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# Transocoeanic-Class Transmission over Step-Index Profile Standard Cladding 4-Core Fibre with Bidirectional Transmission Technology

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**Abstract** *Transoceanic-class multi-core fibre bidirectional transmission is experimentally demonstrated using step-index profile standard cladding 4-core fibres without trench-assisted pure-silica cores for the first time. 4-SDM/16-WDM channels modulated with 24-Gbaud DP-QPSK are successfully transmitted over 7,000 km with no impact of core-to-core crosstalk. ©2022 The Author(s)*

## Introduction

Multi-core fibres (MCFs), a type of space-division multiplexing (SDM) technology, have been investigated to overcome the theoretical transmission capacity limitation in standard single-mode fibres (SMFs) [1]. In particular, MCFs with a 125-μm standard cladding diameter [2] are expected for early commercialization of SDM systems due to their high mechanical reliability and applicability to conventional optical terrestrial and submarine cable structures. Two types of weakly coupled MCFs have been proposed that have high compatibility with existing SMF systems because conventional transmitters and receivers can be applied: a step-index (SI) profile MCF (SI-MCF) [3-5] with a stepped refractive index profile similar to that of a standard SMF and a trench-assisted MCF (TA-MCF) [6] with a trench structure to suppress crosstalk (XT) between cores. Although SI-MCFs have a simple refractive index profile compared to TA-MCFs and can be expected to have superior manufacturability for mass production [3], the transmission distance is limited by the relatively large core-to-core XT. To suppress the degradation of the transmission performance due to core-to-core XT to achieve MCF long-haul transmission, bidirectional transmission technologies have been proposed [7-14]. However, to the best of our knowledge, long-haul transmission experiments using SI-MCFs with bidirectional transmission technology have not been reported thus far.

In this paper, we experimentally demonstrated transoceanic-class MCF transmission using standard cladding SI-type 4-core fibres (SI-4CFs) with bidirectional transmission technology for the first time. First, the $Q^2$-factors as a function of the fibre launch power were measured using the centre channel of 16-WDM 24-Gbaud dual-polarization quadrature phase shift keying (DP-QPSK) signals to clarify the tolerance to the nonlinear effects in the SI-4CFs. In addition, we compared the $Q^2$-factors as a function of the transmission distance in the unidirectional and bidirectional cases. Finally, we also measured the $Q^2$-factors for all 4-SDM/16-WDM channels after 7,000-km transmission.

## Step-index profile 4-core fibre

A cross-sectional image and the core number assignment of the SI-4CF [3-5] used in this experiment are shown in the inset of Fig. 1. The four cores were arranged in a square lattice. The transmission loss and core pitch for the SI-4CF at a wavelength of 1550 nm were approximately 0.19 dB/km and 40 μm, respectively. In this experiment, two SI-4CF spans were constructed. The first span (span#1) consisted of a single SI-4CF bobbin of 55.6 km, and the second span (span#2) consisted of six SI-4CF bobbins with fusion splices for a total of 52.1 km. Table 1 shows the span losses for each core in both SI-4CF spans, including the insertion loss of the fan-in (FI)/fan-out (FO) devices, at 1550 nm. In both spans, the span losses for the four cores were approximately 12 dB. In addition, the core-to-core XT characteristics in each span at 1550 nm are given in Table 2. Although the XT between adjacent cores was relatively high at

**Tab. 1:** Span losses at 1550 nm.

| Unit: dB | span#1 (55.6 km) | span#2 (52.1 km) |
|---|---|---|
| core#1 | 12.12 | 11.62 |
| core#2 | 11.96 | 11.90 |
| core#3 | 11.99 | 11.50 |
| core#4 | 11.84 | 11.19 |

**Tab. 2:** Core-to-core XT characteristics in each span at 1550 nm.

| span#1 Unit: dB | FO1 | FO2 | FO3 | FO4 |
|---|---|---|---|---|
| FI1 | - | -21.30 | -42.03 | -22.09 |
| FI2 | -20.93 | - | -20.36 | -41.54 |
| FI3 | -41.75 | -20.42 | - | -20.48 |
| FI4 | -22.16 | -42.05 | -20.65 | - |

| span#2 Unit: dB | FO1 | FO2 | FO3 | FO4 |
|---|---|---|---|---|
| FI1 | - | -19.49 | -39.27 | -19.76 |
| FI2 | -19.72 | - | -19.87 | -39.25 |
| FI3 | -39.52 | -20.14 | - | -19.63 |
| FI4 | -20.20 | -39.65 | -19.72 | - |

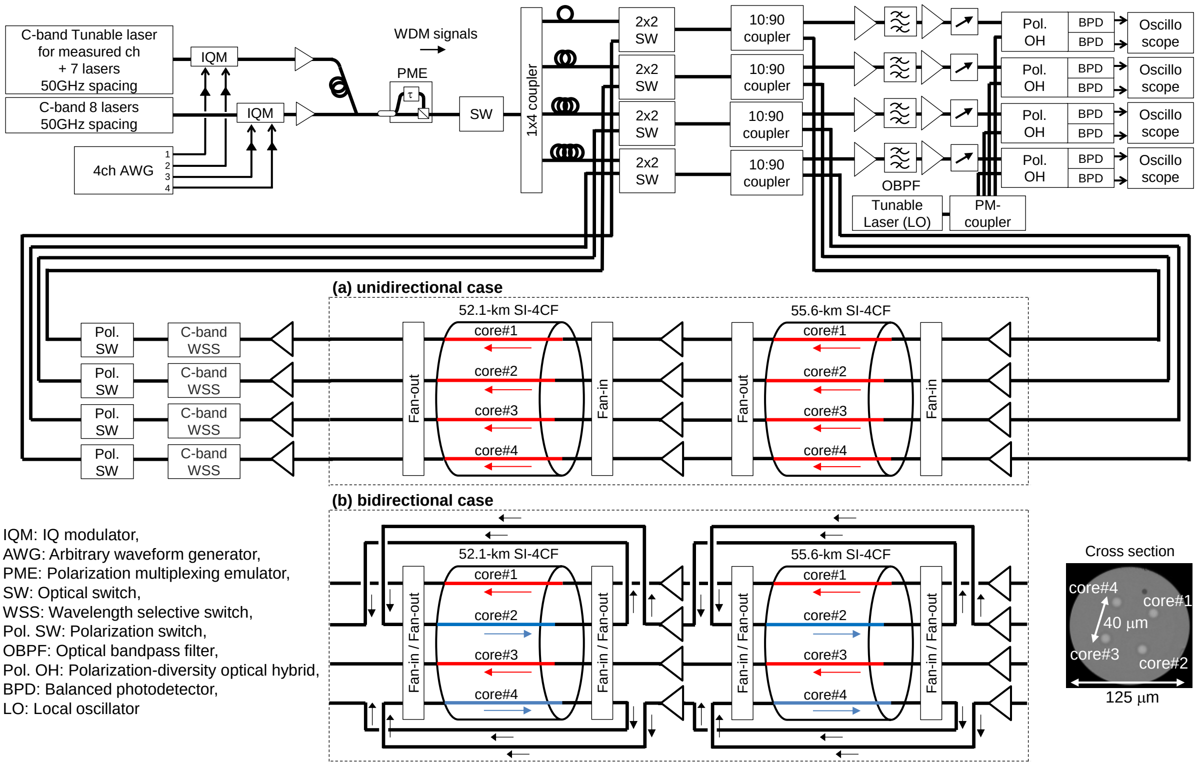


**Fig. 1:** Experimental setup.

approximately −20 dB, the XT between diagonal cores was suppressed to approximately −42 dB for span#1 and −39 dB for span#2. For the case of a square lattice core arrangement, the influence of XT between adjacent cores can be almost ignored for bidirectional transmission, in which signals propagate in different directions between adjacent cores. Thus, for this case, only XT between diagonal cores and XT from a diagonal core via adjacent cores [11] should be considered. Therefore, the transmission distance can be expected to be significantly extended by applying bidirectional transmission technology since the XT from the diagonal core of these SI-4CFs is well suppressed.

## Experimental setup

Figure 1 shows the experimental setup used for evaluating the long-haul transmission performance when using the SI-4CF, based on previous MCF transmission experiments [15-18]. For the transmitter, eight continuous wave (CW) lights were combined with a frequency spacing of 50 GHz for even and odd channels. The even and odd channels were independently modulated by 24-Gbaud Nyquist-shaped QPSK signals using a 4-channel arbitrary waveform generator (AWG) and two IQ modulators (IQMs). 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 [19].

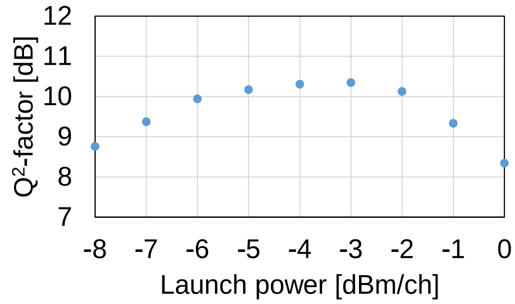


**Fig. 2:** $Q^2$-factors as a function of the fibre launch power after 3,015-km transmission.

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 two SI-4CF spans of 55.6 km and 52.1 km, C-band EDFAs and 2×2 optical switches (SWs). In the unidirectional case, the WDM signal propagated in the same direction in all cores using the transmission line shown in Fig. 1(a). In the bidirectional case, the WDM signal propagated in the opposite directions between the pair of core#1 and #3 and the pair of core#2 and #4, as shown in Fig. 1(b). The WDM signals after 2-span transmission were gain-equalized using four C-band wavelength-selective switches.

For 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). For offline processing, the stored samples were processed by four adaptive 2×2 multi-input multi-output (MIMO) equalizers with 250 taps. The

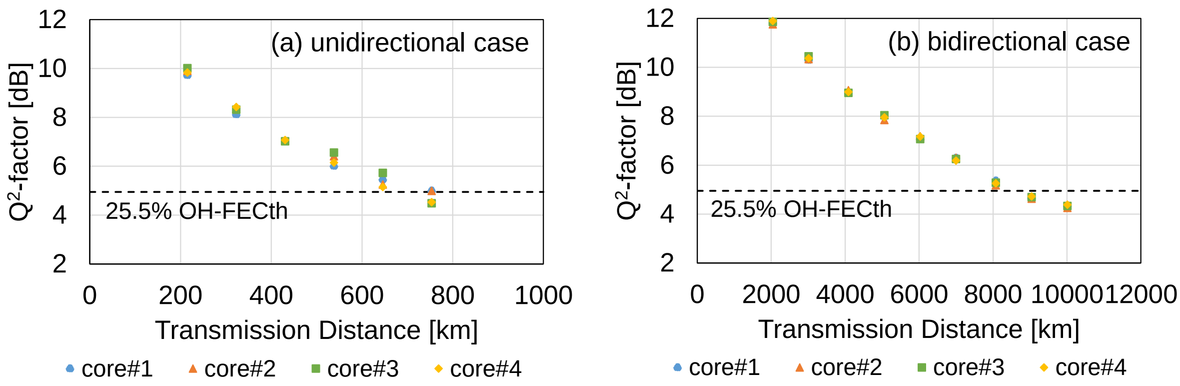


**Fig. 3:** $Q^2$-factors as a function of the transmission distance in the (a) unidirectional case and (b) bidirectional case.

MIMO tap coefficients were updated based on a decision-directed least-mean square (DD-LMS) algorithm [20]. After the symbols were decoded, the $Q^2$-factors were calculated.

## Experimental results

Figure 2 shows the $Q^2$-factors as a function of the power per channel after 3,015-km transmission using the centre channel of 16-WDM 24-Gbaud DP-QPSK signals from 1549.62 nm to 1552.62 nm, to determine the optimum fibre launch power in the SI-4CF. The launch power was defined as the power input to the FI devices. Here, only WDM signals were input to core#1 to avoid degradation of the transmission performance due to core-to-core XT. The highest $Q^2$-factor was obtained at −3 dBm/ch. Therefore, the signal power launched into each core of the SI-4CFs was adjusted to −3 dBm/ch in the following long-haul transmission experiments.

Figure 3 shows the $Q^2$-factors as a function of the transmission distance with the optimum fibre launch power in the (a) unidirectional case and (b) bidirectional case. In the unidirectional case, the $Q^2$-factors for the four cores exceeded the assumed FEC threshold of 4.95 dB [19] after 646 km transmission, although the transmission distance was limited by the XT between adjacent cores. In contrast, in the bidirectional case, the feasibility of 8,077-km transatlantic-class transmission was confirmed because no degradation due to direct XT from adjacent cores occurred.

Finally, to clarify the transmission potential of the SI-4CF across the C-band, the transmission performance was measured using WDM signals around the shorter, centre, and longer wavelengths of the C-band. Figure 4 shows the $Q^2$-factors for all 4-SDM/16-WDM channels after 7,000-km SI-4CF transmission at approximately (a) 1532 nm, (b) 1551 nm and (c) 1560 nm in the bidirectional case. For all measured SDM/WDM channels, $Q^2$-factors exceeding the assumed FEC threshold [19] were obtained. From the results obtained, transoceanic-class bidirectional

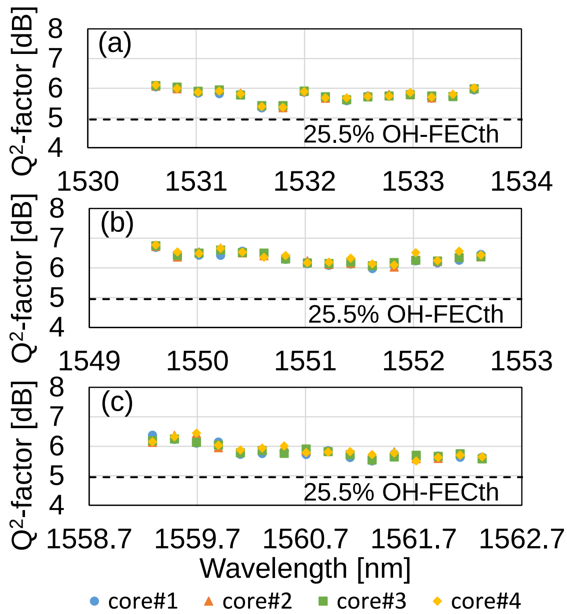


**Fig. 4:** $Q^2$-factors for all 4-SDM/16-WDM channels after 7,000-km transmission at approximately (a) 1532 nm, (b) 1551 nm and (c) 1560 nm in the bidirectional case.

transmission using SI-4CFs can be expected in the full C-band.

## Conclusions

Transoceanic-class SI-4CF transmission was experimentally demonstrated with bidirectional transmission technology for the first time. We confirmed the feasibility of 8,077-km transmission in the bidirectional case using the centre channel of 16-WDM 24-Gbaud DP-QPSK signals, expanding the transmission distance by more than 10 times compared to the unidirectional case. The $Q^2$-factors for all 4-SDM/16-WDM channels exceeded the assumed FEC limits after 7,000-km transmission with bidirectional transmission technology.

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## References


[1] R. -J. Essiambre, G. Kramer, P. J. Winzer G. J. Foschini, and B. Goebel, "Capacity Limits of Optical Fiber Networks," *Journal of Lightwave Technology*, vol. 28, Issue 4, pp. 662–701, 2010, DOI: 10.1109/JLT.2009.2039464.

[2] T. Matsui, T. Kobayashi, H. Kawahara, E. L. T. de Gabory, T. Nagashima, T. Nakanishi, S. Saitoh, Y. Amma, K. Maeda, S. Arai, R. Nagase, Y. Able, S. Aozasa, Y. Wakayama, H. Takeshita, T. Tsuritani, H. Ono, T. Sakamoto, I. Morita, Y. Miyamoto, and K. Nakajima, "118.5 Tbit/s Transmission over 316 km-Long Multi-Core Fiber with Standard Cladding Diameter," *Opto-Electronics and Communications Conference (OECC) and Photonics Global Conference (PGC) 2017*, Singapore, PDP2, 2017, DOI: 10.1109/OECC.2017.8115049.

[3] T. Matsui, T. Sakamoto, and K. Nakajima, "STEP-INDEX PROFILE MULTI-CORE FIBRE WITH STANDARD 125 μM CLADDING TO FULL-BAND APPLICATION," *45th European Conference on Optical Communication (ECOC2019)*, Dublin, Ireland, M.1.D.3, 2019, DOI: 10.1049/cp.2019.0751.

[4] D. Soma, S. Beppu, H. Takahashi, Y. Miyagawa, N. Yoshikane, and T. Tsuritani, "Optical Characterization of Installed Step-Index Profile Standard Cladding Multi-Core Fiber with Multiconnection," *26th Optoelectronics and Communications Conference (OECC) 2021*, Hong Kong, China, S4C.3, 2021, DOI: 10.1364/OECC.2021.S4C.3.

[5] Y. Sasaki, R. Fukumoto, K. Takenaga, S. Shimizu, and K. Aikawa, "Optical Fiber Cable Employing 200 μm-Coated Multicore Fibers for High Density Wiring in Datacom," *Optical Fiber Communication Conference (OFC) 2021*, San Francisco, USA, Tu6B.2, 2021, DOI: 10.1364/OFC.2021.Tu6B.2.

[6] M. Takahashi, K. Maeda, K. Aiso, K. Mukasa, R. Sugizaki, D. Soma, H. Takahashi, T. Tsuritani, M. Mitrovic, B. Pálsdóttir, and Y. Arashitani, "Uncoupled 4-core Fibre with Ultra-low Loss and Low Inter Core Crosstalk," *European Conference on Optical Communications (ECOC) 2020*, Brussels, Belgium, Th1A-5, 2020, DOI: 10.1109/ECOC48923.2020.9333161.

[7] T. Ito, E. L. T. de Gabory, M. Arikawa, Y. Hashimoto, and K. Fukuchi, "Reduction of Influence of Inter-core Cross-talk in MCF with Bidirectional Assignment between Neighboring Cores," *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference (OFC/NFOEC) 2013*, Anaheim, USA, OTh3K.2, 2013, DOI: 10.1364/OFC.2013.OTh3K.2.

[8] A. Sano, H. Takara, T. Kobayashi, and Y. Miyamoto, "Crosstalk-Managed High Capacity Long Haul Multicore Fiber Transmission With Propagation-Direction Interleaving," *Journal of Lightwave Technology*, vol. 32, Issue 16, pp. 2771–2779, 2014, DOI: 10.1109/JLT.2014.2320826.

[9] M. Arikawa, T. Ito, E. L. T. de Gabory, and K. Fukuchi, "Crosstalk Reduction With Bidirectional Signal Assignment on Square Lattice Structure 16-Core Fiber Over WDM Transmission for Gradual Upgrade of SMF-Based Lines," *Journal of Lightwave Technology*, vol. 34, Issue 8, pp. 1908–1915, 2016, DOI: 10.1109/JLT.2015.2509472.

[10] T. Hayashi, T. Nakanishi, K. Hirashima, O. Shimakawa, F. Sato, K. Koyama, A. Furuya, Y. Murakami, and T. Sasaki, "125-μm-cladding eight-core multi-core fiber realizing ultra-high-density cable suitable for O-Band short-reach optical interconnects," *Journal of Lightwave Technology*, vol. 34, Issue 1, pp. 85–92, 2016, DOI: 10.1109/JLT.2015.2470078.

[11] T. Hayashi, T. Nagashima, A. Inoue, H. Sakuma, T. Suganuma, and T. Hasegawa, "Uncoupled Multi-core Fiber Design for Practical Bidirectional Optical Communications," *Optical Fiber Communication Conference (OFC) 2022*, San Diego, USA, M1E.1, 2022.

[12] Y. Tamura, T. Hayashi, T. Nakanishi, and T. Hasegawa, "Low-Loss Uncoupled Two-Core Fiber for Power Efficient Practical Submarine Transmission," *Optical Fiber Communication Conference (OFC) 2019*, San Diego, USA, M1E.5, 2019, DOI: 10.1364/OFC.2019.M1E.5.

[13] T. Gonda, K. Imamura, and R. Sugizaki, "Multicore fiber for bi-directional transmission," *21st OptoElectronics and Communications Conference (OECC) held jointly with International Conference on Photonics in Switching (PS) 2016*, Niigata, Japan, MC1-3, 2016.

[14] F. Ye, and T. Morioka, "Interleaved Core Assignment for Bidirectional Transmission in Multi-Core Fibers," *39th European Conference and Exhibition on Optical Communication (ECOC2013)*, London, UK, We.2.D.5, 2020, DOI: 10.1049/cp.2013.1424.

[15] D. Soma, S. Beppu, H. Takahashi, N. Yoshikane, I. Morita, and T. Tsuritani, "Performance Comparison for Standard Cladding Ultra-Low-Loss Uncoupled and Coupled 4-Core Fibre Transmission over 15,000 km," *European Conference on Optical Communications (ECOC) 2020*, Brussels, Belgium, Mo2E.4, 2020, DOI: 10.1109/ECOC48923.2020.9333132.

[16] D. Soma, S. Beppu, Y. Wakayama, S. Sumita, H. Takahashi, N. Yoshikane, I. Morita, T. Tsuritani, and M. Suzuki, "50.47-Tbit/s Standard Cladding Ultra-Low-Loss Coupled 4-Core Fiber Transmission over 9,150 km," *Optical Fiber Communication Conference (OFC) 2021*, San Francisco, USA, W7D.3, 2021, DOI: 10.1364/OFC.2021.W7D.3.

[17] D. Soma, S. Beppu, Y. Wakayama, S. Sumita, H. Takahashi, N. Yoshikane, I. Morita, T. Tsuritani, and M. Suzuki, "50.47-Tbit/s Standard Cladding Coupled 4-Core Fiber Transmission over 9,150 km," *Journal of Lightwave Technology*, Vol. 39, Issue 22, pp. 7099–7105, 2021, DOI: 10.1109/JLT.2021.3109890.

[18] D. Soma, S. Beppu, Y. Wakayama, S. Sumita, H. Takahashi, N. Yoshikane, I. Morita, T. Tsuritani, and M. Suzuki, "Trans-Pacific class transmission over a standard cladding ultralow-loss 4-core fiber," *Optics Express*, Vol. 30, Issue 6, pp. 9482–9493, 2022, DOI: 10.1364/OE.453597.

[19] K. Sugihara, Y. Miyata, T. Sugihara, K. Kubo, H. Yoshida, W. Matsumoto, and T. Mizuochi, "A Spatially-coupled Type LDPC Code with an NCG of 12 dB for Optical Transmission beyond 100 Gb/s," *Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC) 2013*, Anaheim, USA, OM2B.4, 2013, DOI: 10.1364/OFC.2013.OM2B.4.

[20] Y. Mori, C. Zhang, and K. Kikuchi, "Novel FIR-Filter Configuration Tolerant to Fast Phase Fluctuations in Digital Coherent Receivers for Higher-order QAM signals," *Optical Fiber Communication Conference (OFC) 2012*, Los Angeles, USA, OTh4C.4, 2012, DOI: 10.1364/OFC.2012.OTh4C.4.