European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

Core-to-Cladding Ratio-Optimized L-Band Coupled 12-Core Fibre Amplifier with the Highest Power Conversion Efficiency

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Abstract. *We reveal that the core-to-cladding ratio (R_{cc}) dependence on the power conversion efficiency (PCE) in cladding-pumped multi-core fibre (MCF) amplifiers differs depending on the operating bandwidth. We obtain the highest PCE from the reported cladding-pumped L-band coupled-MCF amplifiers, 5%, with a fabricated R_{cc}-optimized 12-core amplifier. ©2022 The Author(s)*

Introduction

For over a decade, multi-core fibre (MCF) technology has been intensively studied to deal with the future capacity crunch of conventional single-mode fibre [1]. A cost-effective telecommunication system with minimal infrastructure can be developed by introducing MCF technologies owing to high spatial multiplicity of the MCF. Energy efficiency is one important factor for sustainable growth of a fibre-optic communication system [2], and the cladding-pumped MCF amplifier is becoming a promising energy-efficient repeater [3–6]. The coupled MCF design is a suitable approach to both obtaining high spatial density for transmission lines and improving the energy efficiency of the amplifier. Power conversion efficiency (PCE) of more than 10% has been achieved with the coupled 12-core Er-doped fibre amplifier (EDFA) by applying high core-to-cladding ratio (R_{cc}) design [3], which cannot be obtained for the uncoupled MCF. However, the improved PCE of the coupled multi-core EDFA was only achieved for the C band, and fairly low efficiency was reported in the L band with the 12-core EDFA with a high R_{cc} value [3]. Thus, we realized the necessity of designing an energy-efficient L-band amplifier for future high spatial density and wideband transmission systems.

In this paper, we investigate the relationship between the PCE and R_{cc} value in the cladding-pumped MCF amplifier. To the best of our knowledge, we reveal, for the first time, that the R_{cc} dependence on the PCE differs depending on the operating bandwidth (C or L band), and that the PCE can be maximized at a specific R_{cc} value for L-band operation. The fabricated R_{cc}-optimized coupled 12-core fibre showed the PCE of 5%, the highest among the reported cladding pumped L-band coupled MCF amplifiers.

Numerical Investigation

We numerically investigated how the cross-sectional design of the multi-core Er-doped fibre (MC-EDF) affected the amplification efficiency in the cladding pumped scheme. We focused on the R_{cc} value as a key cross-sectional parameter for characterizing the PCE, which is defined as the ratio between the total core and cladding area [7]. Figure 1 shows the calculated PCE as a function of R_{cc} for an MC-EDFA operating on C- or L-band. The PCE is defined as the ratio between the total signal output power and pumping power [8]. We calculated amplification characteristics by solving the rate-equation for each core and deriving the longitudinal evolution of the signal and pump power with the same calculation model described in [9]. We assumed a step-index core MC-EDFA with 12 cores, a 90-μm cladding diameter, and a 6×10^{24} ions/m^3 Er doping concentration, while the core radius was varied. We assumed a −8 dBm/core for the input signal power P_{in} and we adjusted the pumping power P_{pump} and EDF length L to obtain a 20-dB gain for both extreme wavelengths (1530 and 1565 for C band; 1570 and 1605 nm for L band). The blue dashed line in Fig. 1 representing the C-band amplifier demonstrates that the PCE increases as the R_{cc} increases, indicating that a high R_{cc} EDFA for an efficient C-band amplifier should be designed as described in [3]. Unlike the C-band case, the PCE for L-band operation was maximized at a specific R_{cc} value (at 0.017 in this case), then decreased beyond the optimal value. Based on the results,

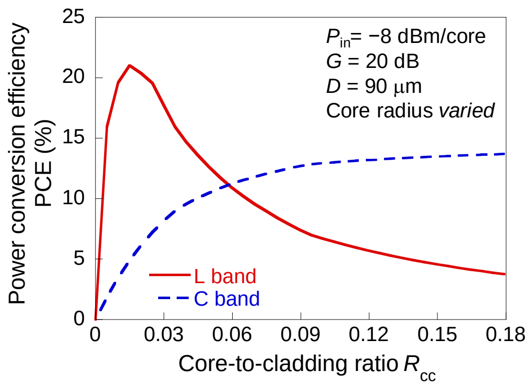


Fig. 1: Calculated relationship between power conversion efficiency (PCE) and core-to-cladding ratio (R_{cc}) in cladding-pumped amplifier for C or L band.

different cross-sectional optimizations of MC-EDF are required depending on the operational wavelength to develop an energy-efficient cladding-pumped amplifier.

Experiment

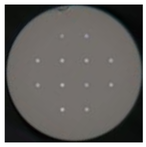
Because the R_{cc} value of our previously fabricated 12-core EDFA was 0.17 [3], which was far beyond the optimal R_{cc} value for energy-efficient L-band amplification, we fabricated additional 12-core Er-doped fibre with a smaller core radius of 2.0 μm (R_{cc} = 0.02), while keeping the same cladding diameter of 90 μm to validate the simulation results shown in Fig.1. The cross-sectional photographs and the structural parameters of the two MC-EDFs are summarized in Tab. 1. The twelve cores with a step-index profile arranged in a square lattice were deployed within the cladding, and the cladding was surrounded by a low index polymer coating to confine the pump light within the cladding.

Figure 2 shows the configuration of the EDFA. The input signal and pump light were multiplexed with a free-space optics-based combiner where the signal light was launched into each core and the pump light from a 105 μm core multi-mode fibre was injected into the cladding area of the MCF. The wavelength of the multi-mode pump light was 975 nm. The input side of the MC-EDF was spliced with the output port of the combiner, and the other side was spliced with the 12-core isolator. The residual pump light was dissipated by the pump stripper deployed between the MC-EDF and the isolator.

Figure 3 shows the setup for measuring the amplification characteristics of the EDF. We used a 4-wavelength continuous wave saturation light with a 10 nm wavelength interval to fix the gain spectrum during the gain and noise figure (NF) measurement for a tested wavelength by using the light from the tunable laser diode (LD). The power of the tunable LD was set to 20 dB below the power of the saturation light per wavelength. The signal was then split into twelve ports by the power splitter, and multiplexed through the 12-core fan-in device after the power level was controlled by the variable optical attenuators. The output port of the 12-core fan-in device was spliced with an MC-EDFA that had an input power P_{in} of −8 dBm/core. The output light from the MC-EDF passed through the 12-core fan-out device and the spectrum from each port was measured individually through the 12×1 optical switch to calculate the gain and NF of the EDFA. The 60 km-long 12-core transmission fibre [3] was inserted between the MC-EDF and fan-out device to prevent the fan-out device from damage from the high total output power from the EDFA. The gain and NF were obtained based on the output spectrum P_{out} from the isolator, which was estimated by compensating the losses of the 60 km fibre, fan-out device, and optical switch from the measured spectrum.

Figure 4 shows the pumping-power dependence of the gain and NF. The dashed or solid line is the results for EDF1 or EDF2. The filled or open symbols represent the measured gain or NF. The average values obtained with the

Tab. 1: Structural parameters of fabricated 12-core fiber amplifiers.

	EDF1	EDF2
Cross-section of EDF		
Core radius a	5.5 μm	2.0 μm
Relative index difference Δ	0.28 %	1.36 %
Cladding diameter D	90 μm	
Core pitch Λ	15.5 μm	16.1 μm
Core-to-cladding ratio R_{cc}	0.17	0.02

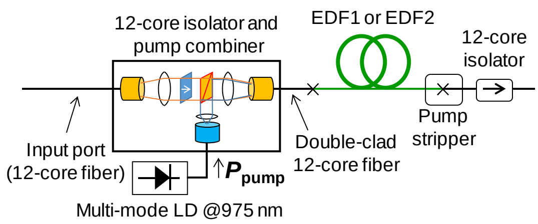


Fig. 2: Configuration of 12-core EDFA.

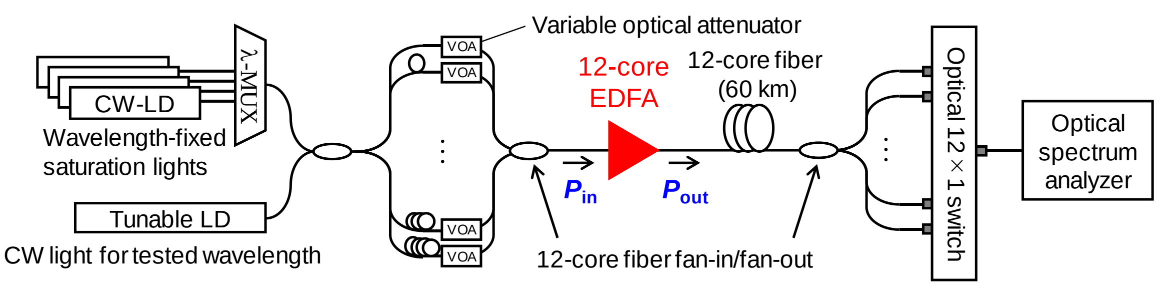


Fig. 3: Experimental setup for measuring gain, NF spectra and power efficiency of 12-core EDFA.

twelve spectra from the fan-out output ports are shown. Figure 4(a) shows the results for C-band operation, where the saturation lights with 1532-, 1542-, 1552- and 1562-nm wavelengths were launched and the gain and NF were measured at a 1550-nm wavelength. The MC-EDF length to obtain the C-band gain spectrum was 10 m for EDF1 or 25 m for EDF2. We found that the EDF1 exhibited higher gain than EDF2. Figure 4(b) shows the results for L-band operation. The wavelengths of the saturation light were 1572, 1582, 1592, and 1602 nm and the tested wavelength was 1590 nm. The MC-EDF length was 60 m for EDF1 or 280 m for EDF2. Contrary to the C-band case, we observed that EDF2 exhibited higher gain than EDF1. For example, the required pumping power of EDF2 for 15 dB gain can be reduced by 72% from that for the EDF1. The NF value for EDF2 was slightly higher than that for EDF1, which was expected from the increased splice loss at the input side of EDF2 (0.5 dB higher than that for EDF1). Figure 5 shows the gain and NF spectra with P_{pump} of 6 or 10 W for 1530~1565 and 1570~1605 nm bandwidth. The MC-EDF lengths are specified in the figure. We successfully obtained more than a 20-dB gain with NF ranged between 5 and 8 dB for each bandwidth by using MC-EDFs with optimum R_{cc} values.

We finally evaluated the PCE of the fabricated EDF. **Table 2** summarizes the measured PCE for EDF1 and EDF2 with a P_{in} of −8 dBm/core and P_{pump} of 10W. The output power from the all cores on the output side of the isolator was directly measured by the optical power meter. As expected from the results shown in **Fig. 1**, the PCE between EDF1 and EDF2 differed more significantly in on the L band than the C band, and EDF2 exhibited a PCE more than ten times higher than EDF1, which is the highest PCE value ever reported for a cladding-pumped L-band coupled-MC-EDFA. Further PCE improvement for EDF2 is expected by optimizing the splicing condition to mitigate the mode field mismatch between the splice points with the passive 12-core fibre.

Conclusion

We numerically demonstrated how the relationship between PCE and R_{cc} in the cladding-pumped MC-EDFA differed during C- and L-band operations, and showed PCE improvement in the specific R_{cc} value, unlike the C-band case. Then, we fabricated the coupled 12-core EDF with the optimum R_{cc} value for L-band amplification and showed a 5% PCE value, the highest among the reported cladding-pumped L-band coupled MC-EDFAs.

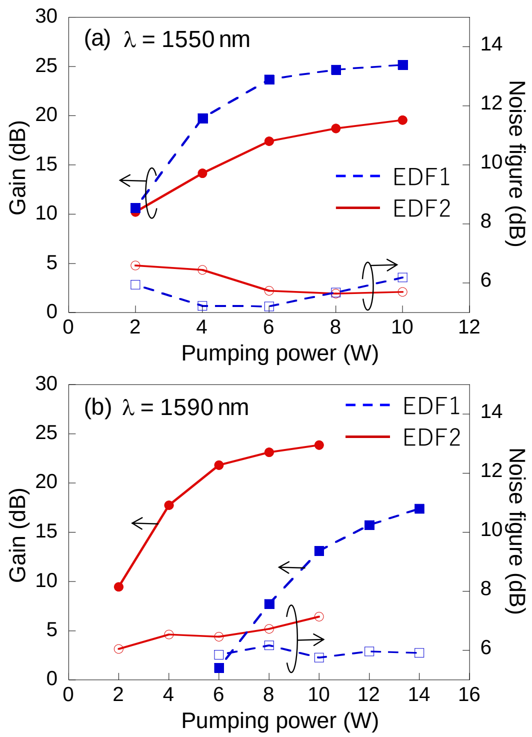


Fig. 4: Pumping power dependence of gain and NF with EDF1 and EDF2 for (a) C-band or (b) L-band operation.

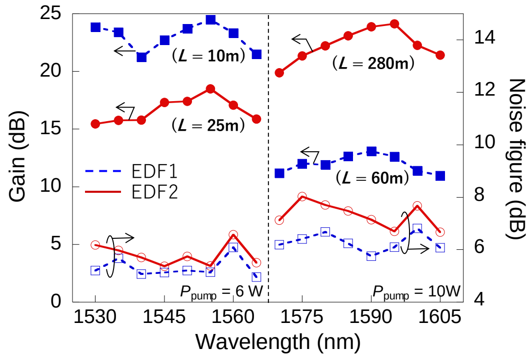


Fig. 5: Gain and NF spectra for EDF1 and EDF2.

Tab. 2: PCE values of EDF1 and EDF2 for C- or L-band operation when P_{pump} = 10 W.

	PCE	
	C-band	L-band
EDF1	10.1 %	0.4 %
EDF2	1.9 %	5.0 %

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