Design guideline for unrepeatered counter-propagating multi-core fiber link

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Abstract: We revealed that crosstalk influence in unrepeatered counter-propagating multi-core fiber link could be minimized at optimum gain and position of remote-optically pumped amplifier (ROPA). 1.5-times longer unrepeatered link was obtained by implementing isolators with ROPA.

1. Introduction

Weakly-coupled multi-core fiber (MCF) with a standard 125 μm-cladding diameter is a promising candidate for overcoming the capacity limitation of current single-mode fiber (SMF) technology in a long-haul terrestrial and submarine systems using the existing transmission technology without complex MIMO DSP [1]. Because of the fixed cladding diameter, the reduction of crosstalk (XT) is in a trade-off relationship with suppressing the confinement loss. It was reported that counter-propagation between neighboring cores reduced the XT penalty compared with a co-propagation for all cores [2, 3]. Recently, the ultra-long distance repeatered transmission has been demonstrated by using the standard-cladding four-core fiber with a counter-propagation technique [4, 5].

MCF can also increase the cable capacity for unrepeatered transmission within a fixed cable diameter. H. Takara *et al* demonstrated a 204-km-long unrepeatered MCF transmission with a remote-optically pumped amplifier (ROPA) [6]. However, XT under the counter-propagation rapidly accumulates in accordance with the square of the span length [3, 7]. Thus, the applicability of unrepeatered counter-propagating MCF link has not yet clarified sufficiently.

In this paper, we reveal that the XT influence of unrepeatered MCF links under counter-propagation closely relates with the pump power and the length between output end and EDF in a ROPA. We show that the maximum unrepeatered transmission length in counter-propagating MCF links with ROPA can be extended 1.5 times by optimizing the pump power and position in the link compared with that without ROPA.

2. XT characteristics of unrepeatered counter-propagating MCF link

Figure 1 shows the schematic image for unrepeatered transmission using the counter-propagation in an MCF. In this case, the ROPA can be separately located at the equivalent distance of L_1 from both left-side and right-side ends of the MCF link. Thus, the total length is $2L_1+L_2$ in that L_2 is the distance between ROPAs.

First, we experimentally investigated the XT characteristics of an unrepeatered MCF link under counter-propagation. Table 1 summarizes the optical properties of the MCFs that we used. We used standard-cladding four-core MCFs with a simple step-index profile, which has advantages in terms of cost-effectiveness due to its manufacturability and stability by using the VAD method to fabricate the fiber preform of each core [8]. These MCFs were fabricated from three manufacturers under common requirements and had fully compatible optical properties with a conventional G.652.D fiber. The losses were 0.2 and 0.25 dB/km at λ = 1550 and 1480 nm respectively, which were comparable

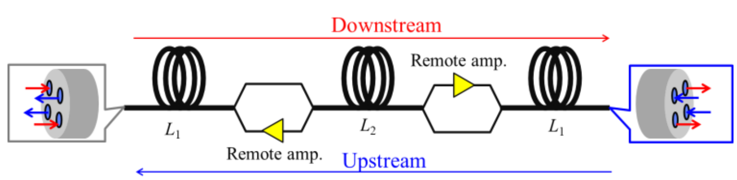


Fig. 1: Unrepeatered MCF link under counter-propagation

Tab. 1: Properties of SI-MCFs

	Wavelength	Span 1	Span 2				Span 3
Loss (dB/km)	1310 nm	0.34	0.34	0.35	0.34	0.34	0.35
	1550 nm	0.20	0.20	0.20	0.19	0.20	0.20
	1625 nm	0.23	0.22	0.22	0.23	0.24	0.23
XT_{co} (dB @ 1km)	1550 nm	-36.4	-41.0	-41.1	-34.4	-40	-41.6
Length (km)	-	54	36	36	20	28	54*
Manufacturer	-	A	B	B	A	C	C

*Concatenating 8 spools of 4CFs. Loss and XT included splice points.

with an SMF. The XT in co-propagation (XT_{co}) was from -34 to -42 dB at 1 km propagation. In co-propagation for all cores, the maximum reach limited by the XT penalty was derived to be about 50 km when considering an XT threshold of -17 dB which corresponded to the 1-dB penalty for the QPSK format [9].

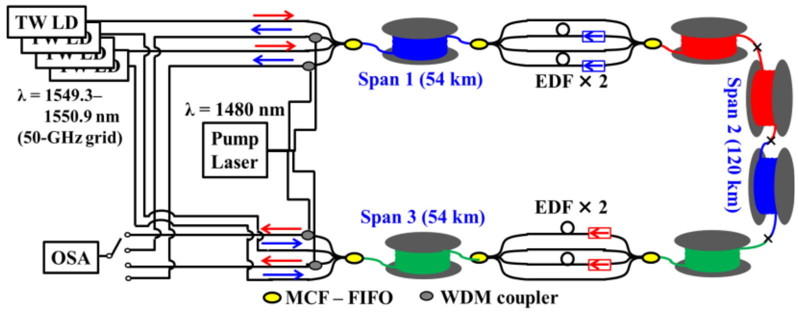


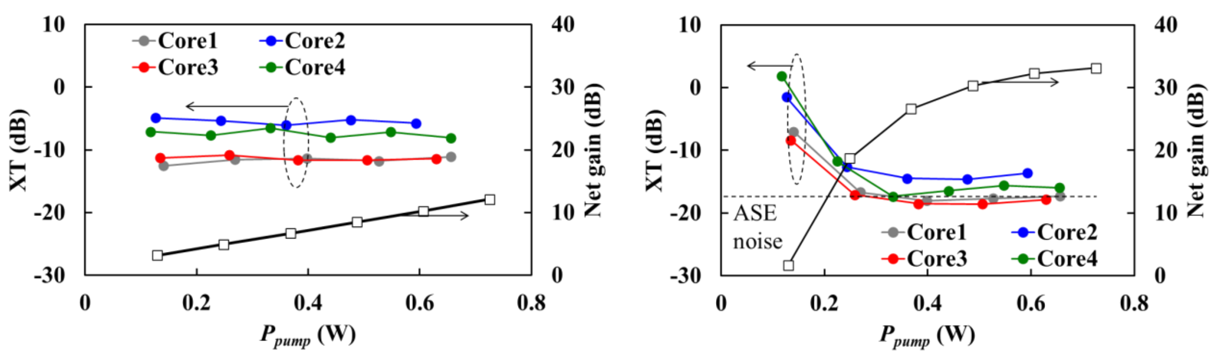
Fig. 2: Experimental setup

Figure 2 shows the experimental setup for measuring the XT characteristics of an unrepeatered MCF link with a ROPA. We assigned four different wavelengths to each core to measure the XT in the wavelength region and launched them under counter-propagation. Conventional 10.8 m-long EDFs were inserted after a 54-km-long MCF via fan-in/-out (FIFO) devices. An optical isolator was also inserted after each EDF to reduce the accumulation of backward propagation of XT from neighboring cores. The pump light at λ = 1480 nm was used for both DRA and ROPA. The pump light was divided into four by an optical splitter and was injected from the receiver side of each core.

Figure 3 shows the measurement results. Circles and squares represent XT and net gain, respectively. Figure 3(a) shows the measurement without EDFs. The XT was high at -5 ~ -11 dB, and its variation was small for the injected pump power (P_{pump}). Here, we found that the XT value varied among cores, and we consider this to be due to loss differences at the splice, FIFO, and optical components. The net gain, which was induced with only DRA in Fig. 3(a), linearly increased in accordance with P_{pump} and exceeded 10 dB at P_{pump} = 0.6 W. Figure 3(b) shows the measurement with the EDFs. We found that the XT reduced as P_{pump} increased. It can be considered that the backward propagation of the XT from the neighboring cores after the ROPA made a small contribution to the accumulation of XT along the total length. Here, the relative ASE noise was about -18 dB and the XT was reduced to the ASE level at $P_{pump} \geq 0.3$ W. We also observed that the net gain reached 30 dB at P_{pump} = 0.5 W for each core which included both the gain of the ROPA and DRA. From these results, we revealed that XT under counter-propagation could be minimized by optimizing the injected P_{pump} and length ratio between L_1 and L_2.

3. Design guideline for unrepeatered counter-propagating MCF link

We then investigated the link configurations and design guideline for maximizing the transmission distance of unrepeatered counter-propagating MCF link. As shown in Fig. 3(b), the influence of XT can be reduced by optimizing the injected P_{pump} to the ROPA. Here, the pump power for reaching the ROPA depends on the span length L_1 because the maximum P_{pump} is limited by the stimulated Raman scattering (SRS). Figure 4 shows the calculated XT as a function of L_1 and the ROPA gain, in which we fixed L_2 to 120 km. Solid curves correspond to the several P_{pump} values for each core. P_{pump} = 0 W represents the link configuration without ROPA. Here, we estimated the ROPA gain from the relationship between the P_{pump} and gain of the EDFs while considering fiber attenuation α_p of 0.25 dB/km at λ = 1480 nm. We confirmed that the XT values can be reduced by utilizing ROPA at $L_1 \leq 80$ km. That is because insufficient gain in the ROPA at long L_1 due to the fiber attenuation to P_{pump} resulted in XT similar to that for P_{pump} = 0 W. In Fig. 4, the dashed line is the XT limitation when assuming a QPSK format as



(a) w/o EDFs (b) w/ EDFs

Fig. 3: Measured XT characteristics and net gain of unrepeatered MCF link under counter-propagation

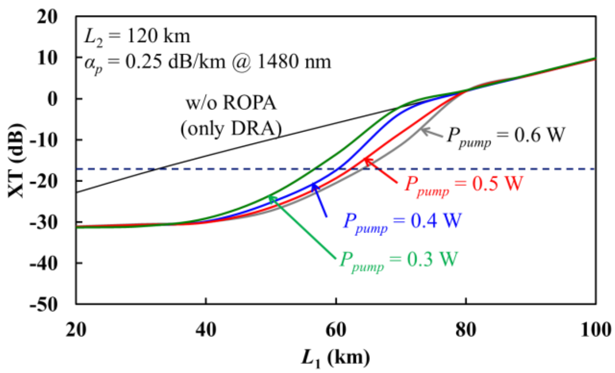


Fig. 4: XT dependence on L_1 and ROPA gain

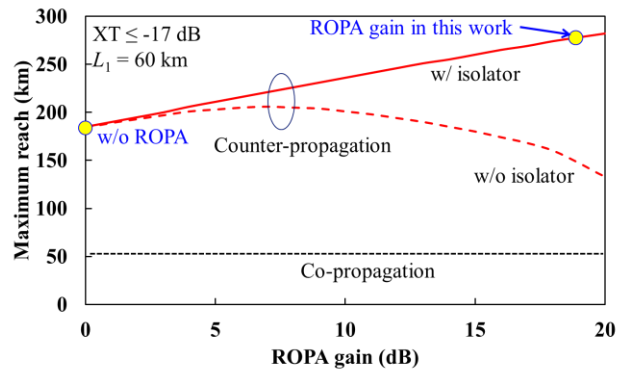


Fig. 5: Maximum reach of unrepeatered MCF link

described for Tab. 1. The maximum L_1 for satisfying the XT limitation increased as P_{pump} increased. It should be noted that the injected P_{pump} was restricted by the SRS threshold which was estimated as about 0.6 W for each core in our MCFs. Thus, we observed an L_1 of about 60 km to be an appropriate condition for reducing the XT under counter-propagation.

Finally, we investigated the maximum reach of unrepeatered counter-propagating MCF link. Figure 5 shows the maximum reach as a function of the ROPA gain when considering P_{pump} fixed at 0.5 W and L_1 of 60 km. Here, we set the threshold of XT limitation at -17 dB as mentioned above. Red solid and dashed curves correspond to the ROPA with and without the optical isolator respectively. The black dashed line is the maximum reach that satisfies the XT limitation for co-propagation. For unrepeatered MCF link without the ROPA, the maximum reach for counter-propagation was 180 km regardless of the use of the optical isolator. When we did not utilize the optical isolators with the ROPA, we found that the maximum reach slightly extended at relatively low ROPA gain of less than 10 dB. It can be considered that the higher gain than span loss at L_1 emphasized the accumulation of the XT. In contrast, the maximum reach for the ROPA with optical isolator monotonously increased at higher ROPA gain. At the ROPA gain of about 19 dB which corresponded to the ROPA gain in our experiment in Fig. 3(b), we observed the extended maximum reach of 270 km which was 1.5 times longer than unrepeatered counter-propagating MCF links without the ROPA. From these results, we observed that the influence of the XT to the transmission distance could be minimized and the maximum reach could be extended by 50 % in unrepeatered counter-propagating MCF links by both the optimized ROPA configuration and utilization optical isolator compared with that without ROPA.

4. Conclusion

We experimentally and numerically revealed that the influence of the XT to unrepeatered transmission distance could be minimized in the counter-propagating MCF links by optimizing the gain and position of the ROPA. Our results showed the transmission distance of unrepeatered MCF link could be extended by 1.5 times by optimizing ROPA configuration and implementing the optical isolator compared with unrepeatered MCF link without the ROPA.

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