Performance Comparison for Standard Cladding Ultra-Low-Loss Uncoupled and Coupled 4-Core Fibre Transmission over 15,000 km

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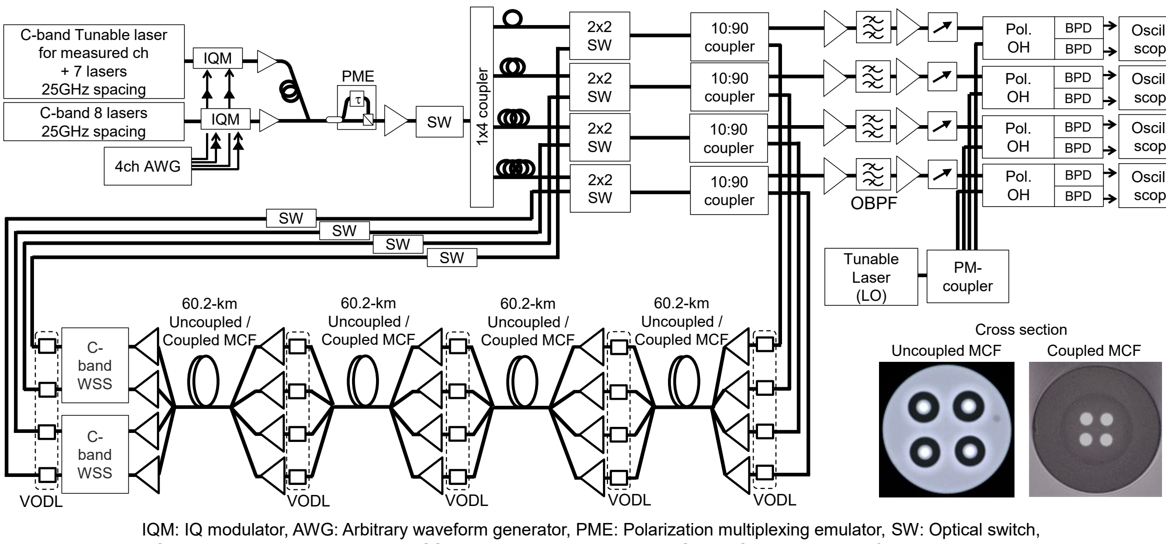
Abstract *We compared the ultra-long-haul multi-core fibre (MCF) transmission performance of standard cladding ultra-low-loss uncoupled and coupled 4-core fibres. From the results obtained, 15,652-km transmission in uncoupled MCF and 16,856-km transmission in coupled MCF was demonstrated using a centre channel of 16-WDM 24-Gbaud DP-QPSK signals.*

Introduction

In an optical submarine cable system as a part of the global communication infrastructure, the total cable capacity must be continuously and dramatically enlarged for future huge traffic demands. Unlike terrestrial transmission systems, the structure of submarine cables is required to withstand water pressure at depths of several thousand meters. Thus, the space for containing the fibres in the cable is limited. In addition, the number of repeaters is also restricted by the power supply limitation from the cable landing stations to the optical amplifiers, which is a particular problem in submarine cable systems. Therefore, in conventional transoceanic submarine cable systems, the number of fibre pairs (FPs) is generally limited to 6 - 8 FPs.

Recently, space-division multiplexing (SDM) techniques have been investigated for improving space efficiency and power consumption. To date, ultra-long-haul transmission experiments using uncoupled multi-core fibre (MCF) [1, 2] and coupled MCF [3 ,4] and developments for multi-core erbium-doped fibre amplifiers (EDFAs) [5] have been reported. In particular, a 125-μm cladding MCF is attractive for deployment in submarine cable systems since it is expected to have similarly high productivity and high mechanical reliability as existing single mode fibre (SMF) with the same cladding diameter [6]. However, the ultra-long-haul transmission performance with standard cladding fibres has been evaluated only between MCF and SMF up to 12,100 km [3, 4].

In this paper, we compared the ultra-long-haul MCF transmission performance of standard cladding ultra-low-loss uncoupled and coupled 4-core fibres. To clarify the tolerance for the non-linear effects in the uncoupled and coupled MCFs, the Q-factors as a function of the fibre launch power were measured using the centre channel of 16-WDM 24-Gbaud DP (dual polarization) - QPSK (quadrature phase shift keying) signals. In addition, we measure the Q-factors as a function of the transmission distance and confirmed the feasibility of 15,652-km transmission for uncoupled MCF and 16,856-km transmission for coupled MCF. We also measured the Q-factors



IQM: IQ modulator, AWG: Arbitrary waveform generator, PME: Polarization multiplexing emulator, SW: Optical switch, VODL: Variable optical delay line, WSS: Wavelength selective switch, OBPF: Optical bandpass filter, Pol. OH: Polarization-diversity optical hybrid, BPD: Balanced photodetector, LO: Local oscillator

Fig. 1: Experimental setup

for all 16-WDM channels at 12,040-km transmission and show that the channel dependence is sufficiently suppressed with about 1 dB Q-factor margin.

Experimental setup

Figure 1 shows the experimental setup. In the transmitter, the CW lights generated from eight external cavity lasers were combined with a frequency spacing of 25 GHz for even and odd channels, respectively. The even and odd channels were independently modulated using a 4-channel arbitrary waveform generator (AWG) and two IQ modulators (IQMs). The IQMs were driven by 24-Gbaud Nyquist-shaped electrical two-level signals for QPSK. The signals were polarization-multiplexed with a delay of 87 ns, and then 16-channel WDM 25 GHz-spaced 24-Gbaud DP-QPSK signals were obtained with a bit rate of 96 Gbit/s including the assumed 25.5% forward error correction (FEC) overhead [7]. Note that we measured only the centre channel for measurements of the fibre launch power dependence and transmission distance dependence.

The generated WDM signal was split into 4 paths, with a relative delay of 200 ns between subsequent paths for decorrelation, and fed into a re-circulating loop system consisting of four spans of 60.2-km uncoupled or coupled 4-core fibres, C-band EDFAs and 2x2 optical switches (SWs). The WDM signals after 4-span transmission were gain-equalized using two 2-channel C-band wavelength-selective switches (WSSs). In this experiment, the skew between the four cores was compensated for each span via variable optical delay lines (VODLs) in only coupled MCF transmission.

The four cores arranged in a square lattice of uncoupled and coupled MCFs have almost the same refractive index profile as an ultra-low-loss pure-silica-core single mode fibre for long-haul transmission. The core-averaged transmission loss, effective area and core pitch for the uncoupled MCF at 1550 nm were approximately 0.156 dB/km, 87 μm^2 and 43.0 μm, respectively. On the other hand, the core-averaged transmission loss, effective area, core pitch and spatial modal dispersion (SMD) for the coupled MCF at 1550 nm were approximately 0.155 dB/km, 113 μm^2, 20.2 μm and 7.1 ps/$\sqrt{\ }$km, respectively. The insertion losses for the fibre-bundled type fan-out (FO) devices for uncoupled MCF and lens-coupled type FOs for coupled MCF at 1550 nm ranged from 0.3 - 0.5 dB and 0.5 - 1.1 dB (including core and individual differences), respectively. In addition, the losses at one splice point were less than 0.4 dB for the uncoupled MCF and 0.1 dB for the coupled MCF. Therefore, in this experiment, the averaged total span losses were 10.1 dB for the uncoupled MCF and 11.7 dB including VODLs with a typical insertion loss of 1.0 dB for the coupled MCF. The core-to-core crosstalk for the uncoupled MCF with FO devices was suppressed to less than -57.3 dB/span due to the trench-assisted refractive index profile.

In the receiver, the transmitted WDM signals were detected by four digital coherent receivers based on heterodyne detection after channel selection with optical bandpass filters (OBPFs). The received electrical signals were digitized at 80 GSample/s using four real-time oscilloscopes. For the offline processing, the stored samples were processed by four adaptive 2×2 MIMO equalizers with 200 taps for uncoupled MCF transmission and an adaptive 8×8 MIMO equalizer with up to 600 taps for coupled MCF transmission. The MIMO tap coefficients were updated based on a decision-directed least-mean square (DD-LMS) algorithm [8]. After the symbols were decoded, the Q-factors were calculated.

Results and discussion

First, we measured the Q-factors as a function of

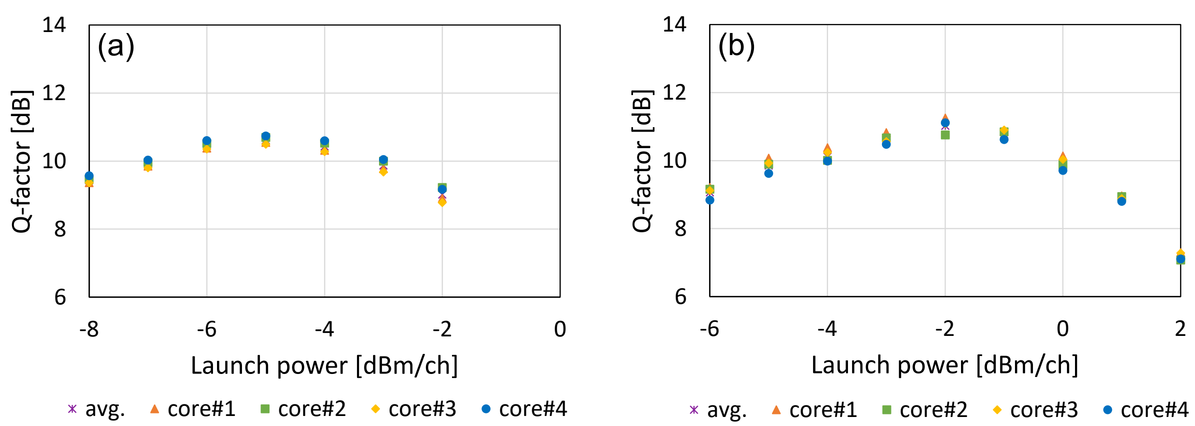


Fig. 2: The Q-factors as a function of the fibre launch power at 6,020-km transmission in (a) uncoupled MCF and (b) coupled MCF

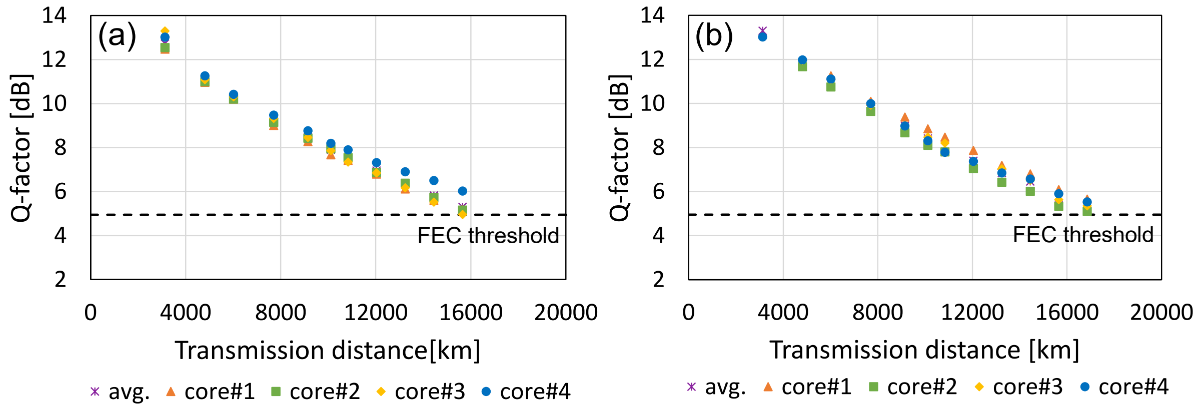


Fig. 3: The Q-factors as a function of the transmission distance in (a) uncoupled MCF and (b) coupled MCF

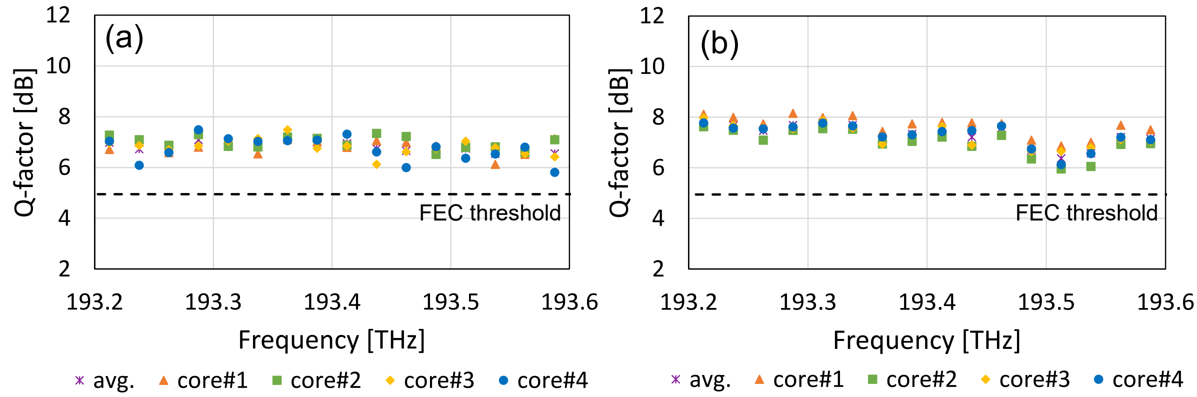


Fig. 4: The Q-factors for all 16-WDM channels at 12,040-km (a) uncoupled MCF and (b) coupled MCF transmissions.

the power per channel at 6,020-km transmission to determine the optimum fibre launch powers in the uncoupled MCF and the coupled MCF, as shown in Fig. 2. The highest Q-factors averaged among four cores were obtained at -5 dBm/ch for the uncoupled MCF and -2 dBm/ch for the coupled MCF. Figure 3 shows the Q-factors as a function of the transmission distance with the optimum fibre launch powers. After 15,652-km transmission in the uncoupled MCF and 16,856-km transmission in the coupled MCF, the Q-factors for all cores exceed the FEC threshold of 4.95 dB [7]. In the uncoupled MCF, compensation for the SMD and core-to-core crosstalk is not required unlike the coupled MCF, and, thus, ultra-long-haul transmission over 15,000 km was demonstrated using only the conventional 2×2 MIMOs with a relatively small number of taps. In the coupled MCF transmission, since the fibre launch power could be increased due to the better non-linear performance [9], the transmission distance could also be extended by approximately 10% compared to the uncoupled MCF. For further long-haul transmission, it is necessary to suppress the fusion splice losses for the uncoupled MCF and the insertion losses for FO devices for the coupled MCF to reduce the fibre span losses. Finally, we measured the Q-factors for all 16-WDM channels at 12,040-km uncoupled and coupled MCF transmissions to verify the channel dependence, as shown in Fig. 4. The average Q-factors between the four cores in the 16 channels ranged from 6.5 dB to 7.2 dB in the uncoupled MCF and 6.4 dB to 7.8 dB in the coupled MCF, and the differences in the Q-factors between the 16 channels were suppressed within ±0.7 dB in both fibres. The differences in the Q-factors between the four cores in each channel were less than 1.3 dB even after both MCF transmissions over 12,040 km.

Conclusions

We compared the ultra-long-haul MCF transmission performance of standard cladding ultra-low-loss uncoupled and coupled 4-core fibres. We confirmed the feasibility of 15,652-km transmission in uncoupled MCF and 16,856-km transmission in coupled MCF using a centre channel of 16-WDM 24-Gbaud DP-QPSK signals.

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