Power Efficient Core Pumped Multicore Erbium Doped Optical Fiber Amplifier

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Abstract: A core pumped 4-core erbium doped optical fiber amplifier with a pump fan-in integrated combiner achieved the highest optical power conversion efficiency of 32.2% among reported C-band multicore erbium doped optical fiber amplifiers. © 2022 The Authors

1. Introduction

Two or four-core optical fibers are currently undertesting to apply to submarine optical cables. In multicore optical fiber (MCF) transmission with 4 or more cores, power efficient multicore erbium doped optical fiber amplifiers (MC-EDFAs) without fan-in/fan-out (FIFO) devices in signal lines can be expected to be applied for transoceanic communication system.

Recently, cladding pumped MC-EDFAs have remarkably improved in the optical power conversion efficiency (PCE) reaching 10.2% [1]. Core pumped MC-EDFAs have been focused again because the core pumped amplifiers have several advantages, such as potentially high PCE, individual gain or power control, and practical drive current for pump lasers [2, 3, 4]. The PCE of core pumped coupled 7-core EDFA was approximately 20 % due to a high loss in the pumping path [2]. Although the PCE of commercial single-core EDFAs reaches over 50% except for gain flattening loss, the use of FIFO in signal lines degrades the PCE in MCF transmission. A combination of an MC-EDF and single-core devices through FIFO, which is another approach, showed the PCE of 18% with gain flatten filters [5].

Removing a pumping fan-in device is the one of effective approaches to improve the PCE [3, 4, 6]. In the core pumped 19-core EDFA with a pump fan-in integrated combiner, the PCE has reached approximately 10% [6]. In this work, we demonstrated an uncoupled 4-core EDFA with a pump fan-in integrated combiner.

2. Uncoupled 4-core EDFA with a Pump Fan-in Integrated Combiner

The uncoupled 4-core EDFA shown in Fig. 1 includes a 15 m long uncoupled 4-core EDF, a pump fan-in integrated combiner, an isolator, and 4 pump lasers. The 4-core EDF was connected to the combiner and isolator through short 4-core bridge fibers. The pump lasers were connected to the combiner through 4 short single-core pump delivery fibers.

The 4-core EDF, bridge fiber, and transmission fiber have a square core arrangement with a core pitch of 45 μm. The 4-core EDF and bridge fiber have the same mode field diameter (MFD) of 5.6 μm at the wavelength of 1550 nm and the same MFD of 3.3 μm at the wavelength of 980 nm. The 4-core transmission fiber has an MFD of 9.5 μm at the wavelength of 1550 nm. The pump delivery fiber has an MFD of 5.9 μm at the wavelength of 980 nm.

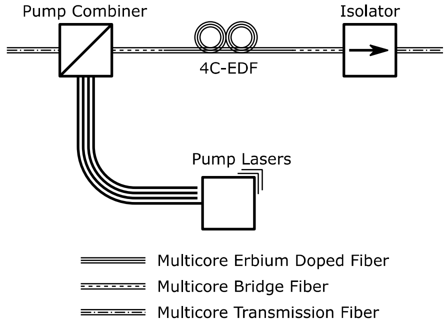

Fig. 1. Configuration of MC-EDFA with a pump fan-in integrated combiner

The pump fan-in integrated combiner shown in Fig. 2 is based on spatial optics. It contains a 4-core transmission fiber for signal input, a 4-core bridge fiber for signal output and a bundle of 4 delivery fibers for pumping shown. The etching fiber bundle has the core pitch of 45 μm and was fabricated based on bundle FIFO technologies [7]. The combiner has insertion losses of 0.5 dB for signals and 0.4 dB for pumps.

The isolator is also based on spatial optics and has an insertion loss of 0.7 dB and an isolation of 55 dB. It contains a 4-core bridge fiber for signal output and a 4-core transmission fiber for signal input.

Fusion splicing loss between different kinds of MCFs is usually higher than loss between the same kind of MCFs. Therefore, the 4-core transmission fibers contained in the combiner and isolator can suppress splicing losses between amplifiers and transmission lines. Likewise, the 4-core bridge fibers contained in the combiner and isolator can suppress splicing losses between these devices and 4-core EDFs.

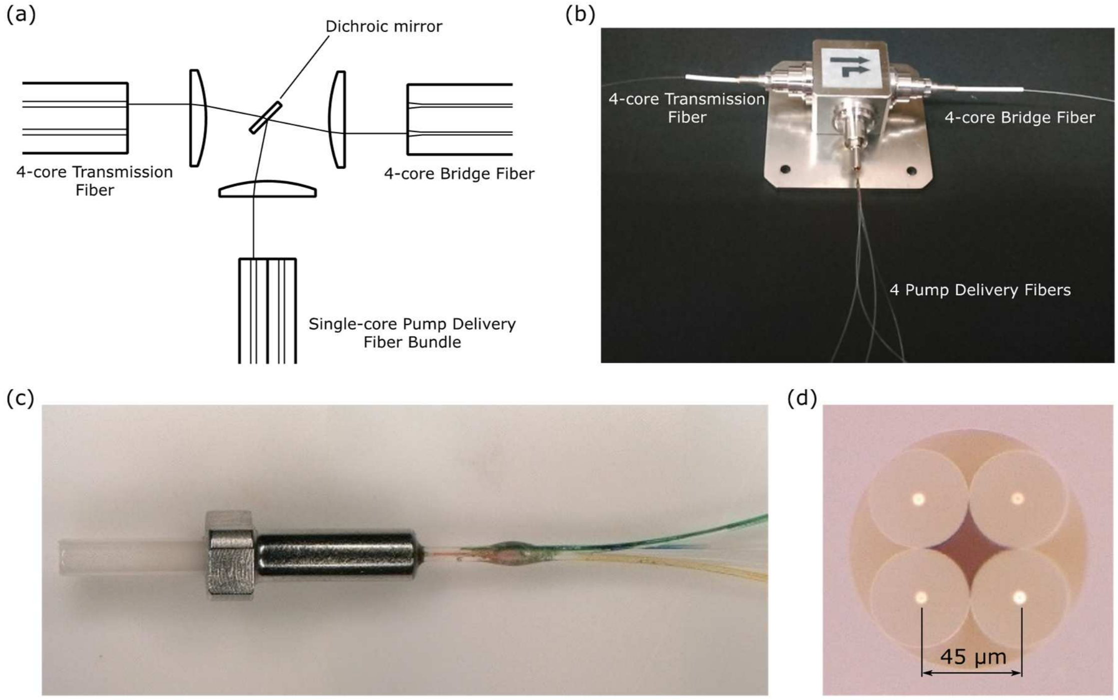

Fig. 2. The schematics of optics (a) and, photograph of the pump fan-in integrated combiner (b), the bundle of 4 pump delivery fibers (c) and its output facet (d).

3. Experimental Setup

Figure 3 shows the setup for measurement on the characteristics of the amplifier. The fan-in and fan-out for signal were included in the measurement system but not included in the amplifier characteristics. The 13-wavelength division multiplex signals were split and applied into all 4 cores through delay lines. They have wavelengths of 1527.994 nm and 1531.898nm to 1563.9 nm with a spacing of 400 GHz. The total power of the input signals at the output of the signal fan-in is 0.0 dBm/core with an inter-wavelength-channel fluctuation of less than 0.5 dBpp. The pump lasers have a wavelength of 976 nm. The pump powers were adjusted to make the signal output power to be 19 dBm/core at the input of the signal fan-out.

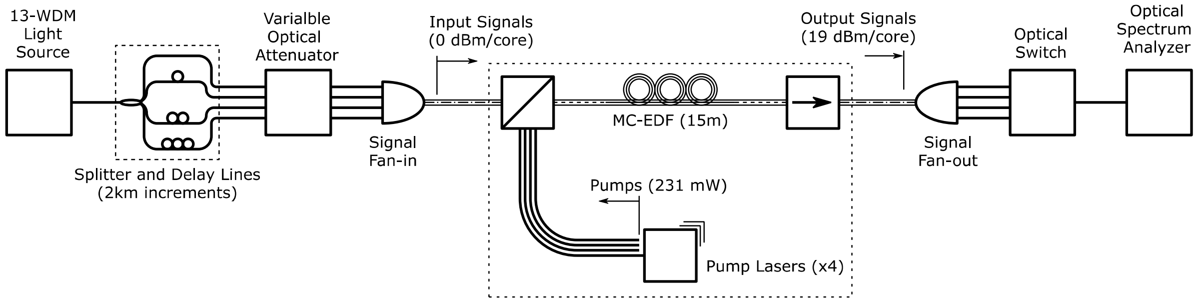

Fig. 3. Setup for gain and noise figure spectra measurement

4. Results and Discussion

Figure 4 shows the gain and noise figure spectra. The amplifier has a gain of 15 dB to 20 dB with a core-dependent gain of 0.7 dB at each wavelength-channel, and an inter-wavelength-channel inter-core maximum noise figure of 4.6 dB under signal inputs of −3.0 dBm/core to 3.0 dBm/core.

The properties of the amplifier are summarized in Table 1. The total PCE of 32.2% under a signal input of 0 dBm/core and an inter-core average pump laser output of 231 mW is the highest value among reported MC-EDFAs to the best of our knowledge. A PCE η_m for mth core and total PCE η are calculated by Eq. (1) and (2), respectively.

$$\eta_m = \frac{S_{\text{out}\,m} - S_{\text{in}\,m}}{P_m} \quad (1),$$

and,

$$\eta = \frac{\sum_m S_{\text{out}\,m} - \sum_m S_{\text{in}\,m}}{\sum_m P_m} \quad (2),$$

where $S_{\text{out}\,m}$, $S_{\text{in}\,m}$, and P_m are signal output, signal input, and pump power for mth core, respectively.

Optical submarine repeaters demand an output power of over 15 dBm and a power feeding current of 1.1 A [8]. Amplifiers in the repeaters are require to be gain-flatten. Thus the output power should be over 18 dBm because the insertion loss of gain flatten filters is estimated at 3 dB. The signal output of this amplifier achieved 18.8 dBm /core. The pump laser output of 231 mW corresponded to a laser driving current of 0.38 A. Therefore, this amplifier satisfies a practical drive condition for optical submarine repeaters. The optical PCE is lower as compared with commercial single-core EDFAs but the reduction of losses, especially fusion splicing losses with MC-EDFs, can drive MC-EDFAs to an optical PCE of over 50%.

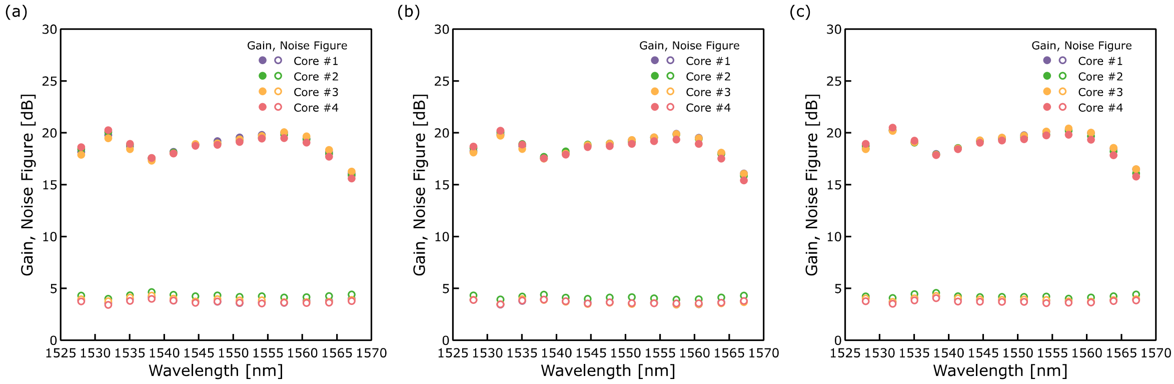

Fig. 4. Gain and noise figure spectra under the signal inputs of 0.0 dBm/core (a), 3.0 dBm/core and –3.0 dBm/core.

Table 1. Properties of the amplifier

Signal Input [dBm/core]	Average Signal Output [dBm/core]	Average Gain [dB]	Maximum Noise Figure [dB]	Average Pump Laser Output [mW]	Total PCE [%]
0.0	18.8	18.8	4.6	231	32.2
3.0	21.8	18.8	4.4	484	30.3
–3.0	16.1	19.1	4.6	126	32.2

5. Conclusion

We demonstrated a core pumped 4-core EDFA with the high PCE of 32.2% under the practical driving condition. MCF pump combiners, isolators, and fusion splicing points still have enough margin to reduce insertion loss. Therefore, core pumped MC-EDFAs can reach a higher PCE over 50%, and thus a strong candidate for submarine MCF transmission systems with 4 or more cores.

6. References

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