# Energy-efficient Cladding-pumped Amplifier for Coupled Multi-core Fiber Transmission

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**Abstract:** We review energy-efficient cladding-pumped multi-core amplification technologies and experimentally demonstrate the advantages of using a coupled-12-core amplifier for improving the amplification efficiency. © 2024 The Author(s)

## 1. Introduction

Coupled multi-core fiber (MCF) is a promising space division multiplexing (SDM) fiber for achieving ultra-high capacity because it enables a greater number of cores to be used compared to un-coupled MCF. Coupled MCF also has the unique feature of reduced modal dispersion thanks to designing the propagation modes to randomly couple (i.e., randomly coupled MCF (RC-MCF) [1]), and helps to reduce the multiple-input multiple-output (MIMO) processing complexity. SDM amplifiers are a key technology for achieving a long-distance SDM transmission line, and the cladding-pumped MCF amplifier is an attractive candidate for such usage since it has the potential to reduce the power consumption of the repeaters by using an energy-efficient multi-mode laser [2]. It has recently been reported that the coupled MCF transmission line can reduce the electrical power consumption by energy-efficient cladding-pumped coupled-12-core-MCF amplifiers [3].

In this paper, we review the technologies for energy-efficient cladding-pumped SDM amplifiers and present an overview of the advantages of RC-MCF amplifiers by introducing our experimental results with a coupled-12-core erbium-doped fiber amplifier (EDFA).

## 2. Energy-efficient coupled multi-core erbium-doped fiber design

Figure 1 summarizes the latest techniques for improving the energy efficiency of cladding-pumped MCF amplifiers. The techniques can basically be divided into two approaches: active fiber design optimization and amplifier configuration optimization. It is well known that increasing the core-to-cladding ratio ($R_{cc}$) of the fiber, which is defined as the ratio between the total core area and the fiber cross-sectional area, is effective for efficiency improvement [2−4]. This is because the pump light absorption factor in the cladding-pumped amplifier is much lower than the core-pumped amplifier owing to the pumping light propagating widely across the fiber cross-section, and non-negligible pumping power is not used for the amplification. There are also various approaches for increasing pumping power absorption by applying a non-circular shaped [5] or non-uniform cladding index design [6–8] for the

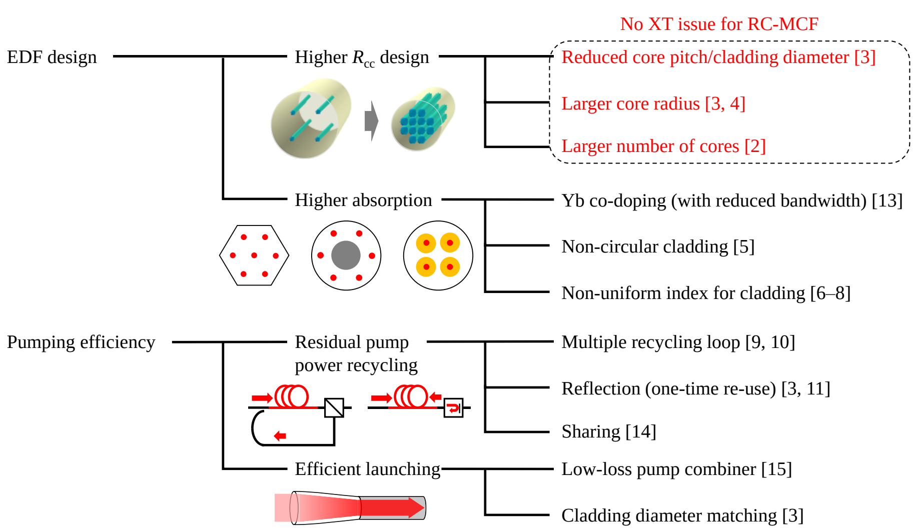


Fig. 1 Latest techniques for improving energy efficiency of cladding-pumped multi-core amplifiers.

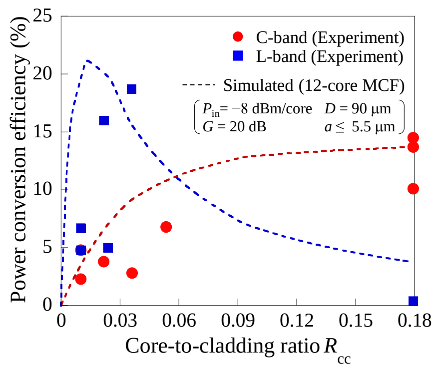


Fig. 2 Power conversion efficiency vs. $R_{cc}$ of reported C- or L-band SDM amplifiers.

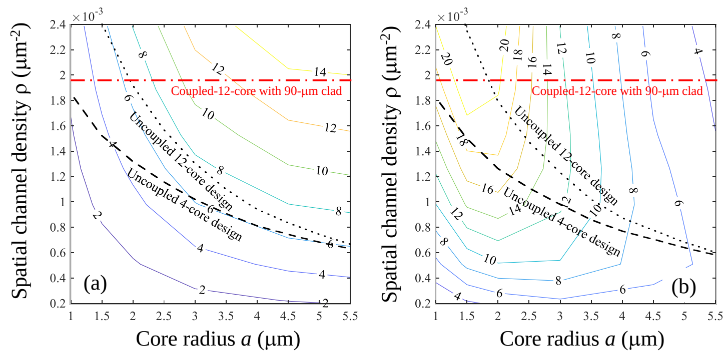


Fig. 3 Power conversion efficiency as functions of core radius and spatial channel density for (a) C-band or (b) L-band single-mode MCF amplifiers.

cladding. These designs help increase the absorption of pumping light in the EDF by increasing the pumping power density in the erbium-doped core region compared to the conventional uniform cladding design. There are also studies on how to reduce pumping light loss by optimizing the amplifier configuration, e.g., by pump recycling [3, 9–11].

First, we discuss the energy efficiency advantage of RC-MCF amplifiers in terms of the EDF design. Various EDF designs with a larger core radius [3, 4], reduced cladding diameter [3], or larger number of cores [2] have been reported. One advantage of the RC-MCF amplifier is its high potential for increased $R_{cc}$ design, since there is no cross-talk requirement and a much smaller core pitch is possible compared to un-coupled MCF amplifiers. Figure 2 shows the measured power conversion efficiency (PCE) as a function of the $R_{cc}$ of the reported SDM amplifiers. Circles and squares respectively denote the results for C- and L-band amplifiers and dashed lines show the calculated results by assuming a single-mode-core 12-core EDFA. The simulated parameters are listed in the inset. We found that the $R_{cc}$ dependence is different depending on the operational bandwidth, and a higher $R_{cc}$ is required to improve the power efficiency in the C-band. The amplifiers with $R_{cc}$ of more than 0.1 were all RC-MCF EDFA, which experimentally confirms the high potential of the RC-MCF. The PCE for the L-band amplifier shows unique $R_{cc}$ dependence and the power efficiency can be maximized at a specific $R_{cc}$ value, which is also confirmed by the simulation. We previously reported that the PCE is a function of the core radius and the spatial channel density which is defined as the number of spatial channels per unit area [12]. Figure 3 shows the calculated structural dependence of the MCF amplifier on the PCE values. It is confirmed from Fig. 3(a), which shows the results for the C-band, that the MCF design with a larger core radius and spatial channel density is required for improving the PCE. Black dashed and dotted lines respectively indicate possible design examples for in-coupled 4- and 12-core EDFA, where the *V*-value, inter-core cross-talk, and cladding thickness are assumed to be 2.42, −30 dB/10 m, and 20 μm. The core pitch of the MCF was adjusted in accordance with the core profile design so as to obtain the target cross-talk value. We found that a PCE value exceeding 8% is difficult to obtain for the un-coupled MCF even when considering a 12-core structure. In contrast, the RC-MCF amplifier can achieve a PCE of more than 10% owing to its better design flexibility (e.g., the red dash-dot line is a coupled 12-core EDF with a 90-μm cladding design, similar to the design in [12]). Figure 3(b) shows the results for the L-band. The core pitch for the un-coupled MCF amplifier was designed to be −30 dB/50 m, and the other parameters were the same as those in Fig. 3(a). Unlike the C-band case, a high PCE value can be obtained for the specific core radius design, and thus a power-efficient amplifier can be achieved for either the un-coupled or coupled MCF design. As the C-band is a commonly used low loss transmission band, the RC-MCF amplifier plays an important role for future high-capacity communication systems with low power consumption.

### 3. Optimization of amplifier configuration for reduced pump loss

As shown in Fig. 1, optimizing the amplifier configuration is another approach for improving the efficiency. Recycling the residual pumping light has been intensively investigated [9, 10], as it is an essential technology for the un-coupled MCF amplifier because the power of the residual pump light tends to be large. Since pump light recycling is also effective for the RC-MCF amplifier, a reflection-based recycling method has been proposed [3]. The point is that the effectiveness of the pump recycling differs depending on the EDF design. Figure 4 shows how the pumping light absorption is enhanced by the recycling with the recycling loop or one-time reflection scheme. The horizontal axis indicates how much the pumping light is absorbed for one-way pumping light propagation through EDF, and the solid

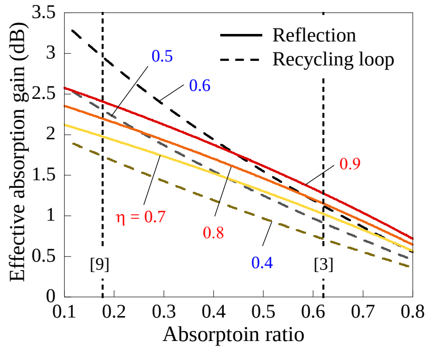


Fig. 4 Calculated effective absorption gain vs. absorption ratio of EDF for reflection (solid) or recycling loop (dashed) configuration.

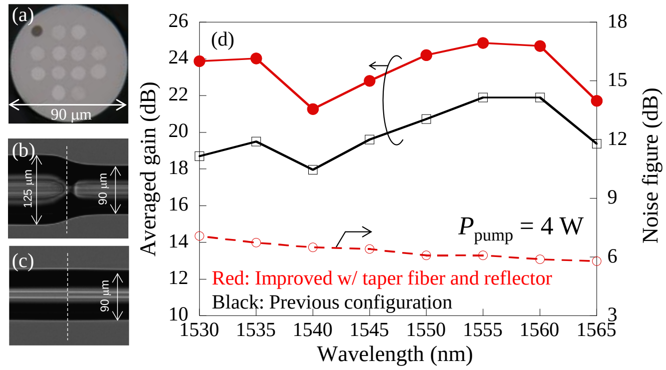


Fig. 5 (a) Cross-section of fabricated 12-core EDF and side-views of splice points between passive fiber and EDF (b) without or (c) with taper fiber. (d) Measured gain and noise figure spectrum of 12-core EDF.

and dashed lines respectively correspond to the cases of reflection and recycling loop. We assume that the recycling efficiency reflects realistic values based on the reported values (0.8 for reflection, 0.5 for recycling loop). It is seen that the recycling loop technique is more effective for the amplifier with a lower absorption ratio, whereas the simple reflection type shows a better absorption gain than the recycling loop for the amplifier with a higher absorption ratio. The vertical dashed lines indicate the reported absorption ratios for un-coupled or coupled MCF amplifiers. These ratios indicate that the recycling loop is effective for the un-coupled type but that the one-time reflection scheme has a comparable or even better performance for the coupled-MCF amplifier.

Finally, we introduce the results of our recent experiments with coupled-12-core fiber [3]. The fabricated 12-core EDF has a 15.5-µm core pitch, 5.5-µm core radius, and 90-µm cladding diameter, as shown in Fig. 5(a). The reflection type pump recycling technique was applied. One additional issue for such a small cladding diameter design is the degradation of the pump power launching efficiency owing to the cladding diameter mismatch between the passive fiber and EDF, as shown in Fig. 5(b). We therefore inserted a taper fiber between the passive fiber and EDF, where the cladding diameter was down-tapered from 125 to 90 µm to match the cladding diameter at the splice point (Fig. 5(c)). Figure 5(d) shows the measured gain and noise figure spectra, where black and red symbols respectively show the results without and with the taper and pump reflector. The gain within the whole C-band was significantly improved and only 4 W (0.33 W/core) pumping was enough for obtaining a gain of more than 20 dB. The measured PCE was 14.5%, whereas the EDF with taper fiber showed a PCE of 13.7% and a 0.8% improvement owing to the pump recycling. These results indicate the potential for offering a lower power consumption than the single-mode EDF configuration. In future work, we will conduct the coupled MCF repeated transmission experiment for achieving both high capacity and low power consumption when used in conjunction with MIMO digital signal processing technology, which is essential for coupled MCF.

## 4. Conclusion

The recent techniques and progress for improving the power efficiency of cladding-pumped MCF amplifiers were briefly reviewed, and the advantages of the RC-MCF amplifiers were discussed. Numerical and experimental results revealed that the cladding-pumped RC-MCF amplifier is promising for achieving higher energy efficiency and offering additional value to MCF transmission systems regarding both energy saving and increased capacity.

## References


[1] T. Hayashi et al., *Proceedings of the IEEE*, vol. 110, pp. 1786–1803 (2022).
[2] S. Takasaka et al., *ECOC2019*, P77.
[3] T. Sakamoto et al., *ECOC2023*, We.C.3.3.
[4] Y. Tsuchida et al., *ECOC2016*, M2A.2.
[5] K. Maeda et al., *ECOC2023*, P10.
[6] H. Chen et al., *Nature Photonics*, 10(8), pp. 529–533 (2016).
[7] S. Takasaka et al., *EOC2020*, Th2A.2.
[8] Z. Gu et al., *Opt. Express*, vol. 30, pp. 34973–34983 (2022).
[9] K. Maeda et al., *ECOC2019*, Th.2.D.3
[10] H. Takeshita et al., *J. Lightw. Technol.*, vol. 38, pp. 2922–2929 (2020).
[11] C. M-Breton et al., *Opt. Express*, vol. 30, pp. 17824–17835 (2022).
[12] T. Sakamoto et al., *J. Lightw. Technol.*, vol. 41 pp. 3860–3865 (2023).
[13] G. Mélin et al., *OFC2020*, M4C.2.
[14] H. Takeshita et al., *ECOC2023* We.C.3.2.
[15] Y. Jung et al., *J. Lightw. Technol.*, vol. 38, pp. 2938–2943 (2020).