Power Savings in MC-EDFA Repeated Transmission by Cladding Pumping

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***Abstract*— We measured gain and NF of the cladding pumping MC-EDFA for various inputs and pumping powers and estimated bidirectional pumping saves 27.2 % power relative to forwarding pumping at 3,000 km transmission using 16QAM.**

Keywords—Uncoupled multicore fiber, Multicore Amplifier, Erbium-Doped Fiber Amplifier (EDFA)

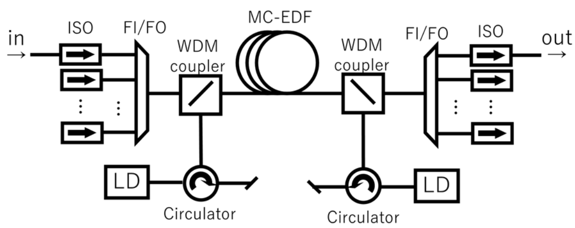
I. Introduction

In recent years, the spread of high-capacity wireless communications and streaming services such as 5G has increased the demand for increased capacity of optical fiber communications between wireless base stations and backhaul [1]. The transmission capacity of single-core optical fiber is limited to 100 Tbps to suppress fiber fuse [2]. Therefore, SDM (space-division multiplexing) technology is being considered, increasing the spatial transmission paths or modes. Few-mode fiber, multimode fiber, multicore fiber, and reduced-diameter fibers have been studied as SDM technologies. Since un-coupled multicore fiber can increase the number of cores with the same outer diameter as conventional single-core fiber, it is being considered for use in submarine transmission systems with an upper limit to the number of fibers that can be accommodated.

Although un-coupled multicore fibers suffer transmission quality degradation due to inter-core crosstalk, it has been reported that uncoupled multicore fibers with a broader pitch between cores can suppress inter-core crosstalk to less than -80 dB/km [3]. Furthermore, it has been reported that transmission degradation due to inter-core crosstalk can be reduced in four-core uncoupled fibers when the transmission direction is changed in the appropriate core [4,5]. Un-coupled multicore bidirectional transmission has also been shown to reduce the number of multicore fibers in branching units in regional SDM submarine cables [6]. Based on the above, un-coupled multicore fibers bidirectional transmission suits long-haul submarine transmission of large capacities. However, submarine cables have a power supply limitation [7]; if we employ core pumping for multicore fiber EDFA, the number of pumping light sources are same as the number of all cores. There is a limit to the volume of the repeater due to the need for the enclosure to withstand the high pressures of the deep sea. So, it is not easy to increase pumping light sources. Therefore, it is considered that cladding pumping using multimode LDs, which have an electrical-to-optical conversion efficiency is 1.5 times higher than that of single-mode LDs [8].

Furthermore, it has been reported that bidirectional multicore cladding pumping uses up to 24% less power than forward pumping [9]. However, the power-saving effect of bidirectional pumping compared with forward pumping has only been confirmed under a single condition of the number of input signal channels and pumping optical power. In actual optical transmission, the signal and pumping power depends on the requirements of the transmission system, so it is necessary to evaluate whether bidirectional cladding pumping can achieve the need of transmission systems such as submarine cables, which are expected to be the first to introduce MC-EDFA.

In this paper, we measured the gain and NF(noise figure) of an un-coupled multicore cladding pumping optical amplifier with various input and pumping powers for forward, backward, and bidirectional pumping configurations and investigated the power saving ratio of the other pumping configuration compared with forward pumping. And we estimated the power saving ratio by optimizing the repeater spacing for each pumping configuration when transmitting over long distances. The calculations show that at 3,000 km under the conditions of the estimates in this paper, QPSK and 8QAM show power savings of 26.8% and 25.1% with backward pumping and 16QAM of 27.2% when using bidirectional pumping.



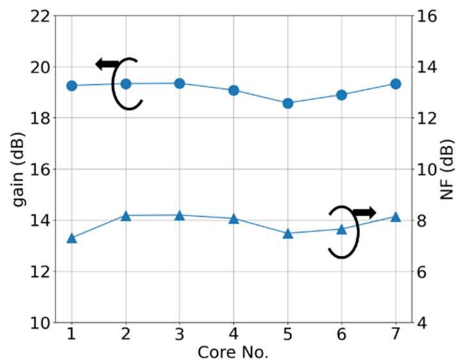


Fig.2 Gain and NF of each core with input power of -5 dBm/core and 1545 nm signal with bidirectional pumping

II. CONFIGRATION OF 7-CORE EDFA BY CLADDING PUMPING

First, the characteristics of the un-coupled multicore cladding pumped optical amplifier used in this experiment are described. Fig. 1 shows the configuration of the 7-core cladding pumping optical amplifier used in this experiment, in which WDM (Wavelength Division Multiplexing) couplers and FI/FO (Fan-in/Fan-out) are arranged symmetrically to the 7-core EDF (Erbium-Doped Fiber). We employed the 7-core EDF in this study because increasing the core number improves the cladding pump power efficiency of MC-EDFA [10]. The WDM coupler combines or splits the signal light propagating through the multicore fiber and the pumping light propagating from the multimode fiber by spatial coupling [11].

Fig. 2 shows the gain and NF of each core when a signal with an input power of -5 dBm/core and a wavelength of 1545 nm is input. We calculated the average gain and NF for each core's values. After calculation, there was a difference of 0.8 dB in gain and 0.9 dB in NF. In this result, we consider that a core-by-core variation of gain and NF is small, and we measure the center core (core 1) for the representative value of this MC-EDFA after this chapter.

III. MESUREMENT GAIN, NF AND POWER SAVING RATIO

We measured gain and NF for various input and pumping powers. The input signal was a 100 GHz spaced 47ch signal, and the pumping intensity varied from 1~20 W. The power available at the repeater is limited due to the power feed limitation of submarine cable systems. Therefore, the input power was set in the range of -20~0 dBm/core in this experiment because the power of the transmitted signal is expected to decrease as the number of cores increases when the multicore fiber is used.

Fig. 3(a) shows the pumping power vs. gain, and Fig. 3(b) shows pumping power vs. NF for different pumping configurations with input power fixed at -5 dBm/core. This paper defines the power saving ratio for a repeater as the difference between the pumping power (P_{pump}) and the forward pumping power ($P_{Forward}$) at the same gain divided by $P_{Forward}$. This equation is as follows,

$$Power\ Saving\ Ratio(\%) = \left(1 - \frac{P_{pump}}{P_{Forward}}\right) \times 100. \quad (1)$$

For example, Fig.3(a) shows the gain of each pumping configuration. When the gain is 17.3 dB, the pumping power difference of the forward and bidirectional pumping is 3.3 W. Therefore, the bidirectional pumping case's power saving ratio is 16.5 %. Similarly, the power saving ratio is 26.0 % at backward pumping. Fig.3(b) shows pumping power vs. NF for different pumping configurations. Relative to forward pumping, the NF of bidirectional pumping is 0.2 dB higher, and the NF of backward pumping is 0.7 dB higher. When input power is -5 dBm/core, forward pumping has the lowest NF and gain, backward pumping has the highest NF and gain, and bidirectional pumping has moderate gain and NF when the same pumping power.

Next, we evaluate the gain, NF, and power saving ratio when the input power was varied from -20~0 dBm/core and the pumping power from 1~20 W. Fig. 4(a) and Fig. 4(b) show the power-saving ratio of bidirectional and backward pumping against forward pumping, respectively, as color maps. In submarine transmission, the repeaters' gains are set to compensate for the transmission loss between the repeaters. Therefore, assuming a fiber transmission loss of 0.155 dB/km, input power of -5~0 dBm/core, and a repeater spacing of 60~80 km, the required gain is 9.3~12.4 dB. In the gain range of 9.3~12.4 dB, Fig. 4(a) shows that bidirectional pumping saves 17~19 % of power compared to forward pumping.

Similarly, backward pumping saves 24% less power than forward pumping. We compared NF for each pumping configuration. Fig. 5 (a)~(c) shows gain and NF for forward, bidirectional, and backward pumping. The horizontal axis is input power per core, the vertical axis is gain, and the color is NF. For example, forward pumping has NF 8~9 dB in the gain range of 9.3~12.4 dB, assuming submarine transmission. On the other hand, bidirectional pumping has NF 8~10 dB, and backward pumping has NF 8~12 dB in the same gain range.

From the results of the above measurements, the characteristics of each pumping configuration of the cladding pumped optical amplifier are clearly similar to those of the core-pumped optical amplifier of single-core fiber:

- Forward pumping has low NF.
- Backward pumping has high gain and high NF.
- The gain and NF of bidirectional pumping are between forward and backward pumping.

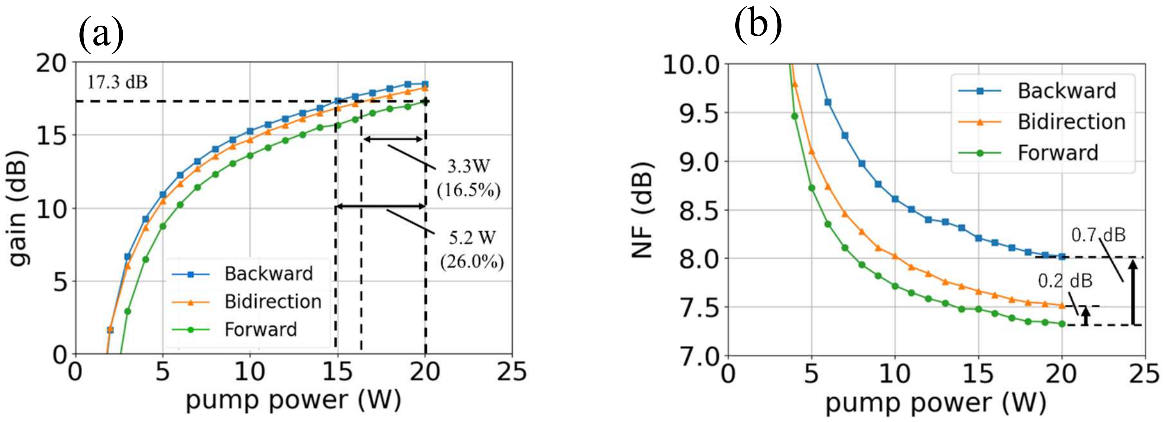


Fig.3 (a)Gain vs. pumping power and (b)NF versus pumping power for each pumping configuration. Input power is -5 dBm/core.

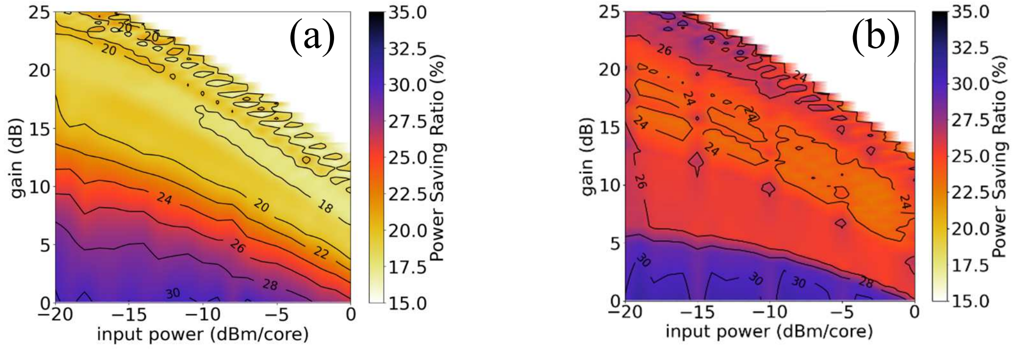


Fig.4 Input power vs. gain and the power saving ratio at that time (a) bidirectional vs. forward pumping, (b) backward vs. forward pumping

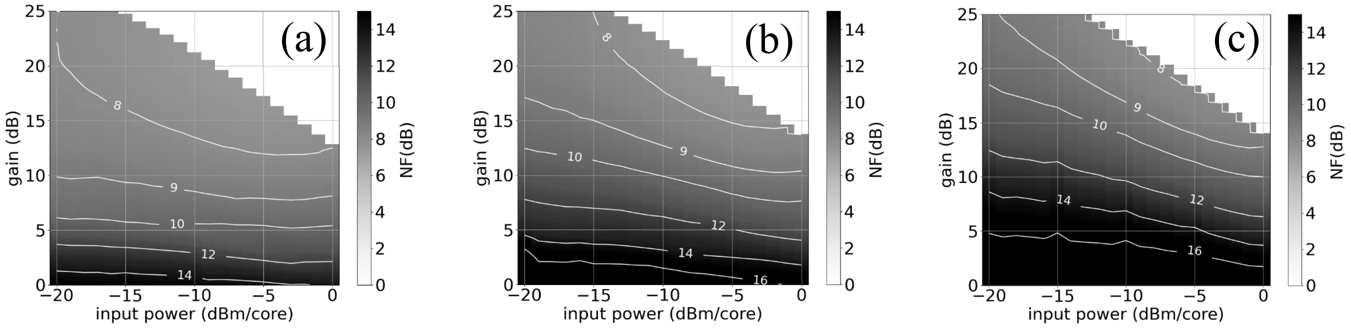


Fig.5 Input power (horizontal axis) vs. gain (vertical axis) and NF (color and contour line). (a) forward pumping, (b) bidirectional pumping, (c) backward pumping

IV. ESTIMATING THE POWER SAVING RATIO IN THE LONG-HAUL TRANSMISSION SYSTEM

The transmission system power saving ratio is evaluated assuming a repeater in a long-haul transmission system. When the repeater spacing is the same, forward pumping has the lowest NF among the three pumping methods and thus can extend the transmission distance. However, as described in Chapter III, NF is different by pumping configuration. And also, a comparison with the same gain shows that bidirectional pumping saves 18% and backward pumping saves 24% of power compared with forward pumping. Therefore, we performed calculations based on the idea that optimizing the repeater spacing can construct a transmission system with less power consumption than forward pumping. In this chapter, we use the transmission systems PSR which is modified from (1) using a number of repeater N_{rep} and a number of forward pumping repeaters $N_{Forward}$.

$$Transmission\ System\ PSR(\%) =$$

$$\left(1 - \frac{P_{pump}\ N_{rep}}{P_{Forwared}\ N_{Forward}}\right) \times 100 \qquad (2)$$

In the repeated transmission system, we considered ASE noise from optical amplifiers and nonlinear interaction in the fiber. In general, ASE noise P_{ASE} is described as follows[12],

$$P_{ASE} = FGh\nu B_{ch}. \qquad (3)$$

Where F is a noise figure, G is a gain which is defined by $G = \exp(\alpha L)$ using repeater span length L and transmission loss of fiber α. h is the Planck's constant, ν is a signal frequency and B_{ch} is a signal bandwidth.

In addition, we employed the Gaussian noise (GN) model for analytical calculation of the nonlinear interference noise P_{NLI}. From (15) and (26) in ref. [13].

$$P_{NLI} = \frac{\eta}{B_{ch}^2} P_{ch}^3 \qquad (4)$$

P_{ch} is a signal channel power. η is defined as follows,

$$\eta \sim \frac{8}{27}\gamma^2 L_{eff}^2 \frac{\operatorname{asinh}\left(\frac{\pi^2}{2}|\beta_2|(2\alpha)^{-1} B_{ch}^2 N_{ch}^{2\frac{B_{ch}}{\Delta f}}\right)}{\pi|\beta_2|(2\alpha)^{-1}}. \qquad (5)$$

γ is the nonlinearity coefficient, β_2 is the dispersion, and the effective fiber length L_{eff} is defined by (1-exp(-2αL))/2α. Δf is a signal channel space and N_{ch} is a number of channels. In this condition, GSNR(Generalized Signal to Noise Ratio) which contain ASE noise and a nonlinear noise is described by following equation.

$$GSNR = \frac{P_{ch}}{(P_{ASE} + P_{NLI})N_{rep}} \qquad (6)$$

Accordingly, GOSNR(Generalized Optical Signal-to-Noise Ratio) is as follows,

$$GOSNR = \frac{B_{ch}}{B_n} GSNR. \qquad (7)$$

B_n is an optical noise bandwidth of 0.1 nm(=12.5 GHz).

We assume that the transmission distance is 3,000 km, a regional submarine cable length, and the transmission loss α is 0.155 dB/km. The output power per channel P_{ch} has assumed -2 dBm/ch because the nonlinear noise is more negligible.

Fig. 6 shows the results of GOSNR calculations for various repeater spacing for each pumping configuration. The horizontal line on the graph shows the GOSNR that becomes error-free pre FEC (Forward Error Correction) limit for DP-QPSK, 8-QAM, and 16-QAM modulation formats with 32 Gbaud [14,15]. From the view of reducing the cost, the power saving ratio against forward pumping was compared under conditions where the set GOSNR was exceeded and the relay interval was widest.

The transmission system PSR of optimizing the repeater spacing is summarized in Fig. 7. Horizontal axis is GOSNR and vertical axis is transmission system PSR. The transmission system PSR here was calculated by (2). The transmission system PSR of backward pumping is the highest when the GOSNR under 19.2 dB. However, at GOSNR 20 dB, which is required by the higher-capacity 16QAM modulation format, bidirectional pumping is the most power saving for the entire system. In this case, bidirectional pumping can reduce the power by 27.2 % compared to forward pumping. Backward pumping has a higher NF than the other pump configuration and thus does not achieve an GOSNR 20 dB.

V. Conclusion

In this paper, we measured the gain and NF of a multicore cladding pumping amplifier with different input and pumping powers for three pumping configurations: forward, backward, and bidirectional. As a result, it was found that forward pumping has low NF, backward pumping has high gain and high NF, and bidirectional pumping has a moderate characteristic in un-coupled multicore cladding pumping as well as in single-core fiber. Then, when the repeater spacing is optimized for each pumping configuration, we calculated the power-saving effects of backward and bidirectional pumping relative to forward pumping when transmitting 3,000 km. The power saving ratio was based on received GOSNR assuming DP-QPSK, 8QAM, and 16QAM. The calculation results show that bidirectional pumping can reduce the power by 27.2 % compared to forward pumping with GOSNR 20 dB (assuming 16QAM). And backward pumping saves the most power GOSNR under 20 dB (assuming DP-QPSK and 8QAM). The above shows that backward pumping is more power-saving using low-order modulation formats. In comparison, bidirectional pumping is more power-saving using higher-order modulation formats.

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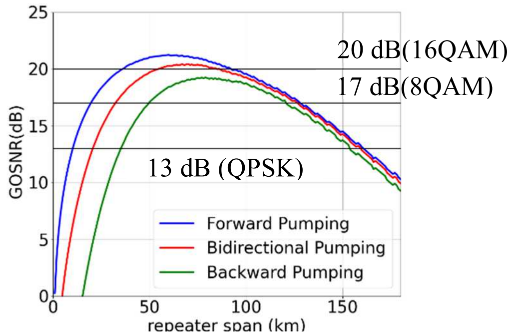

Fig.6 GOSNR at different repeater spacing for each pumping configuration.

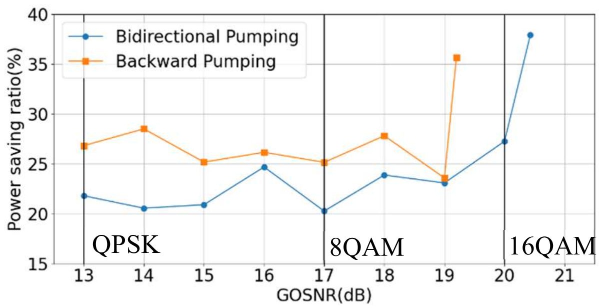

Fig.7 Power savings ratio of backward and bidirectional pumping relative to forward pumping at each GOSNR.

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