, 19-core, and 12-core MCFs [34-38], respectively or long distance transmission over 1,000 km [39-40]. Multi-mode (MM) or multi-core (MC) optical amplifiers are strongly required for long-haul systems and should be major enablers to make SDM systems cost-effective and energy-efficient compared to present systems. MM/MC amplifiers, either EDFA-based or Raman-based, have been proposed and even used in the transmission experiments mentioned above [29, 31, 41-47].

Recently, one Pb/s transmission (12 SDM x 222 WDM x 456 Gb/s) over 52 km with an aggregate spectral efficiency of 91.4 b/s/Hz has been demonstrated employing a low crosstalk, 12-core MCF with a one-ring configuration and PDM-32 QAM modulation where 2M (multi-level modulation [48-49], multi-core fiber) technologies were used [38]. The 12-core fiber with its fan-in/fan-out (FI/FO) device corresponding to S-MUX/DEMUX, and its experimental setup are shown in Fig. 2 and Fig. 3, respectively. The MCF has a core pitch of 37  $\mu\text{m}$ , a cladding diameter of 225  $\mu\text{m}$ , and the effective core area ( $A_{\text{eff}}$ ) at 1550 nm and 1625 nm are 80.7  $\mu\text{m}^2$  and 84.7  $\mu\text{m}^2$  on average, respectively. Attenuation at 1550 nm and 1625 nm are 0.199 dB/km and 0.207 dB/km, respectively. The average total crosstalk including the FI/FO at 1526-1620 nm ranged from -38 to -32 dB.

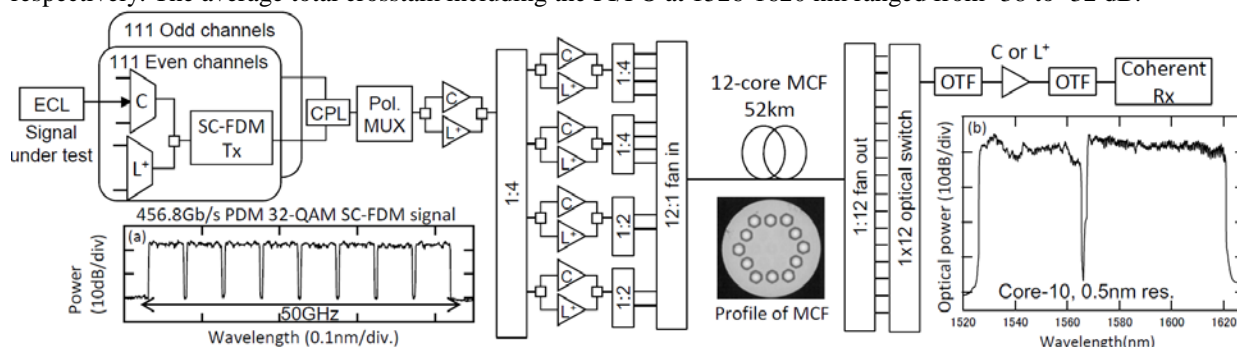


Fig. 3. Experimental setup for Pb/s transmission: (a) Optical spectra of single channel 456.8 Gb/s PDM 32-QAM SC-FDM signal (left), (b) Received optical spectrum after 52km transmission (core-10) [38].

### 3. Future perspectives

A capacity-distance product of 1 Eb/s-km (1 Pb/s x 1,000 km, for example) should be the next mile stone in SDM transmission technologies, with further progress needed for larger scalability to meet the demands foreseen for the next few decades, where an SDM gain of more than 100 should be anticipated. This could be realized by a combination of > 20 cores per fiber and > 5 modes per polarization per core. Obviously, fiber nonlinearity and attenuation loss of new fibers as well as NFs/bandwidth of optical amplifiers will limit the WDM/SDM capacity and transmission distance. Lower nonlinearity and lower attenuation loss with a new wavelength window are what hollow core photonic bandgap fibers (PBGFs) are pursuing and further progress will be desired [50-53]. Optical amplifiers with lower NFs and new bandwidths, node and switching architectures [54] as well as new measurement techniques [55] will be important research subjects to fully utilize the vast capacity offered by new fibers and SDM. As mentioned, space resources are actually limited for accommodating optical fibers and optical amplifiers if we think of >30 dB capacity increase just as wavelength resource is limited in WDM systems. It is therefore desirable that the SUE be also considered in designing SDM systems.

## 4. Conclusion

Recent development of space-division multiplexing is briefly described including a recent one Pb/s transmission experiment. A combination of multi-level modulation, multi-core/ multi-mode technologies will further advance the SDM technologies and provide us with great means to achieve more system capacity, scalability, and flexibility.

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