High Figure–of–Merit Multi–Core Fiber with Standard Cladding Diameter for 10,000 km–class Submarine Transmission

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Abstract *We demonstrate a standard cladding 4–core fiber with highest figure–of–merit by optimizing its design of effective area, loss and crosstalk characteristics simultaneously for submarine transmission. The 10,140km transmission with spectral efficiency of 7.52bit/s/Hz is achieved with counter–propagation configuration among neighbouring cores.*

1. Introduction

A demand for much larger transmission capacity has been rapidly growing in a long–haul system, in particular, trans–oceanic submarine system. A weakly–coupled multi-core fiber (MCF) is a promising candidate to overcome the limitation of current single-mode fiber (SMF) technology and has the advantages in upgradability from the existing optical equipment and in requiring no complex signal processing for optical MIMO. Moreover, adopting a standard 125 μm–cladding diameter and optical consistency with current fiber standards can improve the mass–productivity and enables us to utilize SMF based optical components [1].

An inter–core crosstalk (XT) is one of important parameters in the MCF design since the XT induced noise accumulates along with the fiber length. Several standard cladding MCFs with the extremely low XT property which can be applicable to trans–oceanic submarine system have been reported [2–5]. The loss and effective area (A_{eff}) are important parameters in long–haul network and the 4–core fiber (4CF) with lowest loss of 0.155 dB/km has been shown [5]. Regarding A_{eff}, larger A_{eff} improves the transmission performance by reducing nonlinear impairment. However, there is a trade–off relationship among enlargement of A_{eff} and reduction of XT, and the reported A_{eff} of 4CFs have remained 75–90 μm^2 [2–4] although 2–core fiber could realize 110 μm^2 [5].

In this paper, we demonstrate the standard cladding MCF with high transmission performance for 10,000 km–class submarine system. We numerically investigate the design of the MCF to maximize the figure–of–merit (FOM) by considering A_{eff}, loss and XT under counter–propagation among neighbouring cores. Our transmission experiment for which we utilized the fabricated 4CF indicates its potential to 1 Pbit/s capacity in one conventional submarine cable over 10,000 km transmission.

2. Standard cladding MCF with high FOM

To quantify the transmission performance of an SMF in long–haul transmission, the FOM has been known to compare the transmission performance among fiber types by considering ASE noise and nonlinear interference [6, 7]. Regarding an MCF, maximum spectrum efficiency of an MCF (SE_{MCF}) with optimum signal power has been derived to consider the XT induced noise [8]. For the optically repeating system with constant span length L_s, SE_{MCF} is represented as

$$SE_{MCF} = N \cdot \log_2\left(1 + \frac{1}{\eta_{TRX}}\left(N_s \cdot 3\left(\frac{\chi P_{ASE}^2}{4}\right)^{\frac{1}{3}} + \kappa\right)^{-1}\right).$$

Here, N, N_s and κ are the number of spatial channels, the number of spans and XT coefficient. η_{TRX} is impairment factor of transponders. ASE noise P_{ASE} can be given from noise figure of optical amplifier and span loss in the ideal configuration [6]. The nonlinear impairment parameter χ can be simplified as $k(L_{eff}/\gamma)(\alpha/D)$ when focusing the impairment from the fiber itself and ignoring other impairment factors [7], where α, γ, L_{eff}, D are the loss in dB/km, nonlinear coefficient, nonlinear interaction length and dispersion coefficient respectively. k is a constant. Therefore, the FOM of the MCF can be derived by utilizing the first equation as

$$FOM = 10\log\frac{SE_{MCF}}{SE_{ref}}.$$

In this study, we assumed channel bandwidth, noise figure, L_s and N_s of 50 GHz, 5 dB, 80 km and 125 (total length of 10,000 km) respectively. We assumed a conventional single–core G.654 fiber with A_{eff} = 110 μm^2 to obtain SE_{ref}.

Figure 1 shows the structure of our standard cladding MCF. We consider four homogeneous cores in a standard 125 μm–cladding diameter, which utilizes a trench-assisted index profile with pure–silica core. It has been reported that the XT induced noise can be reduced by utilizing counter–propagation between neighbouring

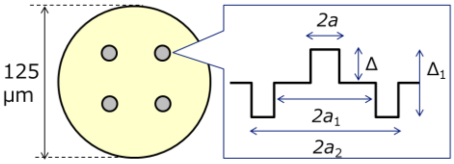

Fig. 1: Structure of standard cladding MCF.

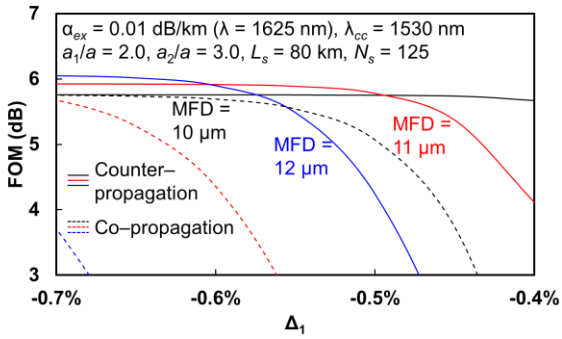

Fig. 2: Achievable XT and FOM of standard cladding 4CF for co–/counter–propagation

cores in an MCF [9, 10]. In our study, we assumed the counter–propagation to relax the trade–off relationship between XT and other optical properties. We also considered optical requirements consistent with existing G.654 fibers, that is cable cut–off wavelength λ_{cc} of less than 1530 nm and bending loss of less than 0.1 dB/100turns on 30 mm–radii at λ = 1625 nm.

Figure 2 shows the relationship between the calculated FOM of the standard cladding 4CF as a function of Δ_1. In this calculation, we set the other core parameters to obtain λ_{cc} of 1530 nm and core pitch to supress excess confinement loss α_{ex} to 0.01 dB/km at λ = 1625 nm. To consider the contribution of the loss to the FOM, we assumed the Rayleigh scattering loss α_R which was derived from the overlap between index profile and electric field [11] in addition to α_{ex}, that is $\alpha = \alpha_R + \alpha_{ex}$ in calculation. Solid curves correspond to counter–propagation to be derived according to refs. [9, 11] and dashed ones to co–propagation for comparison. The FOM increased on the larger mode–field diameter (MFD) for counter–propagation although larger MFD severely degraded the FOM for co–propagation due to the XT induced noise. We confirmed that the FOM of 6 dB in counter–propagation was obtained at $\Delta_1 \leq -0.6$ % and the MFD of 12 μm, which corresponded to four times higher transmission performance than a conventional G.654 fiber with A_{eff} = 110 μm^2.

Figure 3 shows the calculated FOM of the standard cladding 4CF under counter–propagation. Because the counter–propagation reduced the XT noise greatly, the larger MFD could be designed and resulted in higher FOM. When considering XT for counter–propagation ($XT_{counter}$) of less than -25 dB at 10,000 km which

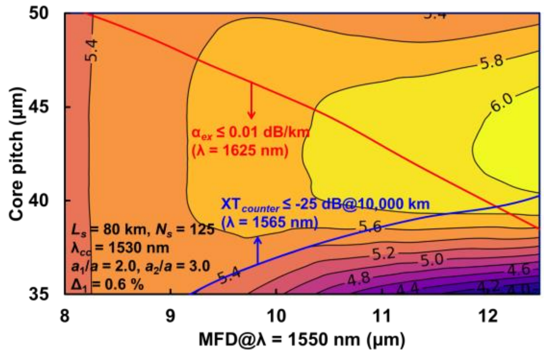

Fig. 3: Relationship among MFD, core pitch and FOM of standard cladding 4CF

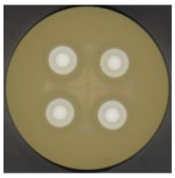

Fig. 4: fabricated 4CF

Tab. 1: Measured results

	Wavelength	
Cladding diameter	–	125 μm
Core pitch	–	40.5 μm
MFD	1550 nm	11.7 μm
Loss	1550 nm	0.166 dB/km
λ_{cc} (22m–long)	–	<1530 nm
Bending loss (30 mm–radii)	1625 nm	<0.03 dB/100turns
Dispersion	1550 nm	20.7 ps/nm/km
XT_{co}	1550 nm	-47 dB@1 km
	1625 nm	-40 dB@1 km

corresponded to the 0.1 dB or less in FOM reduction and $\alpha_{ex} \leq 0.01$ dB/km at λ = 1625 nm to avoid undesired loss increase, the MFD was enlarged to 12 μm at the core pitch of 40 μm.

From these results, we clarified the design of the standard cladding 4CF to obtain higher FOM which was almost four times higher than a conventional G.654 fiber.

3. Applicability of fabricated 4CF to submarine transmission

We fabricated the standard cladding 4CF based on design above. Figure 4 shows the cross–sectional photo of the fabricated 4CF, and Table 1 summarizes the geometrical and optical properties. The cladding diameter and core pitch were 125 and 40.5 μm respectively. The MFD was 11.7 μm at λ = 1550 nm which corresponded to A_{eff} of 112 μm^2. The propagation loss was 0.163–168 dB/km (0.166 dB/km in average of four cores) at λ = 1550 nm. The λ_{cc}, bending loss and chromatic dispersion properties were also consistent to ITU-T Recommendations G.654. The XT for co–propagation (XT_{co}) was -47 and -40 dB at 1 km at λ = 1550 and 1625 nm respectively, which corresponded to -30 and -24 dB at 10,000 km with 80 km–long span for counter–propagation.

We then constructed the MCF link by utilizing the fabricated 4CFs. We spliced 5 samples of the fabricated 4CF by utilizing a commercially available fusion splicer with side–view based rotational alignment [12, 13]. The total length was 65 km and span loss was 12.1–12.5 dB at λ =

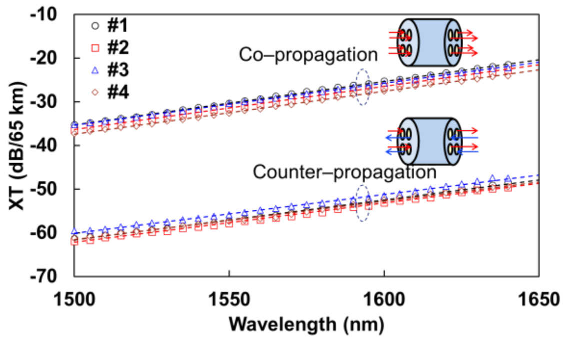

Fig. 5: Measured XT for co–/counter–propagation in 4CF link

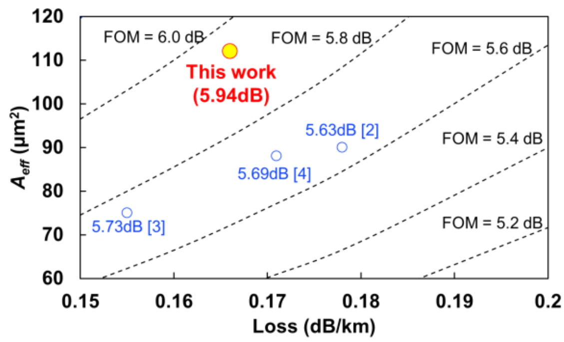

Fig. 6: FOM of fabricated 4CF

1550 nm including MCF fan–in/–out [14]. Figure 5 shows the XT spectrum which we measured as the ratio between output power of each core and accumulated XT power from other cores [9]. The upper group was co–propagation and the lower one was counter–propagation. We found that the counter–propagation reduced 25 dB in the XT for the 65 km span compare with the co–propagation. The $XT_{counter}$ was sufficiently low of less than -55 dB in C–band for one span.

Figure 6 shows the FOM of the standard cladding 4CF as a function of A_{eff} and loss. Here, we assumed SE_{ref} of a G.654 fiber with A_{eff} = 110 μm^2 and loss of 0.16 dB/km to estimate the FOM, and dashed curves are calculated FOM of the 4CF for 10,000 km transmission with 65 km–long span and XT in fig. 5. We also estimated FOM values of previously reported 4CFs by using their A_{eff}, loss and XT under same system condition. Figure 6 confirmed us that our proposed 4CF had the highest FOM of 5.94 dB among the standard cladding 4CFs, thanks to the large A_{eff} and relatively low loss properties.

Finally, we investigated the transmission performance of our MCF link. Figure 7 shows the experimental setup. We used commercially available transceivers to generate 5 WDM channels at λ = 1546.77–1548.46 nm which were aligned with 53.125 GHz spacing and modulated with 50.9 GBaud/s 200Gb/s coded–QAM format. Broad ASE dummy light filled the entire transmission band except the wavelength band of modulated signals. These signals were

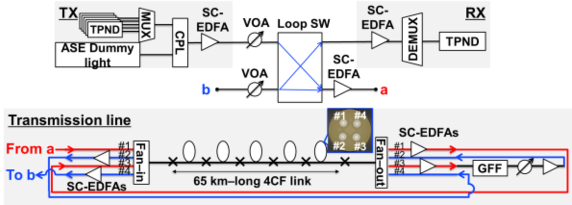

Fig. 7: Experimental setup

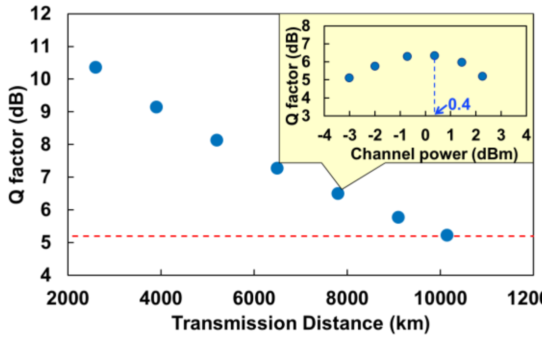

Fig. 8: Transmission performance

launched into 65 km–long MCF link and output signals were amplified with conventional single–core EDFAs (SC-EDFAs) and equalized with a WSS-based gain flattened filter (GFF). Signals circulated the concatenated cores in the 4CF link under counter–propagation configuration by using acousto-optic modulator based loop switch, and received by a real-time transceiver that synchronized with a re-circulating trigger signal.

Figure 8 shows the experimental results. We confirmed that the Q factor beyond the FEC limit Q (5.2 dB) was able to be achieved after 10,140 km transmission with optimum channel power of 0.4 dBm/ch. This spectral efficiency was 7.52 bit/s/Hz (3.76 bit/s/Hz x 2 core–pair) in one 4CF, which can achieve 16.9 Tb/s capacity per core–pair with a general C-band submarine transmission bandwidth of 4.5 THz. This results also indicated the possibility of exceeding 1 Pbit/s capacity in one cable over 10,000 km transmission by assuming a conventional 32–fiber Φ17 mm submarine cable [15].

4. Summary

We clarified the design of the standard cladding MCF with the high FOM by considering the counter–propagation between neighbouring cores. The fabricated 4–core fiber had large A_{eff} of 112 μm^2 and relatively low loss of 0.166 dB/km at λ = 1550 nm, which resulted in the highest FOM than previously reported standard cladding 4CFs. We also demonstrated the long–haul transmission experiment by utilizing the MCF link based on the fabricated high FOM 4CF and achieved 10,140 km–long 7.52 bit/s/Hz in one 4CF. The experimental results indicated 1 Pbit/s/cable submarine transmission with assuming a conventional 32–fiber cable.

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