

First Experimental Demonstration of Cross-SDM/WDM Q-difference Compensation at Multicore Fiber Transmission

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Abstract: The Q-difference compensation scheme among SDM/WDM signals is evaluated at 192-km 4-core-path MCF transmission line. The Q-difference is mitigated within 0.1 dB and the Q-factor of the worst quality signal is improved as 0.7 dB.

1. Introduction

Nowadays, the requirement for higher capacity optical fiber communication systems is increased steadily. To support the demand, the space-division-multiplexing (SDM) technologies are fiercely researched for the next generation transmission systems [1-9]. Especially, the uncoupled-core multicore fiber (UC-MCF) is considered as the first possible candidate because of the compatibility of current single-core single-mode fiber (SMF) [1-6,8]. For example, 118.5-Tbit/s transmission has been reported over 316 km-long 4-core MCF with the standard cladding diameter using the uncoupled type [1]. However, the signal quality difference between SDM signals is concerned because the multicore optical device/module doesn't necessarily have an individual core-by-core capability such as cladding-pumped-uncoupled-core multicore erbium-doped fiber amplifier (CP-MC-EDFA) [7]. It means that the lowest quality signal limits the system performance such as reachable distance. To address this problem, the core-to-core Q-difference compensation scheme in vector domain has been proposed to equalize SDM signal qualities without using adaptive multi-input-multi-output (MIMO) equalizer [8,9]. It was successfully confirmed to compensate Q-difference between same wavelength signals at MCF transmission line repeated by CP-MC-EDFA [8]. The feature of this scheme is the utilization of high SNR signals to improve worse signal quality. But still, the SDM system with wavelength-division-multiplexing (WDM), these better and worse signals are not necessarily on same wavelength among multiple cores. From this point of view, the cross-SDM/WDM compensation scheme is required. So, in this paper, the first demonstration of cross-SDM/WDM signal Q-difference compensation is described. It is confirmed that the Q-difference is mitigated within 0.2 dB and the Q-factor of the worst quality signal is improved as 0.7 dB after 192-km MCF transmission.

2. Principle of cross-SDM/WDM Q-difference compensation scheme in vector domain

Figure 1 shows the principle of cross-SDM/WDM Q-difference compensation scheme. The basics of the scheme is described in ref. [8,9]. For a system with the total SDM/WDM signal number, N, the ultimate size of transfer function can be N x N. However, considering the implementation of near-future transponder, the practical size of 2-signal and 4-signal cases are shown in Fig. 1a and 1b, respectively. At the transmitter, the waveforms of 2 or 4 baseband signals are combined by the 2x2 or 4x4 transfer function H_{TX} in vector domain, and then the H_{TX} generates 2 or 4 converted signals. These converted signals are assigned to any SDM/WDM signals at core# k to n and wavelength λ# p to s, respectively. After the transmission, these transmitted signals are put in the inverse-transfer function, H_{TX}^{-1}. After that, the H_{TX}^{-1} recovers original 2 or 4 baseband signals. Note that the noise element imposed at transmission line haven't been applied H_{TX} in advance, therefore the noise element distributes all recovered signals by H_{TX}^{-1} equally. With this effect, the all of recovered signals can have same averaged signal-to-noise ratio (SNR) which means the signal quality shown as Q-factor is improved for the worse quality signals. The point of this scheme is that it is possible to choose any signal combination from all of SDM/WDM signals.

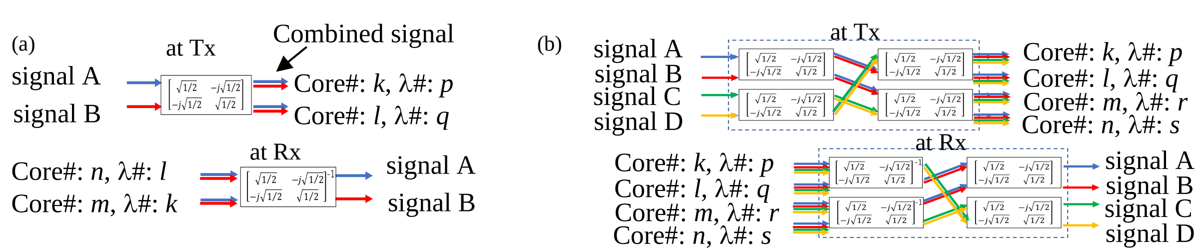

Fig. 1. The principle of cross-SDM/WDM Q-difference compensation scheme, a) for 2 signals, b) for 4 signals.

3. Experimental setup for cross-SDM/WDM compensation scheme for 192-km MCF transmission

Figure 2 shows the experimental setup to evaluate cross-SDM/WDM Q-difference compensation scheme at 192-km UC-MCF transmission line repeatered by CP-MC-EDFA. The transmitter (Tx) configuration is described at the left side of Fig. 2, similar to ref. [9]. In this figure, 4x4 case is explained. Firstly, 3 continuous wave (CW) lights with different wavelengths generated from fiber laser #1, fiber laser #2 and tunable external cavity laser (ECL) are multiplexed by 4x1 coupler. These CW lights are modulated by an optical vector IQ modulator (IQ Mod) with a baseband signal from an arbitrary waveform generator (AWG). The waveform data of the baseband signal is generated as shown in left top of Fig. 2. The 4 original signals (A to D) are modulated as the orthogonal-frequency-division-multiplexing (OFDM) signals. The OFDM innately uses block processing in the time/frequency domain and is synchronized by the training symbol; therefore, it is easy to apply the H_{TX4}^{-1} to the received signals with appropriate timing. The used IFFT/FFT size is 1024, from which 600 subcarriers carry data with 16QAM subcarrier modulation. Some overheads are utilized and considered for the polarization-division multiplexing (PDM) and demodulation, such as 0.98% for the cyclic-prefix, 6% for three training symbols (TSs) insertion every 50 data symbols as 5.43-μs interval and 25.5% for the assumed forward-error correction. The nominal and net bit-rate are 46.8 Gbit/s and 34.8 Gbit/s, respectively. Next, these 4 original signals are converted to 4 combined signals by H_{TX4}, excepting TSs. Then, these 4 combined signals are aligned serially. The 10-GSample/s AWG generates I & Q electrical signals, which is put into the IQ modulator for creating the optical WDM signals. The optical signal is converted as PDM signal by the PDM emulator (PDM Emu.) with 103.4 ns delay between two polarizations. The optical signals and amplified spontaneous emission comb (ASE Comb) which is used as dummy signals with 50-comb in the C-band with 25-GHz-bandwidth. The signal is separated into four and the delay time is differentiated by optical delay line. With 5.43-μs difference each other, 4 different signals are aligned in parallel virtually. Note that there are three WDM signals at each core.

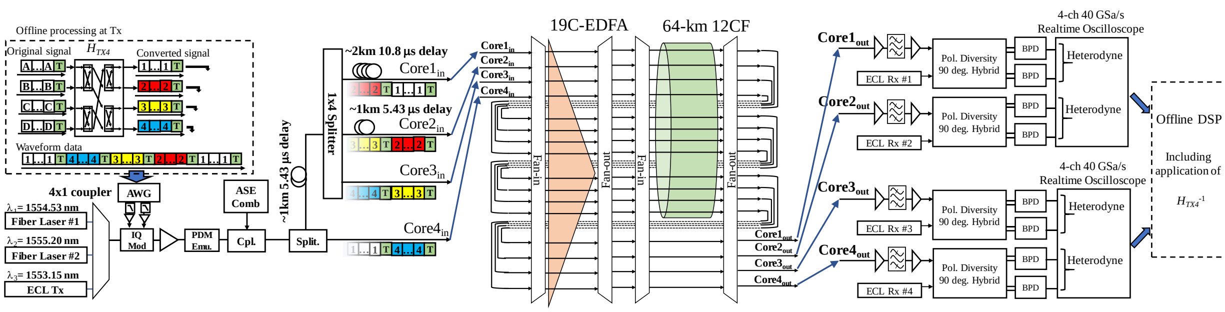

Fig. 2. Experimental setup to evaluate cross-SDM/WDM Q-difference compensation scheme at 192-km UC-MCF transmission line repeatered by CP-MC-EDFA.

The line has 4 individual core-paths which are composed of a 12-core fiber (12CF) repeatered by a cladding-pumped 19-core erbium-doped fiber amplifier (CP-19C-EDFA). The fiber length is 64 km, and the details of 12CF and CP-19C-EDFA are described in Ref. [6,9]. The average attenuation, mode-field diameter, crosstalk and core-pitch of 12CF are 0.218 dB/km, 9.8 μm, -54.9 dB/100km and 44 μm, respectively. The insertion loss of each 12 core varies from 14.2 to 17.1 dB. The four-core group of CP-19C-EDFA and 12CF are connected sequentially. This set is repeated as 3 spans, so the transmission distance becomes 192 km with 4 individual core-paths. The total output power of each core of CP-19C-EDFA varies from 15.6 to 17.1 dBm with the total input power of -2.5 dBm at the input of each core-path. At the receiver, these four signals are received by heterodyne detection individually. The wavelength of ECL Rx#1 to #4 at Rx is set to select one of WDM signals. These optical signals are received in 8 channels by 2 synchronized digital real-time oscilloscopes with 40 GSample/s. These recorded baseband signals are demodulated offline. After cancelling out the phase noise, the PDM signal is separated into each polarization signal individually. After the application of the H_{TX}^{-1}, the original signals (A to D) are recovered. Finally, these signals are demodulated.

4. Experimental results

Figure 3 shows the experimental result of cross-SDM/WDM Q-difference compensation at back-to-back (B2B) condition. Each Fig. 3a and 3b also shows its SDM/WDM signal matrix. The lambda (λ) #1 to #4 mean the center wavelength of signal as 1537, 1545, 1554.52 and 1555.2 nm, respectively, while the core (co) #1 to #4 express the core-paths. The orange circle markers and blue diamond markers express Q-factors with/without this compensation scheme. In this cases, 4 cross-SDM/WDM scheme is applied. In both cases, the Q-difference ΔQ is mitigated within 0.1 dB at both cases. The improvement of the worst signal qualities are 2.6 dB and 0.9 dB, respectively. Note that the

IQ imbalance is optimized for 1554.52 nm, therefore the far position such as 1537 nm shows worse signal quality. In other words, this scheme is also applicable to mitigate the degradation of caused by IQ imbalance.

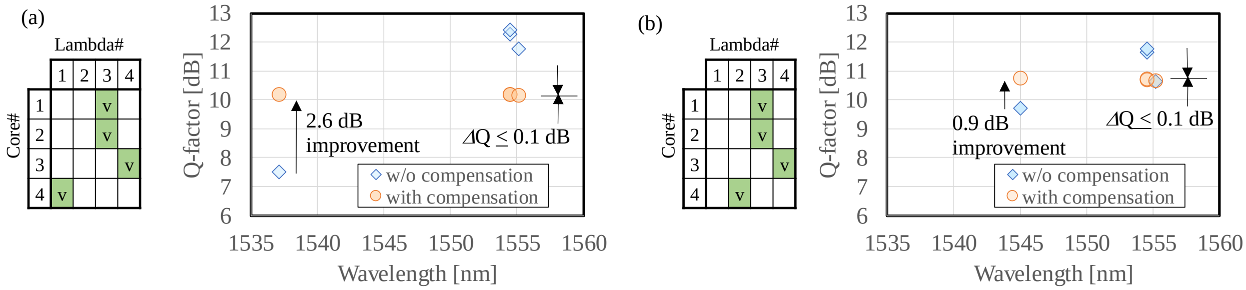

Fig. 3. Experimental results of cross-SDM/WDM Q-difference compensation scheme at back-to-back condition.

Next, this compensation scheme is evaluated with the MCF transmission experiment. Note that 2 cross-SDM/WDM scheme is used for all cases. The optical spectrum of core-path#1 after 192-km transmission is shown in Fig. 4a. The optical SNR (OSNR) degrades from 1555 nm to 1537 nm. Firstly, signal1 is fixed at core#1 with λ#3 (1554.52 nm), and the center wavelength of signal2 in core#2 is varied using tunable ECL. As shown in Fig. 4b, the Q-difference is mitigated within 0.1 dB at all cases. The 1545 nm of signal2 gives wider Q-difference caused by OSNR reduction. The Q-improvement of 0.5 dB is observed. Next, three cases of SDM/WDM signal combination is evaluated. The core# of signal2 is different at the case#1 and #2 with same λ#2, and the core# of signal1 is varied at the case#2 and #3 with same λ#3, respectively. The point is that which combination gives higher system performance. In these cases, the signal combination at core#1 with λ#3 and at core#3 with λ#2 is the best choice in terms of the improvement of the lowest quality signal. Regarding the larger signal number compensation described above, this result indicates that optimization of signal combination chosen from all of SDM/WDM signals will be important.

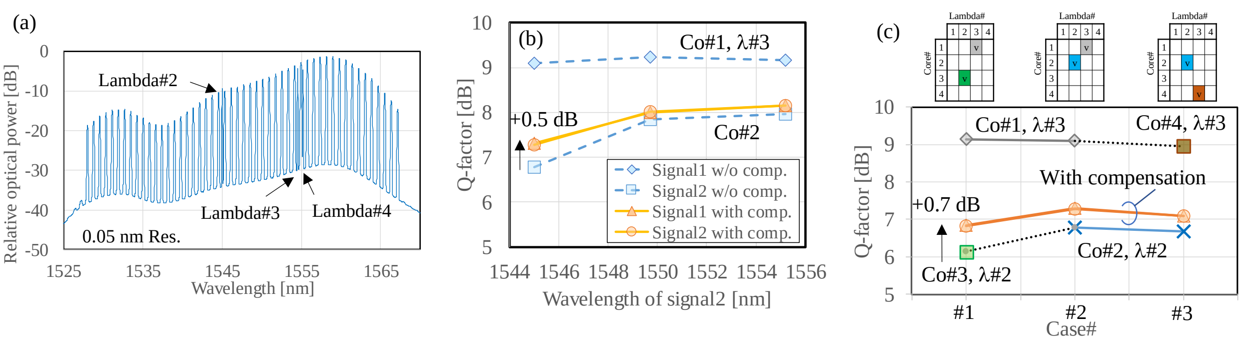

Fig. 4. Experimental results of cross-SDM/WDM Q-difference compensation scheme for 192-km MCF transmission, a) an optical spectrum of core-path#1 after 192-km transmission, b) Wavelength dependency of Q-factor with/without application of the scheme after 192-km MCF transmission, c) SDM/WDM signal combination cases and compensation results.

Conclusions

The cross-SDM/WDM signal Q-difference compensation scheme is evaluated with UC-MCF transmission line with CP-MC-EDFA amplification for the first time. The Q-difference mitigation of within 0.1 dB is confirmed, additionally, 2.6 dB and 0.7 dB Q-improvements are observed with 4-signal and 2-signal cases at B2B and after 192-km transmission, respectively. Finally, it is indicated that the optimization of signal combination will be required to maximize the system performance.

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References

[1] T. Mizuno et al, J. Lightw. Technol., vol. 34, No. 6, pp1484-1493 (2016)
[2] T. Matsui et al, Proc. the 22nd OECC2017, no. PDP, 2, 2017.
[3] S. Chandrasekhar, et al, ECOC2011, Sep. 2011, PDP, No. Th.13.C.4.
[4] A. Turukhin et al, ECOC2016, no. Tu.1.D.3, 2016.
[5] B. Puttnam et al, ECOC2019, Tu.1.A.1, 2019.
[6] D. Soma et al., ECOC2018, Mo3G2, 2018.
[7] S. Takasaka et al, OFC2018, Th1K.2, 2018.
[8] H. Takahashi et al, ECOC2018, Th1F.6, 2018.
[9] H. Takahashi et al, ECOC2019, P40, 2019.