Mode-dependent Gain Reduction in Coupled Multi-core EDF with Smaller Core Pitch

Ryota Imada, Taiji Sakamoto, Shinichi Aozasa and Kazuhide Nakajima
Access Network Service Systems Laboratories, NTT Corporation, 1-7-1, Hanabatake, Tsukuba Ibaraki, 305-0805 Japan
ryota.imada.fh@hco.ntt.co.jp

Abstract: We discuss the reduction in mode-dependent gain (MDG) in coupled-multi-core erbium-doped fiber (C-MC-EDF) with smaller core pitch by optimizing the bending radius. Our results indicate the possibility of C-MC-EDFA with both low power consumption and MDG.

1. Introduction

Cladding pumped amplifiers have received much attention since they can potentially reduce power consumption per spatial channel by amplifying multiple signals simultaneously with one multi-mode laser diode [1]. Coupled-multi-core erbium-doped fiber (C-MC-EDF) is suitable for improving the energy efficiency of such amplifiers because it can increase the core-to-cladding area ratio and improve pumping-light absorption in erbium-doped cores, which leads to better amplification efficiency. A study has shown that a coupled 12-core EDF amplifier (EDFA) achieved the lowest power consumption per spatial channel among the reported C-band cladding-pumped amplifiers [2]. Mode-dependent loss (MDL) severely limits transmission distance in mode-division-multiplexing transmission systems. Mode-dependent gain (MDG) in C-MC-EDF seriously affects the MDL characteristics in transmission systems [2,3]. Therefore, it is important to develop a C-MC-EDFA with higher amplification efficiency and with lower MDG. However, the relationships between the design parameters of C-MC-EDF (core pitch, bending radius, and twisting rate) and MDG characteristics have not been sufficiently clarified.

In this paper, we numerically and experimentally investigated the dependence of MDG on the core pitch and bending radius of C-MC-EDF. We found that the MDG of smaller-core-pitch C-MC-EDF can be reduced by controlling the bending radius. These results suggest the feasibility of a C-MC-EDFA that has both low MDG and high power efficiency.

2. Numerical background

We considered two-core C-MC-EDF with a core pitch Λ, as schematically shown in Fig. 1. The gain of an EDFA depends on the erbium-doped distribution and electric field patterns of pump and signal light. Two-core C-MCF-EDF supports two signal electric fields of $E_{\mathrm{even/odd}}(x,y)$. We express the gain localization factor $\Gamma_{\mathrm{even/odd}}$ as

$$\Gamma_{\mathrm{even/odd}} = \frac{\iint_{\mathrm{core}} \left|E_{\mathrm{even/odd}}(x,y)\right|^2 \mathrm{d}x\mathrm{d}y}{\iint_{\mathrm{all}} \left|E_{\mathrm{even/odd}}(x,y)\right|^2 \mathrm{d}x\mathrm{d}y},. \tag{1}$$

If the pump-field distribution is uniform over the cladding region, Eq. (1) indicates the relative gain coefficient for each mode. As shown as Fig. 1 (i), when Λ is relatively large, the intensity distribution of $E_{\mathrm{even/odd}}(x,y)$ is almost the same in either bent or straight fiber. Thus, the difference between Γ_{even} and Γ_{odd} tends to be small, leading to

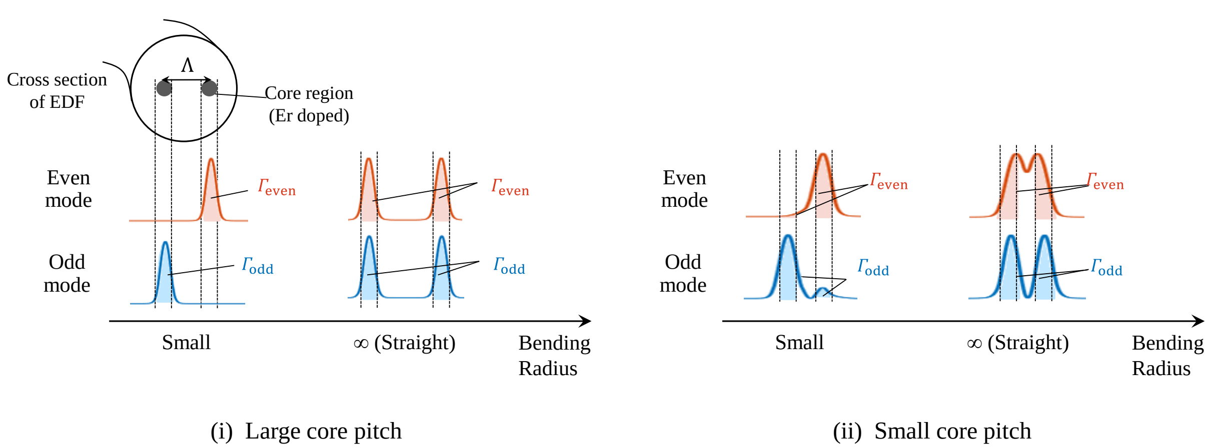

Fig. 1. Conceptual image of gain localization rate $\Gamma_{\mathrm{even/odd}}$ and its dependence on core pitch Λ and bending radius

smaller MDG. When Λ becomes small, as shown as (ii) in Fig. 1, the intensity distribution of each mode becomes different. For straight fiber, the electric-field distribution is different for even or odd mode, leading to a larger difference between Γ_{even} and Γ_{odd}. For bent fiber, the difference Γ_{even} and Γ_{odd} can be reduced at a smaller bending radius because the electric field is shifted into either core caused by the tight bend, thus increasing intensity similarity. Therefore, C-MC-EDF with smaller Λ should result in higher clad pumping efficiency and low MDG simultaneously by controlling the bending radius adequately.

3. Experiments and discussion

Table 1 lists the parameters of three two-core C-MC-EDFs used in our experiments. The Λ of EDF-1, 2 and 3 are 16, 25 and 40 µm, respectively. The cladding diameter D, cutoff wavelength of LP_{11} mode, and relative index difference Δ are 125 µm, 1.4 µm, and 0.34 %, respectively. The core radius was designed to be 5.0 µm. The EDF length is about 12 m. We slightly adjusted the length of each EDF to obtain a modal gain of more than 15 dB in the C-band when the input pumping power was 3.5 W. The core dependence gain was experimentally confirmed to be less than 0.6 dB.

Fig. 2 shows the experimental setup to measure MDG. We used a 1.25-Gb/s PM-QPSK signal at a wavelength of 1550 nm with an input power of −25 dBm for each core. The saturation wavelength-multiplexed continuous wave (CW) light was also input to the EDFs to fix the gain spectrum of the EDFA, where the wavelengths were 1532, 1542, 1552, and 1562 nm and the power was −10 dBm for each wavelength. The signal and saturation lights were split into two ports using the power splitter and multiplexed using a fan-in (FI) device after passing through delay lines to decorrelate the signals. We used a side-coupling-scheme-based pump combiner to couple the pumping light into the EDFs at a wavelength of 975 nm and set the pumping power to obtain 15-dB gain for each core at a wavelength of 1550 nm. We also used a pump stripper to remove the residual cladding pump from the EDFs. We measured MDG by using the singular-value decomposition technique [4] with the detected signal passing through the EDFA and a fan-out (FO) device. The MDL was calculated from the ratio of the maximum and minimum values of the singular values λ_m of the channel matrix from $20\log_{10}(\lambda_{\max}/\lambda_{\min})$. We derived the MDG penalty of the EDFA by subtracting the MDL of the FI/FO devices from the measured MDL with the EDFs.

Fig. 3(a) shows the MDG values as a function of bending radius. The open symbols and solid lines show the measured and calculated results, respectively. Blue, red, and orange represent the results for EDF-1, 2, and 3 with Λ of 16, 25 and 40 µm, respectively. The measurement results represent the average values of 100 measurements to suppress the time-dependent MDG fluctuation, where each measurement analyzed the MDG in 1000-bit duration and averaged them. We observed variations of ±0.1 dB. In the numerical simulation, we ignored the mode coupling in the EDF and solved three-level rate equation with the calculated Γ_{even} and Γ_{odd} on the basis of the mode field obtained using the two-dimensional full-vector finite-element method. We assumed a pumping power of 4 W and that the pump-field distribution remained uniform over the cladding region. The simulation results in Fig. 3 (a)

Table 1. Properties of fabricated three 2-core EDFs

	EDF-1	EDF-2	EDF-3
Core pitch Λ (µm)	16	25	40
Cladding diameter D (µm)	125		
Cutoff wavelength of LP_{11}mode (µm)	≤ 1.4		
Relative index difference Δ (%)	0.34		

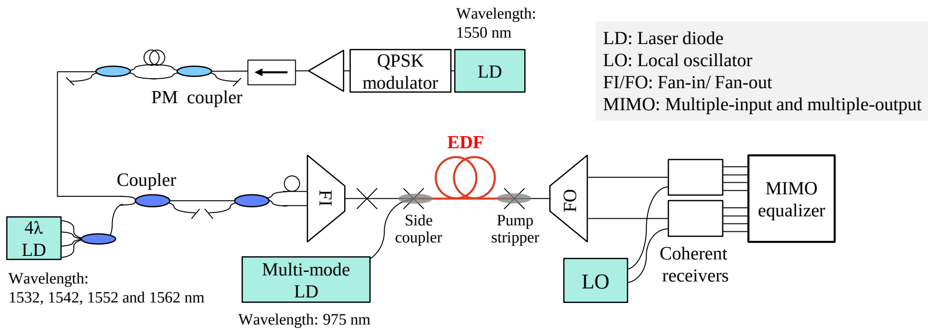

Fig. 2. Experimental setup for measuring MDG of EDFs

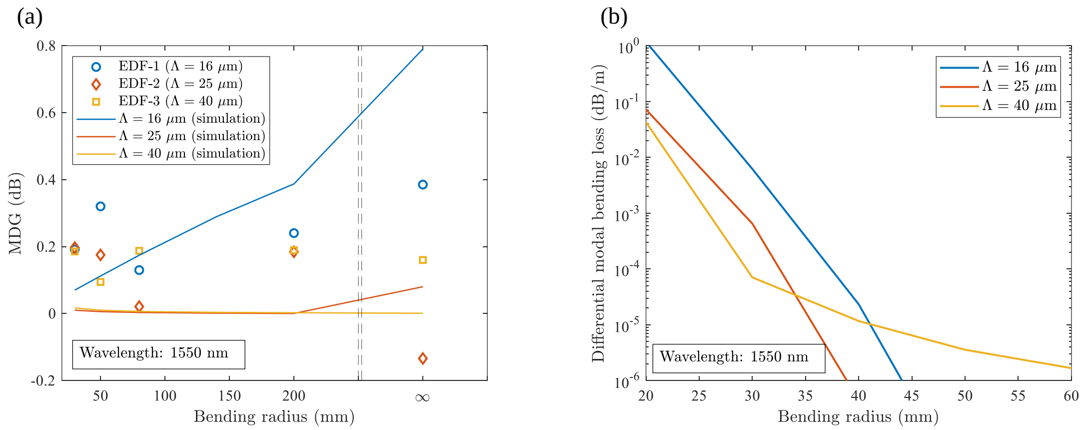

Fig. 3. Bending-radius dependence of MDG (a) and bending-loss difference between even and odd modes (b)

indicate that the bending-radius dependence of MDGs was less than 0.1 dB when $\Lambda = 25$ and 40 µm, but the MDG of EDF-1 ($\Lambda = 16$ µm) markedly increased as the bending radius became larger. The measurement results also indicate a similar trend by taking into account ±0.1-dB measurement uncertainty. The reason the measured MDG was lower than the calculated value is considered due to the effect of random fiber twisting since the calculated MDG was obtained with the uniform worst case bending angle. It was also found from the measurement results that the MDG reduction at a bending radius of less than 80 mm was not clear, particularly for $\Lambda = 16$ µm, which was expected due to the increased bending loss for the odd mode. Fig. 3(b) shows the calculation results of differential modal-bending loss at a wavelength of 1550 nm as a function of bending radius. The differential modal-bending loss means the maximum bending loss difference between even and odd modes. The differential modal-bending loss rapidly increased as the bending radius decreased and became larger as Λ decreased.

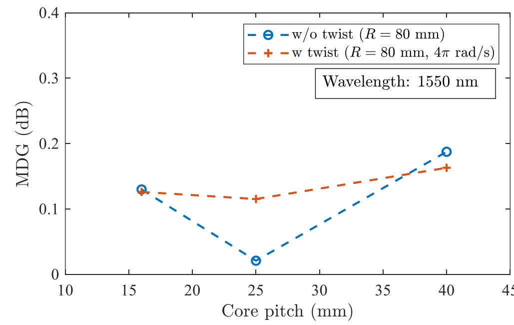

Fig. 4. Measured MDGs as function of core pitch with bending radius of 80 mm with and without intentional twist

Finally, we confirmed the impact of intentional fiber twisting on MDG. Fig. 4 shows the measurement results of MDG as a function of Λ at a bending radius of 80 mm. The orange and blue symbols represent the measurement values with and without the twist, respectively. We twisted the EDFs at a rate of $4\pi\ \mathrm{rad/m}$. The measurement conditions were the same as that shown in Fig. 3. Fig. 4 shows that the effect of twisting on MDG was not observed within the measured uncertainty of ± 0.1 dB.

All these results indicate that the MDG of C-MC-EDF with a smaller Λ can be reduced by appropriately adjusting the bending radius of the EDF. They also indicate that it is possible to improve power-conversion efficiency of C-MC-EDF by reducing core pitch and cladding diameter.

4. Conclusion

We investigated the dependence of MDG on the core pitch and bending radius of C-MC-EDF by taking into account the gain localization factor. We found that the MDG of small-core-pitch EDF can be reduced by controlling the bending radius. Our results indicate that a C-MC-EDFA with higher power-conversion efficiency and with small MDG can be fabricated by simultaneously designing high-core-density EDF and bending radius.

References

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