In this section, I summarize recent development of high capacity optical fiber transmission using space-division-multiplexing (SDM) techniques and related technologies, reported during the period from November 2013 to October 2016. There has been significant interest in SDM techniques realized by MCF and FMF, since it is expected to improve transmission capacity per fiber drastically.

In [1], 31-core MCF was developed for up to 4,000km transmission. In [2-5], MCFs with 125-µm cladding, which are compatible with conventional fibers, were developed. In [6], transmission systems consist of homogeneous single-mode MCF, where each core has the same parameter, were discussed. [7, 8] demonstrated crosstalk reduction with bidirectional signal assignment in MCF, and showed possibility of gradual upgrade of SMF-based line to MCF-based line. Heterogeneous MCFs to reduce inter-core crosstalk with 30 cores [9] and 32 cores [10] were demonstrated.

Coupled-core (CC) MCF described in [11-14] is another type of MCF, which permits strong mode coupling between cores, thus allowing smaller core-to-core distance and higher spatial efficiency compared to uncoupled MCFs. CC-MCF also shows low DGD between spatial modes (SMD), which results in reducing MIMO-DSP complexity, and therefore attractive for long-haul transmission. [15, 16] demonstrated 4-core 125 µm cladding CC-MCF with 0.158 dB/km propagation loss and 6.1 ps/km SMD. [13] also demonstrated strongly-coupled 3-mode 7-core FM-MCF.

In order to further increase the transmission capacity, combining FMF and MCF technologies, referred as FM-MCF is promising. [17] and [18] review 3-mode 12 core FM-MCF. In [19] and [20], 3-mode 36-core FM-MCF with 306-µm diameter cladding was fabricated. In [21], 6-mode 19-core FM-MCF with 318-µm cladding, and in [22], 6-mode 19-core FM-MCF with 246 µm cladding were demonstrated. It should be noted that spatial channel numbers exceed 100 for those fibers. 6-mode 12-core FM-MCF with 227 µm cladding was fabricated for improving spatial efficiency [23]. [24] demonstrated moderately coupled 2-mode 6-core FM-MCF with 125 µm cladding. [25-28] review the current state of the MCFs and FM-MCFs.

In order to realize SDM transmission systems, development of SDM component is important. MC-EDFAs were reported in [29, 30]. FM-EDFAs were reported in [31, 32]. Fiber connectors were demonstrated in [33, 34]. Fusion splicing of MCF was demonstrated in [35]. MCF cable was presented in [36]. FI/FO for MCF and mode MUX/DEMUX for FMF are necessary if conventional fiber devices are used. Various types of FI/FO and MUX/DEMUX were proposed and demonstrated in [20, 37-43]. Parameter measurement of MCF and FMF is also important for realizing SDM transmission systems. Measurement techniques for distribution of mode field diameter and refractive index, mode coupling at FMF splicing point, modal crosstalk of FMF, and mode coupling distribution of FMF were proposed and demonstrated in [44], [45], [46] and [47], respectively. In [48], fiber fuse propagation, that limits maximum launched power to the fiber, in FMF was observed and examined.

Many transmission experiment using MCF or FM-MCF were reported. Using 7-core EDFA and 7-core MCF, 120.7 Tbit/s (7-SDM 180-WDM 95.8 Gb/s) 204 km transmission [49], and 51.1 Tbit/s 2,520
km transmission [50, 51] were demonstrated. 2.15 Pbit/s 31 km transmission was demonstrated using 22-core MCF in [52]. In [53], 20-WDM PDM-16QAM 96 Gbit/s signals were transmitted over 1,600 km using low-crosstalk heterogeneous 32-core MCF. The aggregate spectral efficiency was 201.46 bit/s/Hz. In [54], 1.200 km transmission experiment was made using 19-core EDFA and 19-core MCF.

Transmission capacity can be further improved by using FM-MCF. In [55], 20-WDM PDM-32QAM 105 Gbit/s signals were transmitted over 40 km using 3-mode 12-core FM-MCF. The aggregate spectral efficiency was 247.9 bit/s/Hz. In [56, 57], 20-WDM PDM-QPSK 40 Gbit/s signals were transmitted over 527 km with 3-mode 12-core FM-MCF. In [19] and [20], 403.7 Tbit/s 5.5 km transmission was demonstrated using 3-mode 36-core FM-MCF. Using 9.8-km 6-mode 19-core MCF, 140.7 Tbit/s 7,300 km transmission were demonstrated by using super Nyquist WDM [58]. Spectral efficiency of 345 bit/s/Hz was obtained in [59]. 2.05 Pbit/s transmission was demonstrated in [60, 61]. The spectral efficiency was improved by 947 bit/s/Hz by using DP-64QAM modulation format [62].

SDM transmission technologies were reviewed in [63-70].

List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>DGD</td>
<td>Differential group delay</td>
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<tr>
<td>DP</td>
<td>Dual polarization</td>
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<td>DSP</td>
<td>Digital signal processing</td>
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<tr>
<td>EDFA</td>
<td>Erbium-doped fiber amplifier</td>
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<td>FI/FO</td>
<td>Fan-in/fan-out</td>
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<tr>
<td>FMF</td>
<td>Few-mode fiber</td>
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<tr>
<td>FM-MCF</td>
<td>Few-mode multicore fiber</td>
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<tr>
<td>MCF</td>
<td>Multicore fiber</td>
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<tr>
<td>MIMO</td>
<td>Multiple-input multiple-output</td>
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<tr>
<td>MUX/DEMUX</td>
<td>Multiplexer/demultiplexer</td>
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<tr>
<td>PDM</td>
<td>Polarization-division multiplexing</td>
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<td>QAM</td>
<td>Quadrature amplitude modulation</td>
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<tr>
<td>QPSK</td>
<td>Quadrature phase-shift keying</td>
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<tr>
<td>SMF</td>
<td>Single-mode fiber</td>
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<tr>
<td>WDM</td>
<td>Wavelength-division multiplexing</td>
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