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Invited Papers

High-capacity transmission over multi-core fibers

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ABSTRACT

The ultimate transmission capacity of standard single-mode fiber (SSMF) is limited by fiber nonlinearity which prevents increasing transmission power and finite amplifier bandwidth. In order to overcome such limitation, space-division multiplexing (SDM) has been proposed. Multi-core fiber (MCF) is a strong candidate to realize practical SDM transmission system because of high isolation of individual spatial modes sharing the same cladding, which enables ultra-high capacity transmission in cooperation with wide band WDM.

1. Introduction

The limited bandwidth of low-loss transmission and optical amplification, together with a limitation of transmission power from fiber non-linearity means increase of transmission capacity of a single optical fiber is increasingly difficult [1,2]. Currently, standard single-mode fibers (SMMFs) use a single fiber core surrounded by 125 μm cladding surrounded by additional coating with many additional layers of environmental protection. With the limited space of fiber ducts in terrestrial and particularly in undersea cables, research into providing drastic increase in per-fiber capacity has turned to expansion into the spatial domain, by using either multiple cores sharing the same cladding or increasing the core diameter to allow transmission of multiple modes. Increasing the number of cores in the cladding is perhaps the simplest approach to achieve higher capacity, but raises new issues of for design of the transmission system. Inter-core crosstalk (XT) is the most important parameter of MCF which is brought by mode-coupling/power-coupling between cores and places limits on how closely cores can be spaced leading to larger cladding diameters. Increasing the cladding diameter results in degradation of mechanical strength. Furthermore, adjustment of propagation constant, effective area, cut-off wavelength, bending loss also need to be taken into account (see Fig. 1).

The first transmission demonstration exceeding 100 Tb/s was achieved in 2011, using the first homogeneous, trench-assisted, 7-core fiber [3], shortly followed by 112 Tb/s transmission [4] and extended a year later to 305 Tb/s in a homogeneous, trench assisted, 19-core fiber using wideband polarization-division multiplexed (PDM) – quadrature phase shift keyed (QPSK) modulation [5]. By the end 2012, the experimentally demonstrated transmission capacity already exceeded 1 Pb/s [6] with 50 GHz-spaced, 222-channel WDM signals, each carrying 456-Gb/s PDM-32 quadrature amplitude modulation (QAM) single carrier frequency division multiplexing in each core of a 52 km, 12-core homogeneous MCF. Shortly afterwards, 1.05 Pb/s transmission was achieved using a combination of twelve single-mode cores carrying PDM-32QAM-OFDM signals and two few-mode cores carrying PDM-QPSK in their LP01 and two LP11 modes [7]. In 2015, two capacity demonstrations exceeding 2 Pb/s were reported. One [8], used a 22-core homogeneous single core MCF in combination with a wide-band comb source and is described in more detail below. At the same time, the record capacity of few-mode MCFs was achieved. 2.05 Pb/s transmission was reported using a FM-MCF with 6 modes in each of 19 cores [9]. Each of the 114 spatial modes carried 360 C-band wavelength channels with duo-binary data at 15GBd, suggesting that if the spectral efficiency (SE) and transmission band can be increased, such fibers perhaps offer the best possibility of attaining single fiber capacity towards and beyond 10 Pb/s.

2. Transmission experiments

2.1. Initial demonstrations of over-100 Tb/s SDM transmission

The aim of our research has been to lead with experimental demonstrations and encourage the photonics research community to aim for further technical advance. With such a goal in mind, we

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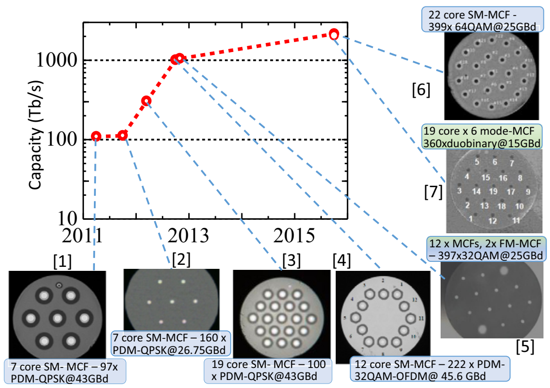

Fig. 1. High-capacity transmission experiments using SM and FM-MCFS.

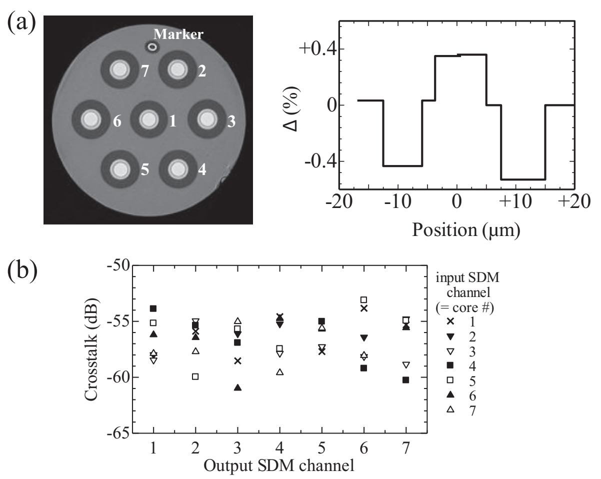

Fig. 2. Trench-assisted 16.8 km, 7-core fiber [1]. (a) Structure, (b) inter-core XT in the SDM transmission system.

conducted two initial demonstrations of over-100 Tb/s SDM transmission [3,5,10,11]. The first demonstration used the first trench-assisted 7-core fiber ever reported and was significant since it demonstrated an alternative path to increasing capacity than the pursuit of ever increasing order quadrature-amplitude modulation (QAM) as a means of increasing the SE. As shown in Fig. 2, the refractive indices of the cladding near the step-index cores were reduced to improve the optical field confinement within cores and inter-core XT was suppressed as a result. The dedicated measurement showed that the XT of the fiber was in the range of <−90 dB/km at 1550 nm wavelength and 140 mm bending radius [12], but in the transmission system more compromised XT of <−53 dB was achievable for 16.8 km fiber length.

The transmission performance of the MCF system was evaluated by using 43.0184 GBaud DP-QPSK signals. Fig. 3(a) shows the OSNR dependence of BER for each SDM channel. The similar performance of 7 SDM cases and 1 SDM case show that the impact of inter-core XT was negligible. Fig. 3(b) shows BER of each SDM-WDM channel in a 97 WDM x 7 SDM transmission demonstration. The BER of all channels was measured to be below 1.5×10^{-3} assumed as the threshold% FEC overhead, hence 109 Tb/s aggregated capacity was achieved. No capacity record which exceeds these values has been achieved for transmission over SMF.

Next, we moved the research target to 19-core fibers. By reducing the core pitch from 45 μm of the 7-core fiber to 35 μm, all the cores could be packed within 200 μm diameter cladding as shown in Fig. 4(a). The inter-core XT between neighboring cores shown in Fig. 4(b), was −32 dB in average at 1550 nm and even higher by around 6 dB at longer wavelength region. Fig. 5(a) shows a comparison of BER-OSNR curves taken with and without inter-core XT at around L-band edge. The OSNR penalty was still limited to around 1 dB and high applicability for DP-QPSK transmission was expected. 305 Tb/s transmission was achieved by employing 100 WDM channels ranged from 1533 to 1615 nm, 19 SDM channels and 43.0184 GBaud DP-QPSK signals. All the BER values stayed below of 7% FEC threshold as shown in Fig. 5(b). Our successful demonstration opened up the research trend of pursuing various high-core count MCFs, which in the end lead to realization of 2.15 Pb/s transmission capacity through a 22-core fiber [8].

2.2. Record capacity of 2.15 Pb/s transmission

In this section we describe a recent transmission experiment using a homogeneous SM-MCF. Transmission capacity exceeding 2 Pb/s was demonstrated by exploiting an extended wavelength range, enabled by a wideband optical comb source in combination with high spectral efficiency modulation of 22-core Spatial Super Channels (SSCs) [8]. The homogeneous, 22-core MCF was based on a new 3-layer design with a two-pitch layout and total cladding diameter of 260 μm, as shown in the inset of Fig. 6. The 31.4 km span was spliced from 5 separately drawn sub-spans, giving rise to total link crosstalk of −37.5 dB at the comb seed wavelength of 1559 nm. The dynamic skew between several core pairs of the fiber was measured to vary over only a few picoseconds range in 24 h in lab condition. Such low variation in propagation delays between SDM channels is expected to be advantageous with respect to sharing of both transmitter hardware and DSP resources for which SSCs were originally proposed [13].

The frequency comb source, custom designed by RAM Photonics, consisted of a narrow linewidth (5 kHz) seed laser modulated with a low noise 25 GHz oscillator with the resulting 25 GHz

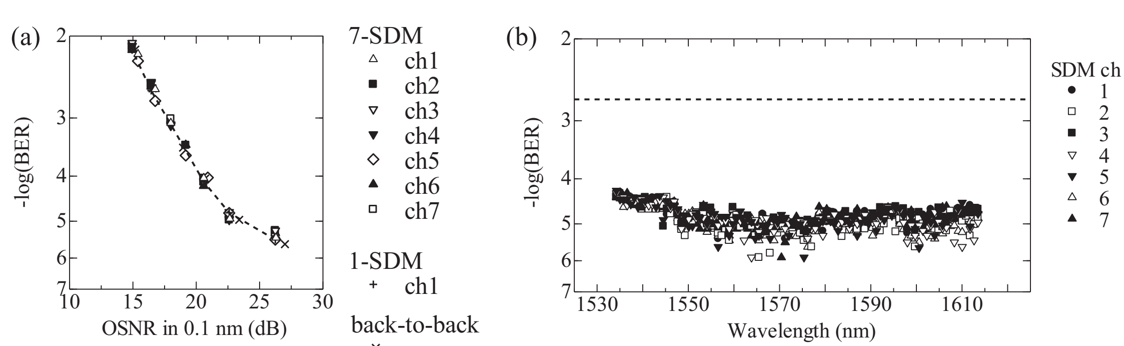

Fig. 3. SDM transmission results on 7-core fiber [1,8]. (a) BER as a function of received OSNR. (b) BER for each 7-SDM x 97 WDM channel.