C+L-Band 2,160 km Bidirectional Transmission using Three Vendor-Installed 4-Core Fibre Cables

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Abstract *Full C+L-band transmission is experimentally demonstrated using multivendor 4-core fibre cables installed in an outdoor environment. By applying bidirectional transmission technology to suppress core-to-core XT, the transmission distance can be extended to 2,160 km, which is 1.5 times longer than that for unidirectional transmission. ©2023 The Author(s)*

Introduction

Multi-core fibres (MCFs), a space division multiplexing (SDM) technology, have the potential to exceed the theoretical limit of the transmission capacity in widely used standard single-mode fibres (SMFs) [1]. In particular, MCFs with a standard cladding diameter of 125 μm [2] are attracting attention for early commercialization of SDM transmission systems because of their superior manufacturability and mechanical strength comparable to that of conventional SMFs. To date, testbeds have been constructed by installing MCF cables to simulate outdoor environments, and their optical characteristics and transmission performance have been reported [3-6]. However, the bandwidth of signals was limited to the C-band in transmission experiments using installed MCF cables [6]. For further expansion of the transmission capacity, extending the bandwidth from the C-band to the C+L-band is a promising approach. However, the mode field diameter of each core increases at longer wavelengths, and core-to-core crosstalk (XT) tends to accordingly increase in MCFs [7]. Therefore, even for a trench-assisted MCF (TA-MCF) with a trench structure to suppress the core-to-core XT, the degradation of the transmission performance due to the XT for long-distance transmission in the L-band would not be negligible compared to the C-band. Meanwhile, bidirectional transmission technology, in which signals propagate in different directions in adjacent cores, has been proposed as a method to suppress the degradation of the transmission performance due to XT [8-16]. Actually, we have confirmed that the transmission distance can be extended by applying bidirectional transmission techniques to step-index MCFs, where the influence of XT is dominant in long-distance transmission [16].

In this paper, full C+L-band transmission was experimentally demonstrated using multivendor 4-core fibre (4CF) cables with multiple connections realized via connectors and fusion splicing installed in aerial areas and underground ducts. First, the wavelength dependence of the core-to-core XT in 4CF cables was measured. In addition, we confirmed that the transmission distance is limited to 1,440 km at longer wavelengths in the L-band when the signal light is transmitted in the same direction in all the cores of the 4CF. Furthermore, the transmission distance could be extended to 2,160 km, which is 1.5 times longer than that for unidirectional transmission, by applying bidirectional transmission technology to suppress the degradation of the transmission performance due to XT between cores. In this case, a total transmission capacity of 121.9 Tbit/s was achieved with the four cores.

Installed TA-4CF Optical Cables

The installed TA-4CFs and TA-4CF cables [6] were fabricated by three different vendors (vendors A, B, and C). The cladding diameter and core pitch of the TA-4CFs were 125 μm and 40 μm, respectively. The length of the TA-4CF optical cables was 3 km. As shown in previous work [6], the three vendors' cables were installed in an outdoor environment consisting of an aerial section and an underground section. In addition, a 60 km transmission span was constructed for each vendor's cable by connecting the 20 TA-4CFs in the 3 km cable via connectors or fusion splicing [6]. The average span losses for the four cores of cables A, B, and C at 1550 nm were 15.7 dB, 14.8 dB, and 17.6 dB, respectively.

Figure 1 shows the wavelength dependence

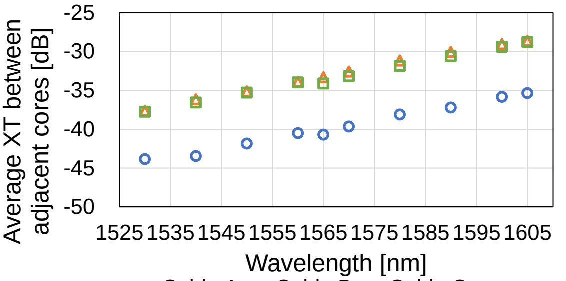
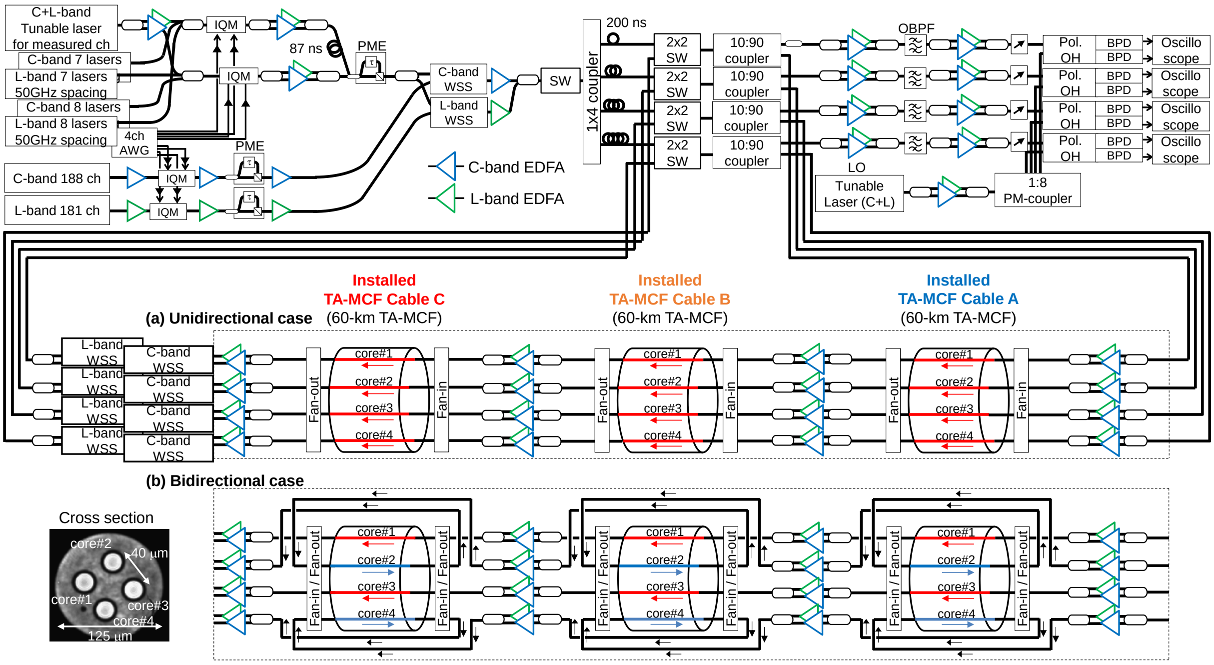


Fig. 1: Wavelength dependence of the average XT between two adjacent cores over a 60 km span for each vendor's cable.



IQM: IQ modulator, AWG: Arbitrary waveform generator, PME: Polarization multiplexing emulator, SW: Optical switch, WSS: Wavelength selective switch, EDFA: Erbium Doped Fibre Amplifier, OBPF: Optical bandpass filter, Pol. OH: Polarization-diversity optical hybrid, BPD: Balanced photodetector, LO: Local oscillator

Fig. 2: Experimental setup.

of the average XT between two adjacent cores over a 60 km span for each vendor's cable. Although the absolute values of the XT are different among the vendors' cables due to differences in fibre design, the XT increases with wavelength for all three vendors' cables. At a wavelength of 1605 nm, the average XT between two adjacent cores in a 180 km transmission line connecting cables A, B, and C is -25.3 dB, resulting in a total XT of -22.3 dB from two adjacent cores excluding a diagonal core. Therefore, the total XT from the two adjacent cores after 2,160 km transmission is estimated to be -11.5 dB. In such large XT cases, the transmission distance could be limited not only by the amplified spontaneous emission (ASE) noise from the optical amplifier acting as a repeater but also by the XT. Thus, the transmission distance is expected to be extended by applying bidirectional transmission technology that eliminates the influence of XT between adjacent cores.

Experimental Setup

We have demonstrated C+L-band transmission in unidirectional and bidirectional cases using installed TA-4CF cables. Figure 2 shows the experimental setup, which expands upon previous MCF transmission experiments [6, 16].

In the transmitter, eight even channels and eight odd channels for measurement and 188 channels in the C-band (1527-1565 nm) and 181 channels in the L-band (1570-1607 nm) as loading channels were independently modulated, resulting in 25 GHz-spaced 24-Gbaud 369 WDM dual polarization (DP)-QPSK signals.

The generated WDM signals were split into 4 paths, with a relative delay of 200 ns for decorrelation, and fed into a recirculating loop system consisting of three spans of installed 60 km TA-4CFs, C- and L-band erbium-doped fibre amplifiers (EDFAs), 2×2 optical switches (SWs), and C- and L-band wavelength-selective switches (WSSs). The signal power launched into each core of the TA-4CFs was set to -3 dBm/ch for both the C- and L-bands. In the unidirectional case, the WDM signal propagated in the same direction in all the cores using the transmission line shown in Fig. 2(a). In the bidirectional case, the WDM signal propagated in the opposite directions in adjacent cores, as shown in Fig. 2(b).

In the receiver, the transmitted WDM signals were detected by four individual digital coherent receivers. For offline processing, the stored samples were processed by four individual adaptive 2×2 multi-input multi-output (MIMO) equalizers. The MIMO tap coefficients were updated based on a decision-directed least-mean square (DD-LMS) algorithm [17].

Results and Discussion

Figure 3 shows the average Q^2-factors of the four cores of the typical channels after 360, 720, 1,080, 1,440, 1,800, and 2,160 km transmissions in the unidirectional case. While the wavelength dependence of the Q^2-factors is roughly flat at each transmission distance in the C-band, the Q^2-factors in the L-band degrade with increasing wavelength. Therefore, the transmission distance is limited to 1,440 km to obtain Q^2-factors that exceed the assumed FEC threshold with the maximum overhead [18] for all WDM channels in the full C+L-band in the unidirectional transmission. Figure 4 shows the calculated effective signal-to-noise ratio (SNR) after transmission, considering the performance of the transmitter and receiver (Tx/Rx), the ASE noise of the repeater, and the XT obtained from the measurements shown in Fig. 1. Here, the SNR of Tx/Rx and the noise figure (NF) of the repeater were assumed to be 14 dB and 6 dB, respectively, and no wavelength dependence of the ASE noise was assumed. Since the Q^2-factors in Fig. 3 and the effective SNR in Fig. 4 show similar tendencies, the degradation of the Q^2-factors at the longer wavelengths of the L-band is due to the wavelength dependence of the XT.

Figures 5(a) and (b) show the Q^2-factors for all 4-SDM/369-WDM channels in the unidirectional case after 1,440 km transmission and in the bidirectional case after 2,160 km transmission, respectively. In this experiment, we assumed three different soft-decision FECs based on low-density parity-check codes: a 6.5 dB FEC limit [19] with 12.75% overhead (OH), a 5.7 dB FEC limit [20] with 20% OH, and a 4.95 dB FEC limit [18] with 25.5% OH. From the results in Fig. 5(a), a transmission capacity of 124.0 Tbit/s was obtained after 1,440 km transmission in the unidirectional case. In contrast, Q^2-factors exceeding the assumed FEC threshold were obtained at the longer wavelengths in the L-band even after 2,160 km transmission in the bidirectional case, as shown in Fig. 5(b), resulting in a transmission capacity of 121.9 Tbit/s with the four cores. Based on these results, the transmission distance can be extended by 1.5 times compared to unidirectional transmission by applying bidirectional transmission technology while maintaining the total transmission capacity in the C+L-band.

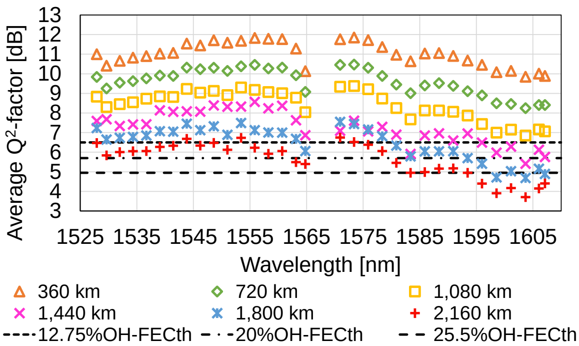


Fig. 3: Average Q^2-factors of the four cores of the typical channels after transmission.

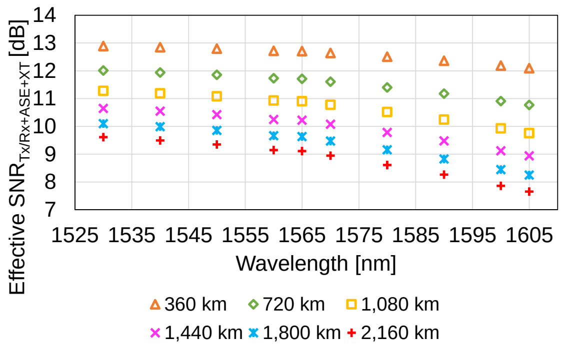


Fig. 4: Calculated effective SNR after transmission.

Conclusions

Full C+L-band transmission is experimentally demonstrated using multivendor 4-core fibre cables installed in aerial areas and underground ducts. By applying bidirectional transmission technology to suppress the degradation of the transmission performance due to XT between cores, the transmission distance can be extended to 2,160 km, which is 1.5 times longer than that for unidirectional transmission. In this case, a total transmission capacity of 121.9 Tbit/s is achieved with the four cores.

Acknowledgements

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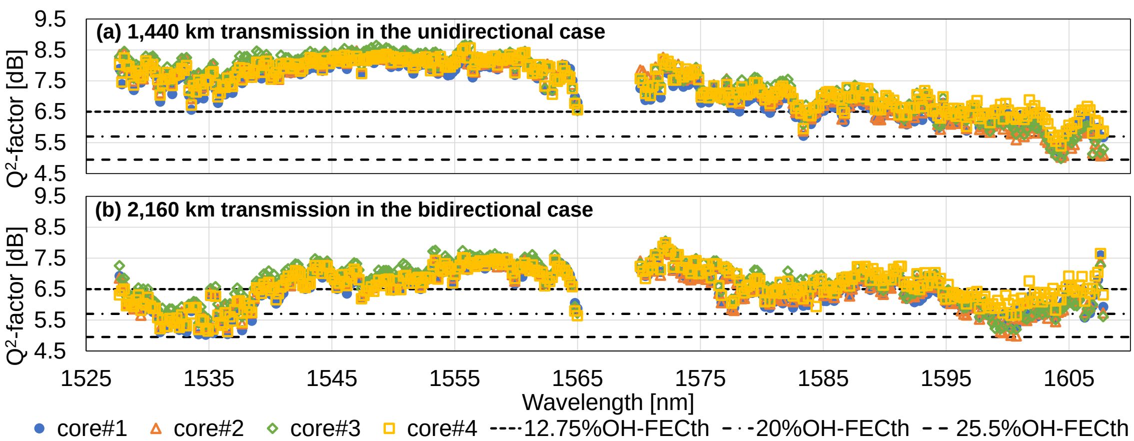

Fig. 5: Q^2-factors for all 4-SDM/369-WDM channels (a) after 1,440 km transmission in the unidirectional case and (b) after 2,160 km transmission in the bidirectional case.

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