Transmission capacity expansion using bidirectional multicore EDFA under bidirectional signal assignment

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Abstract: Bidirectionally cladding pumped multicore EDFA was found to have 13 and 7 points advantages in optical reachability and transmission capacity expansion, respectively, compared with unidirectional one under bidirectional signal assignment condition.

1. Introduction

Special division multiplexing (SDM) technology is promising to meet the demand for increasing communication capacity over the next decade [1-5]. We focus on amplification technology and have been researching a way to develop an efficient multicore erbium doped fiber amplifier (MC-EDFA) using cladding pumping [6,7], which has a unique feature of batch bidirectional amplification of many cores [8,9]. Uncoupled multicore fiber (UC-MCF) is used for the bidirectional transmission by a single fiber, which is called a bidirectional signal assignment scheme (BSA). BSA enables extension of the optical reachability because the inter-core crosstalk (IC-XT) can be suppressed [10,11]. The IC-XT suppression effect by so far is mainly due to the MCF used for transmission line [12-14]. Reference [15] presents that effect due to a single unidirectionally (UD) cladding pumped MC-EDFA alone. For the repeated long-haul transmission systems such as submarine optical cable, IC-XT due to multi-span connected MC-EDFA using MC-EDF, must also be studied. At a fixed transmission distance, the IC-XT suppression contributes to the capacity expansion of the transmission system [16]. As is well known, the optical reachability of repeated transmission systems depends on the operation condition of EDFA such as gain and noise figure (NF). Here, both optical gain and NF depends on the pump direction [17,18]. The pump direction of cladding pump is identical for all cores. When BSA is applied, the direction of some signal propagation in some cores becomes opposite to pump direction, resulting in the presence of both forward and backward pumped cores in the MC-EDF. The possible transmission distance as a MCF could be limited by cores of backward pumped which NF is larger than forward pumped cores. This limitation spoils the merit of BSA. Therefore, optical reachability could differ for each core in a single MCF when BSA is used with cladding pumped MC-EDFA. Our developed bidirectionally (BD) cladding pumped MC-EDFA can solve this problem because BD-MC-EDFA has identical gain and NF used together with BSA [9].

In this study, we investigated the advantage of the BD-MC-EDFA on transmission capacity expandability through the possible transmission distance evaluation when signal assignment was both uni and bidirectional. The IC-XT suppression effect due to the BD-MC-EDFA was clarified which has not been sufficiently studied yet. From experimental results, we have found 13 points longer transmission distance than the conventional UD-MC-EDFA when BSA is applied. By using Shannon's theorem [16], its advantage is translated into 7 points increase in transmission capacity expandability under the transmission conditions in this research.

2. Experimental set-up for the investigation of the possible transmission distance

Fig. 1 shows the experimental setup to investigate the possible transmission distance for both USA and BSA. Transmission signal was an eight-wavelength multiplexed (WDM) signals of ITU-T compliant. It consisted of one

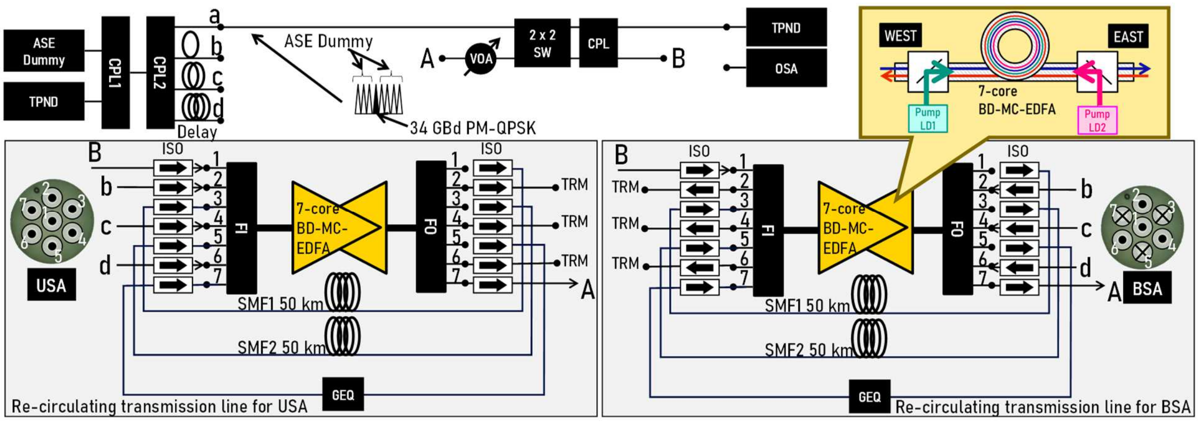

Fig. 1. Experimental set-up of re-circulating transmission line for the optical reachability evaluation

34-GBd polarization multiplexed quadrature phase shift keying (PM-QPSK) modulated signal from a transponder (TPND) and seven dummy signals shaped from amplified spontaneous emission (ASE) light by using wavelength selective switch. This eight-channels WDM signal was split by four and each was de-correlated by using 0.2-, 0.4- and 0.6 km-long single mode single core fiber (SMF) as optical delay. WDM signal “a” shown in Fig.1 was input into the re-circulating transmission line. The WDM signal is introduced into core 1, which is the center core of 7-core BD-MC-EDFA through FI. Insertion loss and IC-XT of the FIFO is 1 and -40 dB/pair, respectively. The WDM signal propagates the MC-EDFA core 1 and is input into 50 km-long SMF1 that had transmission loss of 0.18 dB/km. Then SMF1 output was input into core 3. In the same way, core 3 output of the EDFA propagates SMF2. Intensity of each the eight wavelength channels of core 5 output of the BD-MC-EDFA was equalized by using gain equalizer (GEQ). For cores 2, 4 and 6 of the BD-MC-EDFA, the WDM signal of “b”, “c”, and “d” was input as IC-XT source light, respectively. In the case of BSA, the propagation direction of “b”, “c”, and “d” was reversed together with the isolators (ISO). Core pitch and outer cladding diameter of the MC-EDF was 38.5 and 135 μm, respectively. Its length of 8 meters was an optimization result to obtain as large as possible gain. Core 7 output of the BD-MC-EDFA was introduced into TPND synchronized with the 2×2 loop switch, and bit error rate (BER) of the transmission signal was measured in real-time. An optical spectrum analyzer (OSA) was used to measure the IC-XT component and optical signal to noise ratio (OSNR). The transmission distance per lap was two spans of 50-km long SMF (100 km), and the number of BD-MC-EDFA passages was four. The IC-XT source was limited to the 7-core BD-MC-EDFA and FIFO since SMF was used for transmission fiber. The BD-MC-EDFA was operated under fixed gain conditions of 10 dB to balance the SMF and FIFO propagation losses. The launch optical power to the transmission line was adjusted to provide the operating conditions for linear transmission to avoid non-linear optical impairment.

3. Influence of inter-core crosstalk on the possible transmission distance in 7-core BD-MC-EDFA

First, the impact of IC-XT due to the BD-MC-EDFA including FIFO was studied. The launch optical power was 1 dBm/core. The BD-MC-EDFA was operated under forward (FW) pumping operation mode with 19.8 W pump. Transmission distance of 2,000 km was equivalent to 20 laps of re-circulation and 80 passages of the 7-core BD-MC-EDFA. The wavelength channel of 1564.88 nm was only input into cores 2, 4 and 6 of the BD-MC-EDFA. Therefore, IC-XT component at wavelength of 1564.68 nm from core 2, core 4 and core 6 to core 1 due to the BD-MC-EDFA was observed by OSA at a wavelength of 1564.68 nm. Fig. 2 shows IC-XT component when USA was applied is 14.2 dB larger than when BSA was applied at a 200 km transmission. An increase of another 9.7 dB in the case of USA is also shown at 2,000 km transmission. Fig. 3 shows the measured results of transmission distance dependence. The measurement parameters are the signal assignment method and wavelength of IC-XT component. Independent of the signal assignment method, intensity of IC-XT component tends to be larger for longer wavelengths, and its difference proportionally increases with the number of the BD-MC-EDFA passage. Fig. 4 summarizes the difference in measured results in Fig. 3 when signal light passed the BD-MC-EDFA 80 times. BSA achieves an 11.5 dB suppression of IC-XT component. From Fig. 4, average wavelength dependence of USA and BSA is 2.4 dB/5.7nm, which corresponds to 0.42 dB/nm. This result is equivalent to the reported wavelength dependence [12]. Thus, these results from Fig. 2 to Fig. 4 indicates the importance to consider the influence of IC-XT due to the EDFA using MC-EDF as well as MCF used for transmission line.

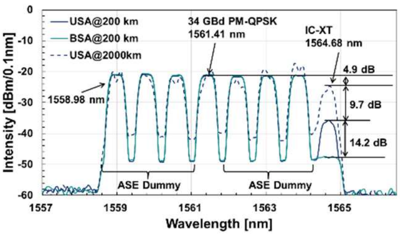

Fig. 2. Output spectrum of transmission line

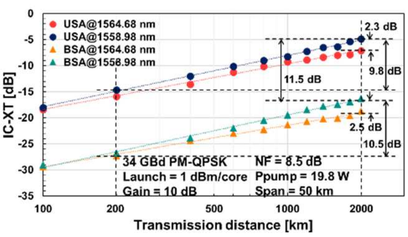

Fig. 3. IC-XT v.s. transmission distance

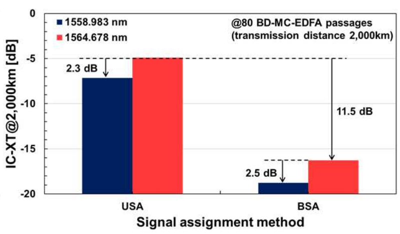

Fig. 4. IC-XT for 80 MC-EDFA passages

4. Influence of noise figure on the possible transmission distance in 7-core BD-MC-EDFA

Next, the influence of the pump direction on the possible transmission distance was studied. For case 2 shown in Fig. 5, directions of pump light propagation for all cores are the same, but the pump direction changes depending on the direction of signal light propagation. As describes in Sec.1, the possible transmission distance for each core in a single MC-EDF could be different according to pump direction when cladding pumped MC-EDFA is used together with BSA. Then the possible transmission distance could be limited by the BW pumped cores which NF is larger than FW pumped ones. As NF shows degrading trend for the shorter wavelength [18], OSNR of the 1533.47 nm wavelength channel was observed. Fig. 6 shows transmission distance dependance when pumping operation mode of the BD-MC-EDFA was changed. NF for each pump direction was different because pump power was adjusted to achieve a constant gain of 10 dB. The decreasing trend of OSNR due to ASE accumulation according to passage number of the BD-MC-EDFA is observed, reflecting NF characteristics. The possible transmission distance with the launch signal power of -3 dBm/core under BER free condition is approximated as 24, 37 and 52 passages for backward (BW), BD, and FW pumping, respectively. Fig. 7 shows the ratio of OSNR with reference to the OSNR of FW pumping at 24 passages transmission. 8 and 20 points degradation are observed for BD and BW pumping, respectively.

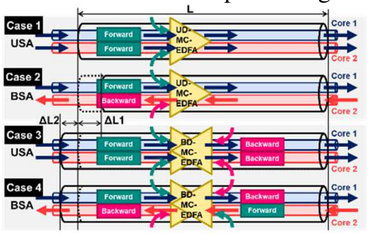

Fig. 5 Signal assignment and pump direction

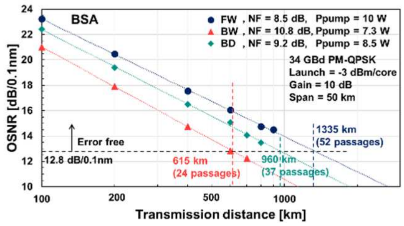

Fig. 6. OSNR v.s. BSA transmission distance

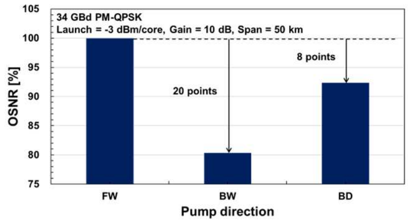

Fig. 7. OSNR @ for 24 passages

5. Discussion about capacity expansion of the repeated transmission system using the BD-MC-EDFA

Though the possible transmission distance for a core pair could be extended using BSA, it would be limited by the BW pumped core when the conventional UD-MC-EDFA is used as an optical repeater as shown in Fig. 5. The BD-MC-EDFA is thought to be able to suppress the limitation. To verify this assumption, we measured Q-value to investigate the influence of both IC-XT and NF due to the BD-MC-EDFA under the same transmission condition as used in Sec. 3 and Sec. 4. The measured results are shown in Fig. 8. At the Q-value of the forward error correction limit of 5.2 dB, the possible transmission distance was changed in accordance with both the signal assignment and pump direction as expected. Fig. 9 summarizes the ratio of the possible transmission distance on the basis of the USA and FW case. BSA and BD achieves the longest transmission distance, 131 %. The advantage of BD over BW in the BSA case is 13 points. This means Q-value improvement at the fixed transmission distance as shown in Fig. 8. The Q-value improvement is translated into transmission capacity expansion using Shannon's theorem [16]. Fig. 10 shows the calculation results of its ratio based on the USA and FW case. Reflecting the longest possible transmission distance, the BD-MC-EDFA operation condition of the BSA and BD case achieves the maximum transmission capacity expandability of 117 %, and its advantage over that of the BSA and BW case is 7 points.

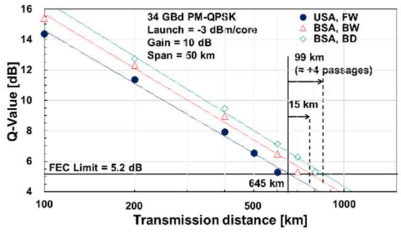

Fig. 8. Q-value v.s. transmission distance

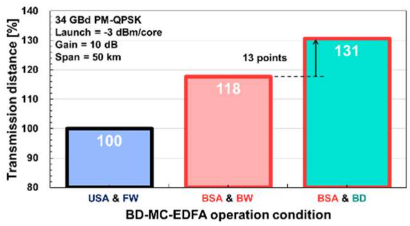

Fig. 9. Transmission distance expandability

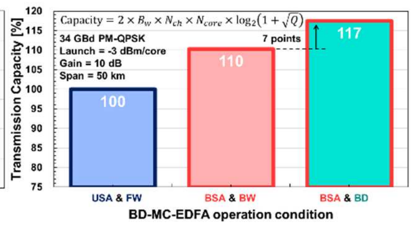

Fig. 10. Transmission capacity expandability

6. Conclusions

In this paper, we studied the influence of both inter-core crosstalk and noise figure due to cladding pumped multicore EDFA on the possible transmission distance experimentally using bidirectionally cladding pumped MC-EDFA. The influence of IC-XT due to MC-EDFA on repeated transmission systems has not been sufficiently studied. The results clarify the BD-MC-EDFA has an advantage in terms of the possible transmission distance compared with conventional unidirectionally cladding pumped MC-EDFA when bidirectional signal assignment is applied. Advantages of 13 points in possible transmission distance and 7 points in capacity expandability of the transmission system were obtained under the experimental conditions in this research.

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6. References

[1] Submarine Telecoms Forum ,.available: https://issuu.com/subtelforum/docs/stf_industry_report_issue_8
[2] P. J. Winzer et. al, JLT, vol. 35, no. 5, pp. 1099–1115 (2017)
[3] T. Matsui et al, OECC 2017, WC2-2
[4] T. Hayashi et al, OECC 2019, PDP3
[5] H. Takeshita et al., JLT, DOI: 10.1109/JLT.2022.3195190
[6] S. Takasaka et al., ECOC 2013, We.4.A.5 (2013)
[7] S. Takasaka et al., ECOC 2022, Th.2A.4
[8] H. Takeshita et al., JLT, Vol. 38, Issue 11, pp. 2922-2929 (2020)
[9] H. Takeshita et al., OECC 2022, Tu.C1.2
[10] T. Ito et al., OFC 2013, OTh3K.2
[11] T. Hayashi et al., OFC 2022, M1E.1
[12] M. Tuggle et al., ECOC 2023, Th.A.6.2
[13] D. Soma et al., ECOC 2023, Tu.B.2.2
[14] M. Hoshi et al., ECOC 2023, Tu.B.2.4
[15] K. Maeda et al, OECC 2020, VP56
[16] J. D. Downie et al., JLT, Vol. 38, No 12, pp. 3214-3220 (2020)
[17] E. Desurvire, PTL, Vol.4, Issue. 7, pp.711-714, July (1992)
[18] H. Takeshita et al, JLT, Vol. 41, Issue 11, pp. 3455-3461 (2023)