Coupled 12-core Fibre Amplifier with Efficiency Improved by Cladding Diameter-matching Pump Injection

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Abstract *We demonstrate a C-band cladding-pumped 12-core erbium-doped fibre (EDF) amplifier with less than 40% electrical power consumption compared to conventional amplifiers enabled by our proposed cladding-tapered pump launching scheme. The highest power conversion efficiency of 14.5% was achieved by applying our pumping reflection technique. ©2023 The Author(s)*

Introduction

Randomly coupled multi-core fibre has recently shown promise as a space division multiplexing (SDM) fibre owing to its high potential for achieving a larger capacity than un-coupled MCF, as the number of cores can be increased with a smaller core pitch design. A structure of up to 19 cores has been reported with a standard cladding diameter [1–2]. Amplification technology for MCF is essential for enabling long-distance SDM transmission. One of the advantages of utilizing an MCF amplifier instead of multiple conventional erbium-doped fibre amplifiers (EDFAs) with a fan-in/fan-out device [3] is the reduced complexity of the amplifier configuration. The cladding-pumped MCF amplifier is also an attractive approach for reducing the electrical power consumption thanks to its use of a power-efficient multi-mode laser [4, 5]. Although a power consumption lower than that of the multiple single-mode EDFA (SM-EDFA) configuration has been demonstrated for the L-band SDM amplifier [5], as yet there are no C-band SDM amplifiers with a low power consumption. A coupled MCF amplifier can offer improved power efficiency even in the C-band with the cladding pumped configuration since its high core-to-cladding ratio design enables the absorption ratio for pump light to be improved. The highest optical power conversion efficiency (PCE) of more than 10% has been reported with a coupled 12-core EDF [6].

In this paper, we propose a cladding diameter-matching pump light injection and reflection scheme for coupled 12-core EDFA to further improve the power efficiency and demonstrate for the first time a lower power consumption than the multiple SM-EDFAs in the C-band. Specifically, we confirmed the relative power reduction factor of less than 0.4 with the tapered fibre-based efficient pump injection and the highest PCE of 14.5% among the reported C-band SDM amplifiers by implementing our pump light reflection technique.

Proposal and Experiments

Figure 1 shows the configuration of the proposed 12-core EDFA. The EDF, 12-core signal-pump combiner, pump stripper, and isolator we used were the same as those reported in our previous study [6]. In this configuration, we deploy the cladding diameter-tapered sections at both sides of the EDF to efficiently guide the pump light into the EDF and deploy the pump reflector at the output side to re-use the residual pump light propagating through the EDF. The proposed configuration is effective for EDFs with a smaller cladding design (e.g., less than 125 μm), which is a realistic situation for coupled MCF. We set the cladding diameter of our EDF to 90 μm so as to increase the core-to-cladding ratio of the EDF with the small core pitch of 15.5 μm. For the type A configuration, we inserted a taper-fibre between the output fibre of the pump combiner and active 12-core fibres where the cladding diameter was down-tapered from 125 to 90 μm. For type B, an up-tapered fibre and pump reflector were connected at the output side of the EDF. The pump reflector only reflects the pump light and re-couples it into the EDF in the counter propagating direction while the signal light passes through the device. The same concept has been utilized in the fibre Bragg grating-based pump reflector [7].

Figure 2(a) and (b) show side- and end-view images of the tapered fibre. The cladding diameter was decreased incrementally from 125 to 90 μm through five sections. As the tapering

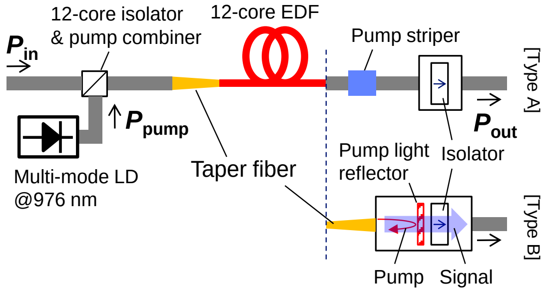

Fig. 1: Configuration of proposed 12-core EDFA

section was fabricated based on the 125-μm 12-core fibre by chemical etching, the core structure remained constant before and after the tapering, as shown in Fig. 2(b). Figure 2(c) shows a photograph of the splice point between passive and active fibres. As we can see, cladding diameter mismatching occurred and a steep change in the cladding diameter was observed without the tapering fibre. In contrast, there was no cladding diameter mismatching at the splice point with the tapered fibre. We confirmed that the pumping light injection efficiency into the EDF was improved from 57% for the conventional setup to 87% for the proposed configuration.

Next, we experimentally evaluated the gain and noise figure (NF) characteristics. The measurement setup was the same as described in [6] except for using 8-wavelength WDM light, with the wavelength allocation in the 1530–1565-nm range at 5-nm intervals. We utilized the fibre bundle-based 12-core fan-in device to input the CW lights into all cores of the EDF with a power of −8 dBm/core. The modal gain was defined as the averaged value calculated by the 12 spectra from 12 ports of the fan-out device. The gain and NF values were derived by compensating for the loss of the fan-out device. Figure 3(a) shows the gain at 1550 nm as a function of the pumping power. Circles, triangles, and squares correspond to the gain for the previous configuration without taper fibre [6], the type A, and the type B configuration, respectively. Note that the gain variation among the 12 results for each plot, which was within ±1 dB, did not significantly change for any configuration. We observed a higher gain for all pumping powers for both type A and type B than the previous setup. The improvement was much more significant from the previous configuration to type A than from type A to type B, which indicates that the deterioration of the pumping light injection efficiency was the dominant factor in the previous setup. Figure 3(b) shows the gain spectra over the entire C-band when the pumping power was 4 W. The gain improvement by our proposed setup was confirmed for all signals within the C-band. We also found that pumping of just 4 W (0.33 W/core) was sufficient for obtaining a gain of more than 20 dB over the C-band. Figure 4 shows the NFs when the averaged gain was about the same (20.2–21.8 dB) for the three configurations. The NF of type A exhibited the lowest value among the three. We presume that the NF improvement is owing to the splice loss decrease, since the core deformation can be suppressed by cladding diameter-matching fusion splicing. On the other hand, the NF of type B was slightly degraded, particularly for shorter

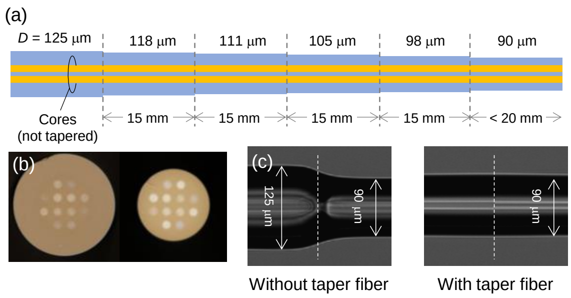

Fig. 2: (a) Schematic image of tapered fibre-section, (b) 12-core fibre end-face before/after tapering, (c) photograph of splice point between passive fibre and EDF.

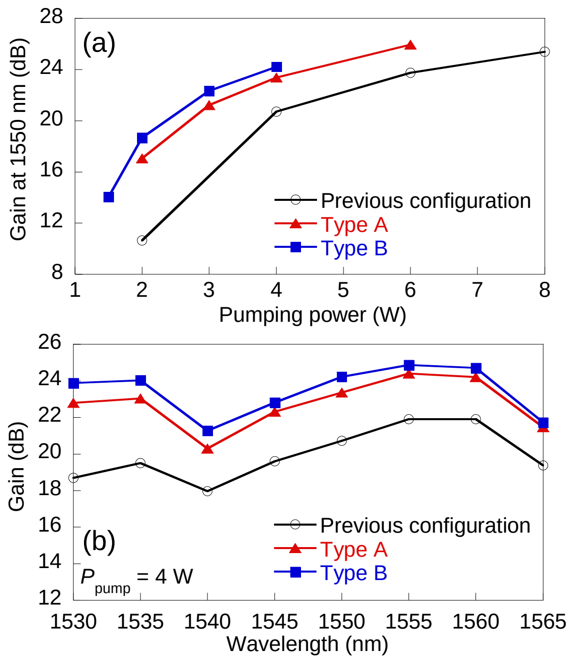

Fig. 3: (a) Gain at 1550 nm as a function of pumping power, (b) gain spectra for 1530–1565 nm when pump power is 4 W for three EDFA configurations.

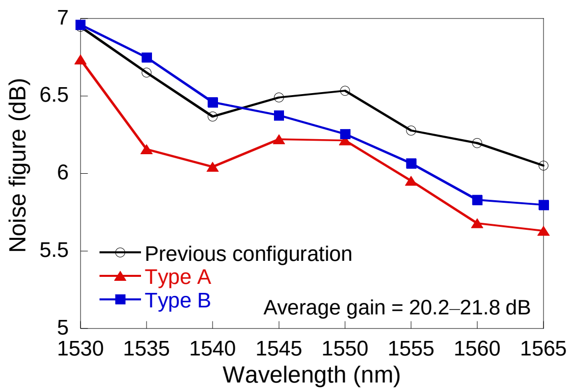

Fig. 4: Noise figure characteristics over C-band when the averaged gain is 20.2–21.8 dB for three EDFA configurations

wavelengths, even though the value was almost the same as that of the previous setup. We numerically confirmed that the insufficient return loss characteristic for C-band light in the pump reflector causes NF degradation at the shorter wavelength, so the suppression of ASE reflection may be necessary for reducing the NF for the type B configuration. These findings demonstrate the effectiveness of cladding diameter-matching pump light injection and reflection, which exploits the power efficiency potential of the small cladding diameter coupled MCF amplifier.

Performance comparison

We investigated the power efficiency of the EDFA. First, the optical PCE, which is defined as (P_{out} – P_{in}) / P_{pump}, was evaluated. The PCE values of 13.7 and 14.5% were confirmed for types A and B, respectively, when the pumping power was 10 W. These are the highest values among the reported full C-band SDM amplifiers (4.4% improvement from the latest value of 10.1% [10]). Since the PCE value tends to be higher for the high input/output power operation even though the operation conditions are quite different depending on the application area, we next investigated the electrical power consumption of the EDFA as another performance analysis. The relative power reduction factor *k* [5] is a useful tool for directly evaluating the power efficiency, where the total electrical power of the EDFA is calculated and compared with the multiple-EDFA configuration. Here, we assume an SM-EDFA for terrestrial use requiring an average gain of about 20 dB with the TEC-based temperature control for a single-mode pumping laser. Table 1 lists the required pumping power from the experimental results, LD driving or cooling power, and the factor *k* normalised when using 12 SM-EDFAs. The electrical power consumed by the SM-EDFA was derived similarly to [5], where we assumed a typical single-mode LD product (M27 series from Lumentum). Regarding the cladding pumped amplifier, the value was based on the MM-LD with the power-saving ventilator (1.1-W power consumption) for LD cooling, which was used in our experiment. The LD temperature was controlled to be < 26 °C for the measurement time period of more than a few hours in our laboratory environment. We found that the factor *k* was below 1 for all types of 12-core EDFAs, and less than 0.4 was possible for types A and B, which is the first demonstration of a C-band MCF amplifier superior to the multiple SM-EDFAs in electrical power consumption.

Next, we compared the effectiveness of the pump reflection scheme and the previously reported recycling method [8, 9]. Figure 5 shows

Tab. 1: Comparison of electrical power consumption

	Pumping power (W)	LD driving power (W)	LD cooling power (W)	Relative power reduction factor
SM-EDFA×12	0.1	7.5	14.3	1.0
Previous	3.9	9.5	1.1	0.48
Type A	2.8	6.9	1.1	0.37
Type B	2.4	6.1	1.1	0.33

For 20-dB average gain in C-band

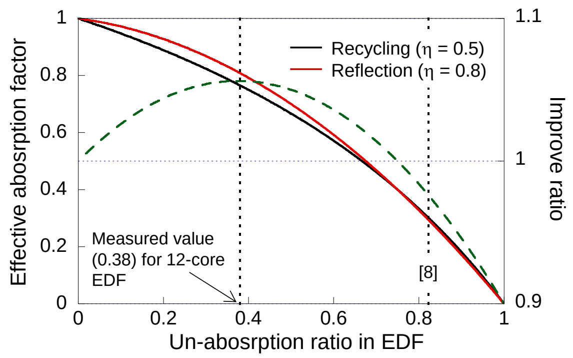

Fig. 5: Comparison of effective absorption factor in EDF between recycling and reflection schemes.

the simulated effective absorption factor ρ in the EDF for the reflection and recycling configurations, where ρ is defined as the total absorbed pumping power in the EDF normalised by the initial injection power. The recycling efficiency was assumed to be 0.5 taking into account the previously reported value [9]. The reflection efficiency was assumed to be 0.8, since the measured reflection ratio and loss of the tapering section were 0.92 and 0.87, respectively. The higher efficiency for the reflection type was owing to the simple free-space-optics-based reflection and re-coupling into the EDF. The horizontal axis in Fig. 5 shows the un-absorption ratio in one-way pumping light propagation through EDF, which indicates a change to the core-to-cladding ratio of the EDF. The right vertical axis shows the ratio of ρ between reflection and recycling. We can see here that the reflection scheme is effective for a lower un-absorption ratio. For example, the measured ρ value for our 12-core EDF was 0.38, which means that only reflecting the residual pumping light is enough to improve the efficiency.

Conclusions

We proposed a 12-core EDFA with improved power efficiency by applying a cladding diameter-matching pump light injection and reflection scheme, which is effective for smaller cladding diameter EDF with a higher core-to-cladding ratio design. Our experiments showed that the proposed EDFA had the highest PCE of 14.5% and demonstrated a relative power reduction factor of 0.4 compared to the multiple-SM-EDFA configuration in the C-band.

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