Petabit/s Optical Transmission Using Multicore Space-Division-Multiplexing

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SUMMARY  The paper presents ultra-high-capacity transmission technologies based on multi-core space-division-multiplexing. In order to realize high-capacity multi-core fiber (MCF) transmission, investigation of low crosstalk fiber and connection technology is important, and high-density signal generation using multilevel modulation and crosstalk management are also key technologies. 1 Pb/s multi-core fiber transmission experiment using space-division-multiplexing is also described.

key words: high-capacity transmission, space-division-multiplexing, multi-core fiber, multilevel modulation

1. Introduction

Optical transmission technologies have advanced rapidly over the past thirty years in three main technological innovations (Fig. 1): time division multiplexing (TDM) technology based on electrical multiplexing, optical amplification technology/wavelength division multiplexing (WDM) technology, and digital coherent technology, which is currently undergoing research and development. Current technologies can attain the total capacity per fiber of 100 Tb/s, but if the capacity is to exceed Pb/s, we have to offset the key factors limiting the capacity of conventional single core fiber. These are optical signal input power limits, signal degradation due to nonlinear optical effects, and the spectral efficiency (SE) limit.

Space-division-multiplexing (SDM) based on multi-core fiber (MCF) is a promising approach to increasing the transmission capacity (power) of fiber [1]–[22]. Recently, over 100 Tb/s high-capacity optical transmission experiments have been described that use multicore space-division-multiplexing.

In this paper, we describe ultra-high-capacity optical transmission technologies based on multicore space-division-multiplexing. This paper is organized as follows. Section 2 overviews optical transmission based on multicore space-division-multiplexing and discusses power-tolerance characteristics and requirements for high capacity transmission. Section 3 focuses on the inter-core crosstalk issue and crosstalk management for high aggregate spectral efficiency. Section 4 presents an example of 1 Pb/s transmission in the results of a feasibility demonstration.

2. Optical Transmission Using Multicore Space-Division-Multiplexing

Optical transmission systems must offer excellent power-tolerance characteristics and suppressed nonlinear optical effects to achieve transmission capacity expansion. For power-tolerance, multicore space-division-multiplexing is promising because the power density per core can be controlled to increase the overall transmission capacity (power).

Figure 2 plots the product of capacity per fiber and distance (Eb/s·km) and the overall input signal power of recent transmission experiments. The overall input power of conventional single-core fiber transmission is under the fiber fuse transmission threshold value (1.2–1.4 W) [27]. On the other hand, MCF transmission with higher optical power has been demonstrated [12], [21], [22]. For example, we conducted 1 Pb/s 52 km MCF transmission with about 1.1 watts of optical signal power [12]. We also have demonstrated 7-core fiber transmission using Raman amplification with 6.5 W per fiber [11]. Fan-in/fan-out (FI/FO) devices are especially important components in such MCF transmission systems. A physical-contact-type FI/FO device with high-power durability has been developed [20]. It is ex-
Investigation of multi-core fiber for large capacity optical transmission has been active since 2009. Reports of MCF transmission experiments using MCFs and FI/FO devices have increased since 2011 [5]–[14]. As shown in Fig. 3, optical transmission experiments using MCFs have demonstrated top class capacity.

Basic configuration of MCF transmission is schematically illustrated in Fig. 4. It consists of transmitters, FI/FO devices, MCFs, multi-core amplifiers, and receivers; connectors, splicing and multi-core amplifiers are also important.

MCFs and connections (FI/FO, connector, splicing) demand low loss and low crosstalk characteristics. Low loss characteristics of MCFs are known to be almost the same as those of conventional single-core fibers [2]–[4]. As mentioned before, high-power durability is also important for ultra-high-capacity optical transmission, and supportable power levels of several W have been obtained [20].

For transmitters and receivers, multi-level modulation and signal processing are essential for high spectral efficiency. Multi-level transmission systems have been investigated to increase the transmission capacity of optical fiber [23], [24]. QAM (Quadrature Amplitude Modulation) format utilizes the amplitude and phase of light and so can improve the frequency utilization efficiency, and increase the transmission capacity in a limited bandwidth.

By considering inter-core crosstalk, Fig. 5 classifies MCF transmission, which consists of negligible-coupling type, weak coupling type, and strong coupling type. In negligible-coupling type, the crosstalk between cores is suppressed to maintain transmission characteristics. Simple design, treated as the number of single-core fibers, is possible. However, there is a problem that fiber thickness is increased with core number to maintain core pitch. Weak and strong coupling types may increase core number because some cross-talk between cores is accepted. On the other hand, signal processing is required to separate supermodes in the case of strong coupling, and crosstalk management that addresses multi-level modulation is indispensable for weakly coupled MCF transmission.

3. Crosstalk Management for High Aggregate Spectral Efficiency

In this chapter, we focus on the general case of MCF transmission, weakly coupled MCF transmission, and discuss crosstalk management. In order to realize ultra-high capacity MCF transmission, increasing the aggregate spectral efficiency (SE), defined as the product of the number of cores, \( N \), and the SE per core, is necessary. Figure 6 shows the relationship between \( N \) and SE of WDM MCF transmission experiments. Crosstalk management to design the optimum combination of \( N \) and SE per core for ma
mum aggregate SE is essential. The crosstalk generally increases with the number of cores while the crosstalk tolerance decreases with higher order multi-level signal transmission [25], [26]. For 19 core fiber, the highest $N$ and aggregate SE of 30-b/s/Hz were achieved with QPSK modulation [10]. However, it seems difficult to employ higher order multi-level signals due to the excessive crosstalk. For seven core fibers, crosstalk under $-30$ dB has been realized, and QPSK transmission with 15-b/s/Hz aggregate SE and 32-QAM-OFDM transmission with 60-b/s/Hz aggregate SE have been reported [7], [8].

We optimized the combination of the number of cores and multiple level of QAM by taking account of the crosstalk between SDM channels. We demonstrated the high aggregate SE of 91.4 b/s/Hz by employing the PDM-32QAM format and low crosstalk 12 core fiber and FI/FO devices. These allowed 1-Pb/s multi-core core fiber transmission [12]. This aggregate SE is the highest reported in MCF transmission experiments.

Employing a hybrid of multi-core and multi-mode is another effective way to improve the aggregate SE. 1.05-Pb/s, 3-km transmission with over 100 b/s/Hz aggregate SE has been demonstrated by utilizing multi-core and multi-mode space-division-multiplexing [14]. 32QAM-OFDM format was used for 12 single-mode cores and QPSK format was used for two few-mode cores.

4. 1-Pb/s Multi-Core Fiber Transmission Experiment

Figure 7 shows the experimental setup for 1 Pb/s MCF transmission. We demonstrated the 52-km 12-core fiber transmission of 222 WDM channels, 456-Gb/s signals, by employing the PDM-32QAM format and low crosstalk 12 core fiber [18] and FI/FO devices [19], [20].

We utilized a 12-core fiber whose cores are arranged on one ring so that the crosstalk is small even if the number of cores is larger than seven [18]. The FI/FO devices split the MCF’s twelve cores into twelve individual small diameter fibers. The core pitch and cladding diameter of the FI/FO devices are the same as those of the MCF. In the FI/FO devices, the MCF and small diameter fibers are connected by fusion-splicing. The total crosstalk from all other cores of the FI device and the FO device after 52-km MCF propagation is shown in Fig. 8. The crosstalk values were small and there was some measurement variability. In order to clarify the characteristics, the crosstalk values of all cores were averaged. The average total crosstalk at 1526–1620 nm ranged from $-38$ to $-32$ dB. The total losses between the FI input and the FO output port, including MCF 52 km-propagation, ranged from 12.4 to 14.8 dB.

Figure 9 illustrates the transmitter and receiver. In this experiment, 222-channel WDM signals of 456-Gb/s PDM-32QAM single-carrier frequency-division-multiplexing (SC-FDM) signals were generated; transmitter and receiver setups were based on previous reports [23]. 222 CW optical
carriers (1526.44–1565.09 nm, and 1567.95–1620.06 nm) with 50-GHz spacing in the C- and extended L- (L+−) bands were used in the transmitter. Each carrier was modulated to create a 12.5-GHz spaced 4-subcarrier signal, and each subcarrier was simultaneously modulated by an IQ-modulator driven by an electrical 5.71-Gbaud Nyquist-pulse-shaped 32QAM signal. The 4-subcarrier signal was split in two, one of them was delayed and frequency-shifted by 6.25 GHz, and recoupled to form a 6.25-GHz-spaced 8-subcarrier SC-FDM signal. The even and odd SC-FDM signals were then combined with an optical coupler, and polarization multiplexed with 25-nsec delay. Consequently, each 50-GHz spaced channel consisted of eight PDM-32QAM subcarriers with line rate of 456 Gb/s (net data rate: 380 Gb/s), resulting in the SE of 7.6 b/s/Hz assuming 20% FEC overhead. Its spectra are shown in the inset of Fig. 9(c). C- and L+−-band EDFAs with parallel configuration were used to compensate the loss of the modulation sections. In this experiment, we used a tunable external-cavity laser (ECL) with a linewidth of about 60 kHz for the test channel; the remaining lasers were DFB lasers (linewidth ∼2 MHz). The signals were then amplified by C- and L+−-band EDFAs and separated into 12 SDM channels by couplers. The transmission line consisted of a 52-km 12-core MCF. Twelve SDM channels were generated by delaying copies of the original WDM channels, and each SDM channel was fed into the corresponding core by 12:1 FI device. The signals were then amplified by C- and L+−-band EDFAs and separated into 12 SDM channels by couplers. The transmission line consisted of a 52-km 12-core MCF. Twelve SDM channels were generated by delaying copies of the original WDM channels, and each SDM channel was fed into the corresponding core by 12:1 FI device. Considering nonlinear impairment, the average power of the 222 WDM channels was set to −4 dBm/ch. The high aggregate SE of 91.4 b/s/Hz was achieved. After transmission, the SDM channels (signals via corresponding cores) were de-multiplexed by the FO device. Desired channel was selected by an optical switch and fed to the coherent receiver.

At the receiver side, the signals were filtered by optical tunable filters (OTFs), and detected by a polarization-diversity intradyne receiver. We used a free-running ECL with linewidth of ∼70 kHz as the LO. Real and imaginary parts of the two polarization tributaries were detected and digitized by the coherent receiver. In this experiment, four subcarriers were simultaneously received, and subcarrier separation and demodulation were post-processed offline using the algorithm described in a previous report [23]. Bit error ratio (BER) was calculated from the 1 Mbit demodulated signals.

Figure 10 shows the back-to-back OSNR-penalty characteristics due to crosstalk at the wavelength of 1545.32 nm. The penalty at the worst crosstalk of the transmission experiment, −32 dB, was 0.3 dB, which is close to the theoretical value of 32-QAM. Received optical spectrum after 52 km transmission (core-10) is shown in Fig. 11. When the spectrum of crosstalk was measured, all cores except for core-10 were exited.

Next, we discuss the performance of 222-channel WDM transmission. Thanks to the low crosstalk MCF and FI/FO devices, the crosstalk from all other SDM channels was −32 dB under the signals. We also measured the Q-factor penalty of core-2 due to the crosstalk components, shown as the triangles in Fig. 8. The Q-factor penalty of core-2 after 52-km transmission was within 0.22 dB. The measured Q-factor performance after 52-km MCF transmission is shown in Fig. 12. Each plot represents the Q-factor calculated from the average BER of the 8 subcarriers. Q-factors of all 222 channels for the twelve cores were confirmed to be better than 6.90 dB, which exceeds the Q-limit (6.75 dB, dashed line) of continuously interleaved BCH hard
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References


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5. Conclusions

We presented optical transmission technology using space-division-multiplexing based on MCF. Multicore space-division-multiplexing enables power-tolerant and nonlinearity-tolerant enhanced transmission, and is a promising approach to increasing the transmission capacity of optical fiber.

In order to realize high-capacity MCF transmission, investigating low crosstalk fiber and connection technologies is important. High-density signal generation using multi-level modulation and crosstalk management are also key issues.

For over 1-Pb/s MCF transmission, we optimized the combination of the number of cores and multiple level of QAM by taking account of the crosstalk between SDM channels. We successfully demonstrated the 52-km 12-core fiber transmission of 222 WDM channels, 456-Gb/s signals, by employing PDM-32QAM format and low crosstalk 12 core fiber and FI/FO devices. These allowed the capacity per fiber to exceed 1.01-Pb/s for the first time and confirmed the feasibility of MCF transmission with 400-Gb/s-class high speed channels.

To clarify how much capacity the future metro/core networks can realize, research and development of MCF transmission technology must become more vigorous.

Fig. 12 Measured Q-factors after 52 km transmission.

decision FEC with 20% overhead.


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