Experimental Verification on Digital Back Propagation Gain in MCF transmission over 6020-km Uncoupled and Coupled 4-Core Fibres

Shohei Beppu, Daiki Soma, Hidenori Takahashi, Noboru Yoshikane, Itsuro Morita and Takehiro Tsuritani

KDDI Research, Inc., sh-beppu@kddi-research.jp

Abstract We experimentally verify the nonlinear compensation gain of digital back propagation in ultra-long-haul 4-core fibre transmissions over 6020 km. The gain was 1.1 dB in the uncoupled core transmission. By contrast, this gain was not observed in the coupled core transmission with spatial modal dispersion.

Introduction

The exponential growth of communication traffic has made it necessary to further increase the capacity of long-haul submarine optical transmission systems. The cable capacity has been increased by increasing the number of fibre pairs and introducing pump sharing, which is called the first step of space division multiplexing [1]. Currently, a commercialisation of 16-fibre-pair cable is planned [2]. For further increase of the capacity, development of SDMs utilising multi-core and multi-mode fibres will also be required. To design the SDM systems, the capacity per cost maximisation under power constraints has been actively discussed [3,4]. Specifically, 125-μm cladding of multi-core fibres (MCFs) has attracted attention because the conventional cabling and splicing technologies for existing single mode fibres can be applied [5]. The fabrications and long-haul transmission experiments utilising 125-μm cladding uncoupled-core (UC) and coupled-core (CC-) MCFs has been reported [5-7]. In UC-MCFs, for the sake of maximising transmission capacity, a low loss UC-4CF has been proposed whose transmission loss is around 0.17 dB/km [8]. The UC-4CF consists of 4 pure silica cores with a depressed cladding structure and 44-μm spacing to reduce the inter-core XTs to -46 dB per 100km even at the expense of the smaller effective area (A_{eff}) of 88 μm^2 (i.e., highly nonlinear). For further increase of the transmission capacity in UC-MCFs with smaller A_{eff}, the adaptation of digital nonlinear compensation (NLC), such as the digital back propagation (DBP) [9] and experimental verification of the NLC gain is significant [10-12]. To date, the NLC gain in ultra-long-haul UC-MCF transmissions have not been verified. On the other hand, in CC-MCFs, the ultra-long-haul transmission experiments utilising CC-4CF with the low loss of around 0.16 dB/km has been reported [7]. The CC-4CF consists of 4 pure silica cores and the core pitch was optimized to be 20 μm for mitigating modal dispersion by intentional strong inter-core coupling. Moreover, the low nonlinearity due to larger apparent A_{eff} originating from strong inter-core coupling [13] was also verified. To further mitigate the nonlinearity in CC-MCFs, the strong coupling DBP (SC-DBP) based on the coupled Manakov equation has been proposed and the NLC gain was clarified by numerical simulations [14]. Ref. [14], shows that for the CC-MCFs with sufficiently large intermodal coupling, the NLC gain decreases with increasing spatial modal dispersion (SMD) because the SC-DBP is derived from the coupled Manakov equation, in which it is assumed that spatial modes propagate with similar group delay. However, the extent to which the SC-DBP gain can be obtained in long-haul transmission experiments in the presence of SMD has not been verified.

In this paper, we verify the NLC gain of DBP in ultra-long-haul multi-core fibre transmission experiments, with utilising 125-μm cladding UC and CC-MCF having 4-pure-SiO_2 cores. The gain was 1.1 dB in the uncoupled core. By contrast, this gain was not observed in the coupled core in the presence of large SMD.

Experimental setup

Figure 1 shows the experimental setup. In the transmitter, a 25 GHz-spaced 16-channel WDM 24-Gbaud Nyquist-shaped QPSK signal at 1550 μm was generated by an even/odd de-corelation method utilising a 4-channel arbitrary waveform generator (AWG) and two IQ modulators (IQMs). The WDM signal was split into 4 paths with a relative delay of 200 ns between subsequent paths for decorrelation and these paths were fed into a re-circulating loop system consisting of four spans of 60.2-km UC or CC-4CF, C-band EDFAs and 2x2 optical switches (SWs). The WDM signals after 4-span transmission were gain-equalised using two 2-channel C-band wavelength-selective switches (WSSs). In the CC-4CF transmission, the skew between 4 cores was compensated for each span by variable optical delay lines (VODLs).

Table 1 shows parameters of our transmission link that consist of UC or CC-4CF. Specifically, the UC-4CF has a larger nonlinear coefficient γ of 1.0 W/km compared with the 0.8 W/km in the CC-4CF. Here, γ was calculated from A_{eff} assuming a typical nonlinear refractive index of 2.2×10^{-2} m^2/W in pure-SiO_2 cores. The SMD of CC-4CF is supressed as small as 7.1 ps/√km thanks to the strong inter-core coupling.

In the receiver, the transmitted WDM signal was demultiplexed into 4 signals by a fan-out (FO) device. The centre channel was extracted by optical bandpass filters (OBPFs) and detected by digital coherent receivers based on heterodyne detection. The electrical signals received were digitised at 80 GSample/s using 4 real-time oscilloscopes and sent to an offline digital signal processor (DSP). In the DSP, the received signals were converted to a base band, and a frequency offset was compensated. After a Nyquist filtering, the signals were resampled to 2 Sa/symbols. For the UC-4CF transmission, a UC-DBP and a 2x2 MIMO in each core was applied. Here, UC-DBP is same as a conventional DBP for a single mode fibre [10-12]. However, for the CC-4CF transmission, an SC-DBP [14] and an 8x8 MIMO was applied. After DBP and MIMO equalisation, effective SNRs of the equalised signals were calculated and averaged over 4 cores and 2 polarizations.

In the UC or SC-DBP, complex electrical fields were propagated over a virtual fibre link whose fibre parameters (i.e., loss, chromatic dispersion and nonlinear coefficient) was of a sign opositte to the actual parameters, by solving the uncoupled or coupled Manakov equation utilising the split-step Fourier method. To maximise the DBP gain, the virtual nonlinear coefficient, γ_{DBP}, was swept and optimised as shown in the following section.

Results and discussion

First, we measured an impulse response by MIMO processing and evaluated an overall SMD of the CC-4CF transmission system as shown in Figure 2. Figure 2(a) shows an intensity of impulse response $|h|^2$ and its Gaussian fitting after a 6020-km transmission. The SMD was evaluated as the $\pm\sigma$ of the Gaussian fitting of $|h|^2$ [15]. Figure 2(b) shows the dependence of SMD on transmission distance, along with a square root fit. The SMD coefficient was 18 ps/√km and larger than expected from Table 1 since the imperfection of skew adjustment

Tab. 1: The parameters of the transmission link consists of UC or CC-4CF

	UC-4CF	CC-4CF
Span length	60.2 km	60.2 km
Core	Pure-SiO_2	Pure-SiO_2
Transmission loss	0.156 dB/km (core-ave.)	0.155 dB/km (core-ave.)
A_{eff}	87 μm^2	113 μm^2
γ	1.0 W/km	0.8 W/km
Maximum inter-core XT	-57.3 dB/span	N/A
SMD of fibre	< 0.1 ps/√km (PMD)	7.1 ps/√km
Loss of FIFO	≤ 0.5 dB	≤ 1.1 dB
Loss per splice	< 0.4 dB	< 0.1 dB
Loss of VODL	N/A	1.0 dB
Span loss	10.1 dB	11.7 dB

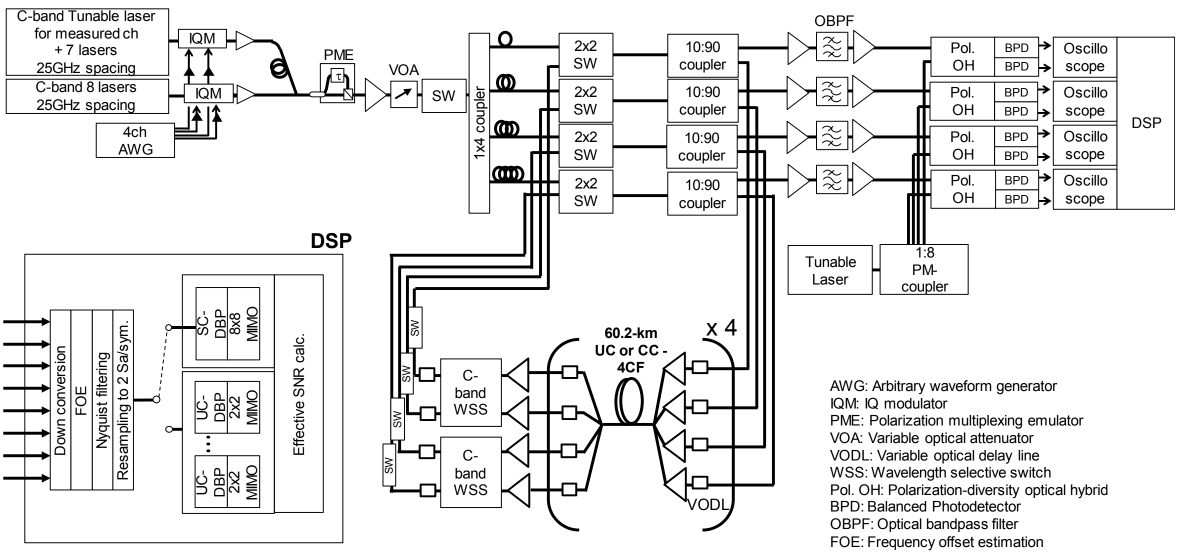

Fig. 1: Experimental setup

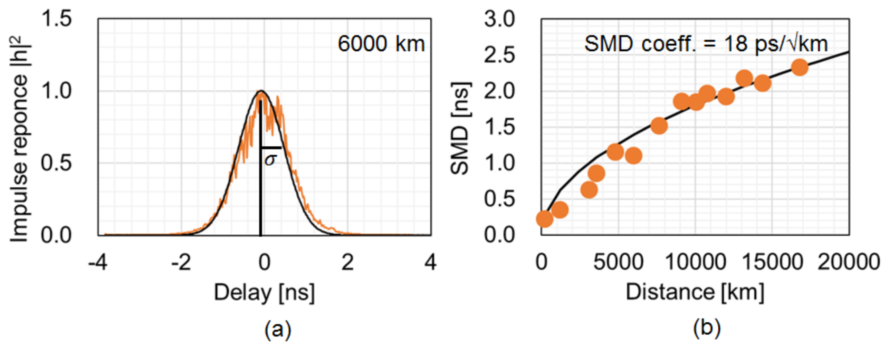

Fig. 2: (a) Intensity of impulse response after 6020 km CC-4CF transmission and the Gaussian fit (black line). (b) Evolution of the SMD as a function of distance, along with a square root fit (black line).

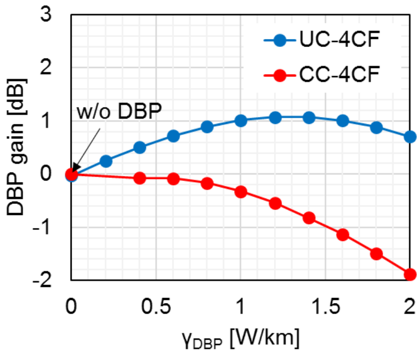

Fig. 3: Dependence of DBP gain on the virtual nonlinear coefficient γ_{DBP} after 6020-km UC or CC-4CF transmission.

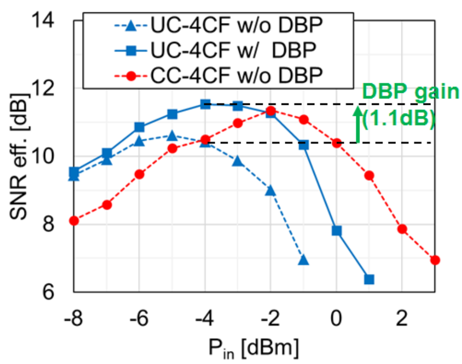

Fig. 4: Effective SNR as a function of fibre launch power after 6020-km CC-4CF and UC-4CF transmission with or without digital back propagation.

between 4 cores was also included. Figure 3 shows the dependence of DBP gain on the virtual nonlinear coefficient γ_{DBP} after 6020-km transmission using UC-4CF at a launch power of -4 dBm and CC-4CF at a launch power of -2 dBm, respectively. Here, the DBP gain was defined as the difference of effective SNR at the centre wavelength before and after the DBP. In the UC-4CF, the UC-DBP gain of 1.1 dB was obtained when γ_{DBP} = 1.2, which is similar to the actual γ of 1.0. However, in the CC-4CF, no gain was observed although γ_{DBP} has been swept up to 2.0. It would be caused by the existence of the non-negligible SMD coefficient of 18 ps/√km since the SC-DBP gain has been significantly reduced as SMD is increasing and limited to 0.5 dB even in the SMD coefficient of 3 ps/√km after 245-km transmission [14]. Figure 4 shows the effective SNR at the centre wavelength as a function of fibre launch power after 6020-km CC-4CF and UC-4CF transmission. The dotted line and solid line are with or without DBP, respectively. In the CC-4CF, the effective SNR was 11.3 dB at the optimum launch power of -2 dBm whereas the effective SNR was 10.6 dB in the UC-4CF at the optimum launch power of -5 dBm without UC-DBP. By adaption of the UC-DBP to UC-4CF transmission, the optimum launch power was increased from -5 to -4 dBm and the effective SNR was improved to 11.5 dB, which results in 0.2 dB exhibiting better effective SNR than the CC-4CF. In this comparison, the span loss of the CC-4CF was larger than the UC-4CF as shown in Table 1. Therefore, there is room to overcome the UC-4CF assisted by the UC-DBP by further reduction of span loss in CC-4CF.

Conclusions

We verified the nonlinear compensation gain of digital back propagation experimentally in ultra-long-haul 4-core fibre transmission over 6020 km. The gain was 1.1 dB in the uncoupled core transmission. By contrast, this gain was not observed in the coupled core transmission in the presence of large SMD.

Acknowledgments

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