Improvement of the Energy Efficiency of Cladding Pumped Multicore EDFA Employing Bidirectional Pumping and Control

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Abstract *Cladding pump optical power ratio between forward and backward was controlled to realize the highest power efficiency. Considering output wavelength channel power equalization, we confirmed 24 % pump optical power reduction at 8 W total pump optical power for 0.8 dB penalty of noise figure.*

Introduction

Recently, much effort has been made to improve MultiCore Fibre (MCF) based transmission system performance from the various viewpoints towards actual use [1-3] to prepare a surge of communication traffic [4]. Our focus is cladding pumped multicore Erbium Doped Fibre Amplifier (MC-EDFA) which has the potential of the optical amplification efficiency improvement in the near future [5-6]. In the case of Single Core Single Mode Fibre (SCSMF) based transmission system, pairs of both fibre and repeater is needed for bidirectional signal transmission like submarine cable system for example. The replacement from SCSMF to MCF enables bidirectional transmission by using only a single MCF with pairs of core. It leads transmission capacity expansion by increasing transmission core as well as the extension of transmission distance by cancelling inter-core crosstalk [7]. For the bidirectional transmission using MCF, the optical repeater suitable for bidirectional MCF transmission system is needed, too. However, there are problems to be clarified for the use of bidirectional transmission such as pump direction dependence of gain and noise figure [8]. Bidirectional signal amplification by using UniDirectional cladding pumped MC-EDFA (UD-MC-EDFA) has been already investigated and showed good results [9]. Further, we have proposed a symmetrical BiDirectional cladding pumped MC-EDFA (BD-MC-EDFA) [10] which enables to reduce the differences in properties between both signal directions.

Besides, for long haul transmission systems which use over a hundred of optical repeaters, EQualization (EQ) technique [11] is indispensable to guarantee the reachability of all wavelength channels. Fundamentally, gain is flattened by attenuating the output power per wavelength channel using Gain Flattening Filter (GFF). Since the repeater output optical power per wavelength channel is equalized to the output of the channel with the minimum gain, the pump optical power for amplification is wasted as the channel with the larger gain. For the systems which available electric power are limited such as submarine cable systems, this pump optical power waste by EQ is serious problem. Realization of energy efficient EQ technique enabled transmission capacity expansion through the improvement of transmission signal OSNR at the signal receiving terminal [11].

In this paper, we use the BD-MC-EDFA and here, we investigate its gain characteristics controlling the pump optical power ratio between forward and backward. We confirm that the gain characteristics can be controlled to reduce EQ and we clarify that it enables to improve the energy efficiency of the BD-MC-EDFA. We report in detail the optimization of the ratio under a fixed total cladding pump optical power.

Configuration and gain control principle under fixed power optical power condition

Fig. 1 shows the configuration of our fabricated 7-core BD-MC-EDFA prototype. The remarkable feature is symmetricity between FIFO1 (Fan-In Fan-Out) and FIFO2. In the case of signal transmission from west to east, Pump LD1 is used for forward cladding pumping. CMB/SPL1

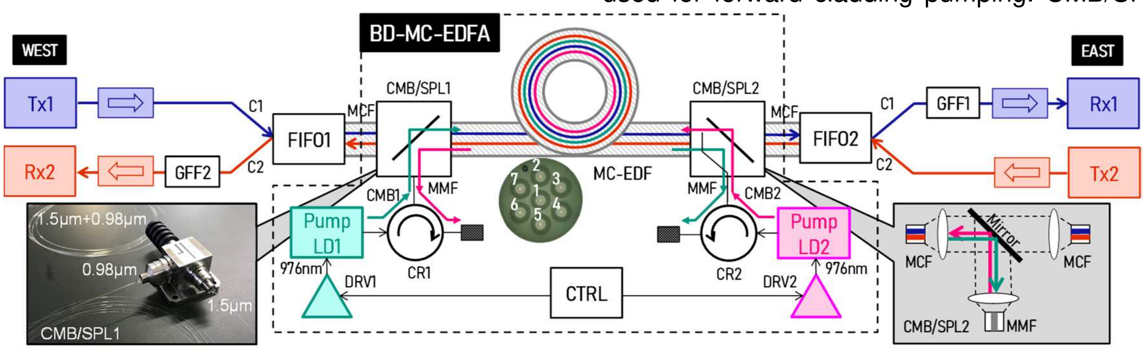

Fig. 1: Configuration of bidirectional cladding pumped 7-core multicore EDFA prototype.

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(CoMBiner/SPLitter) is used as a pump light combining device with signal light and CMB/SPL2 is used as a remaining pump light splitting device from the output of MC-EDF. For the backward cladding pumping using Pump LD2, the role of CMB/SPL1 and CMB/SPL2 is reversed. The CMB/SPL is as small as 37 x 45 x 18 mm and a dichroic mirror is used inside as shown in Fig.1. The loss of CMB/SPL for signal light and pump light is 0.8 dB/core and 0.95 dB respectively. CR1 (CiRculator) has dual role of pump light injection from Pump LD1 to CMB/SPL1 and backward remaining pump light prevention into Pump LD1, which is injected from Pump LD2. Its isolation is 25 dB in the case of this prototype. When the pump light from Pump LD2 is turned off, the BD-MC-EDFA can be used as a forward cladding pumped UD-MC-EDFA. Similarly, the BD-MC-EDFA can be used as a backward cladding pumped UC-MC-EDFA when the pump light from Pump LD1 is turned off. Gain characteristics of forward and backward cladding pumping is different even if the pump optical power of both is identical [8]. Therefore, gain shape of the BD-MC-EDFA can be changed by controlling driving current of Pump LD1 and Pump LD2. When the peak-to-peak value of the BD-MC-EDFA output power per wavelength channel becomes minimum for WDM signal input, namely, the flatness of gain shape becomes the maximum, loss due to wavelength channel output power equalization becomes the minimum and then power efficiency becomes the maximum under a fixed total cladding pump optical power condition.

Gain and noise figure dependence on cladding pump optical power ratio

Fig. 2 shows a measured relationship between pump optical power and wavelength average gain of the centre core when the BD-MC-EDFA is used as the UD-MC-EDFA. UD-FWD(1/0) means 100 % forward cladding pump and 0 % backward cladding pump by shutting down Pump LD2. The direction of signal propagation was from WEST to EAST. Input optical power was -3 dBm/core. Gain of backward cladding pump using only Pump LD1 is always larger than that of forward cladding pump using only Pump LD2. This tendency is as same as conventional SC-EDFA [8]. The difference of gain at 8 W total cladding pump optical power between forward and backward was 2.5 dB. In order to obtain 19.5 dB of gain by only forward cladding pumping, 13 W of cladding pump optical power will be needed. Therefore, the use of backward cladding pumping instead of forward one supposes to enable 39 % of reduction of pump power under this experimental condition. Fig. 3 and Fig. 4 shows wavelength dependence of gain and noise figure, respectively. The measurement parameter was the cladding pump optical power ratio between forward and backward. In Fig. 3, BD(0.33/0.67) means pump optical power ratio between forward and backward is 33 % and 67 % respectively. Though it is explained afterwards, BD(0.33/0.67) is the best under this experimental condition. What should be noted in Fig. 3 is the difference of gain. The difference of wavelength average gain between UD-BWD(0/1) from UD-FWD(1/0), and that between BD(0.33/0.67) from UD-FWD(1/0) shows 2.5 dB and 1.6 dB respectively. Therefore, 100 % backward cladding pumping is preferable to realize the higher gain under this experimental condition. However, Fig. 4 shows that the use of backward cladding pump cladding pumping degrades noise figure. The penalty of noise figure for 100 % backward cladding pumping is 1.8 dB. The noise figure penalty could be improved by using more accurate MCF splicing technology in the future as the configuration of Fig. 1 has four MCF splice points between FIFO1 and FIFO2. So, the cladding pump optical power ratio will be determined how much noise figure penalty could be acceptable for the system using the BD-MC-EDFA. Though the results of the other core are

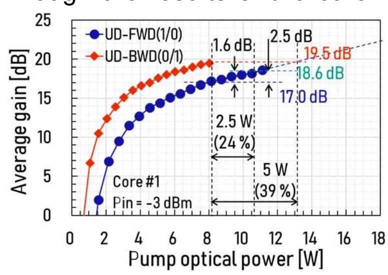

Fig. 2. Relationship between pump optical power and gain.

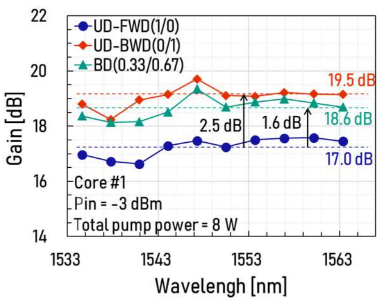

Fig. 3. Gain dependence on pump direction.

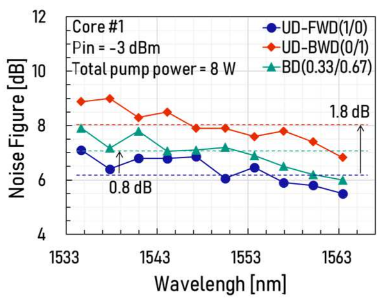

Fig. 4. Noise figure dependence on pump direction.

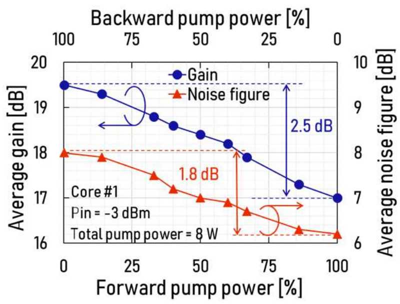

Fig. 5. Difference of gain and noise figure in average.

not shown in this paper for simplicity, a similar tendency was observed.

Equalization of output optical power per wavelength channel

Since gain characteristics of the BD-MC-EDFA can be actively controlled by changing the cladding pump optical power ratio between forward and backward, we expected that gain shape control function will too. Next, equalization of the BD-MC-EDFA output was investigated using Wavelength Selective Switch (WSS) as a GFF as shown in Fig. 1. 100 GHz spaced 47 WDM signals which centre wavelength from 1529.55 nm to 1566.31 nm was inputted into the BD-MC-EDFA. Total optical power of the WDM input was -3 dBm. The BD-MC-EDFA output optical power of each wavelength channel was adjusted to be identical by using WSS. The measurement parameter was the ratio of cladding pump optical power ratio between forward and backward. Total cladding pump optical power was fixed at 8 W. As shown in Fig. 6, equalization was done by attenuating the BD-MC-EDFA output power per wavelength channel to the minimum power among 47 channels. The equalization profile, which is the amount of attenuation per wavelength channel depends on wavelength dependence of gain. Therefore, it will be changed when the ratio of cladding pump optical power between forward and backward.

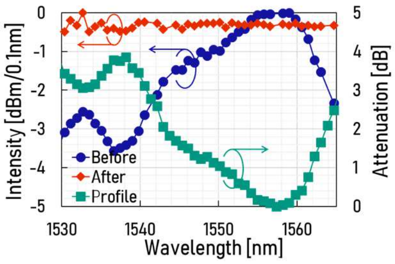

Fig. 6. .BD-MC-EDFA output before and after equalization

Fig. 7 is the attenuation profile of WSS. The profile was changed according to the forward pump optical power ratio. To characterize that profile change, peak-to-peak (p2p) value of the attenuation profile in Fig. 8 was investigated.

Though the p2p of the attenuation profile is almost constant less than 33 % of forward cladding pump optical power ratio, it increases proportional to the forward cladding pump optical power ratio from 3.65 dB to 4.20 dB, when that pump optical power ratio becomes more than 33 %. From this result, forward cladding pump optical power ratio is found out to be required to be set less than 33 % to save optical power loss by equalization. The difference of wavelength average noise figure in Fig. 8, which is replot of Fig. 5, is decreasing proportional to the forward cladding pump optical power ratio. From the view point of noise figure, the higher forward cladding pump optical power is the better. Therefore, the optimum cladding pump optical power ratio of forward for the highest efficiency is obtained as 33 %. Fig. 9 shows optical power loss by equalization calculated by using the measured result of Fig. 7. It shows that 33 % of forward cladding pump optical power ratio can achieve 6.3 % saving of optical power loss caused by EDFA output power equalization. In Fig. 2, pump power reduction becomes 24 % at this operation condition compared with the conventional 100 % forward pump, UD-FWD(1/0).

Conclusions

In this paper, we have confirmed the feasibility of energy efficiency improvement of cladding pumped multicore EDFA employing bidirectional pumping through the detail investigation of gain characteristics. By controlling cladding pump optical power ratio between forward and backward, gain and gain shape can be adjusted under a constant pump power consumption. Taking output power equalization per wavelength channel into account, 33 % of forward cladding pump optical power ratio to backward one is the optimum to obtain the highest efficiency under the condition of 8 W total cladding pump optical power. We have successfully confirmed that 24 % pump power reduction is feasible if 0.8 dB penalty of noise figure is acceptable.

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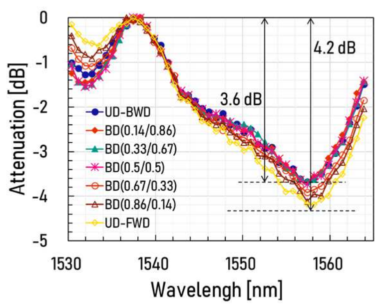

Fig. 7. Amount of attenuation for each wavelength channel.

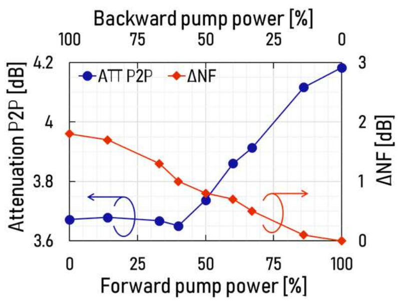

Fig. 8. Peak-to-peak of the attenuation for each wavelength channel.

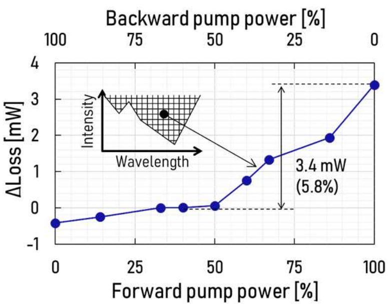

Fig. 9. Loss of optical power by equalization of the BD-MC-EDFA output.

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