# Few Mode Ring-Core Fibre Amplifier for Low Differential Modal Gain

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**Abstract** *We report a few-mode ring-core fibre amplifier for mode division multiplexed transmission. We achieve very low differential modal gain (<1dB) for 5 spatial modes over the C-band highlighting the benefits of the ring core approach.*

## Introduction

Few mode erbium-doped fibre amplifiers (FM-EDFAs) are one of the key building blocks required for the successful implementation of mode division multiplexed (MDM) transmission systems [1, 2] and various active fibre designs have [3-5] been proposed to achieve low differential modal gain (DMG). In a step-index, uniformly doped FM-EDFA the management of DMG becomes more and more challenging as the number of spatial modes is increased since the intensity profiles of the signal mode differ widely from each other. Complicated erbium doping profiles in conjunction with selective pump mode control are thus generally required. In comparison, few-mode ring-core EDFAs (FM-RC-EDFAs) offer inherent advantages in terms of reducing DMG because the intensity profiles of the ring modes are all very similar. This means that they each experience similar gain/absorption in a uniformly doped FM-RC-EDF thereby removing the need for highly sophisticated doping profiles. Recently we have theoretically proposed a FM-RC-EDFA capable of providing almost identical gain among six mode groups within the C-band using either core- or cladding-pumped implementations [6]. In reference [7], the first ring-core fibre (RCF) amplifier supporting two mode groups ($LP_{01}$ and $LP_{11}$) has been demonstrated and a small DMG of around 1dB was realized.

In this paper, we report a five mode ring-core erbium doped fibre amplifier (5M-RC-EDFA) with very low DMG (< 1dB). This experimental demonstration proves again the advantages of the ring-core approach for the realization of low DMG amplifiers.

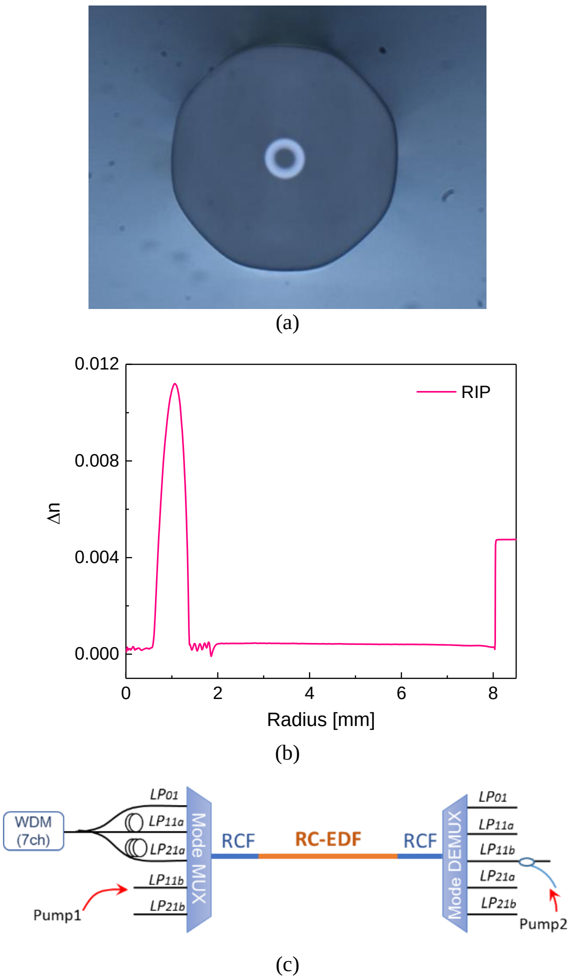


**Fig. 1:** (a) Cross-sectional microscope image and (b) refractive index profile of the fabricated 5M-RC-EDF and (c) the measurement setup for modal gain analysis of the amplifier.

**Fabrication and characterization of 5M-RC-EDFA**

Our Er-doped RCF was designed to support 5 spatial modes with a single-radial-order (i.e. $LP_{01}$, $LP_{11a}$, $LP_{11b}$, $LP_{21a}$ and $LP_{21b}$). It was fabricated using a conventional modified chemical vapor deposition (MCVD) process in conjunction with solution doping. The 110 $\mu$m outer glass cladding was octagonally-shaped to enable cladding-pumping. The preform refractive index profile and cross-sectional microscope image of the fabricated 5M-RC-EDF are shown in Fig. 1(a, b). The fibre core can be clearly seen as a bright annular ring. The inner radius of the annular ring is 5.8 $\mu$m while the outer radius is 9.4 $\mu$m. The core-to-clad refractive index difference is $\Delta n=0.0112$ corresponding to an NA of 0.18. Figure 1(c) shows a schematic of the 5M-RC-EDFA and the associated amplifier test setup. Seven WDM signals were split into three optical paths, each was mode-multiplexed by a mode-selective photonic lantern (PL) and launched into a length of matched passive RCF [8]. The photonic lanterns were in-house fabricated [9] with a mode dependent insertion loss of about 1.8-3 dB and an extinction ratio of >8 dB. The passive RCF tail of the PL was directly spliced to one end of the active RC-EDF while the other end of the RC-EDF was spliced to a second PL for mode-demultiplexing. The mode dependent splice losses between the active and passive RCFs were 1.8, 2.0 and 3.4 dB for $LP_{01}$, $LP_{11}$ and $LP_{21}$, respectively. Originally, the active fibre was intended for cladding-pumping however the fabricated fibre exhibited high background loss at 1550 nm (more than a few dB/m), which made it difficult to achieve reasonable gain with the few meters long active fibre required given the peak cladding pump absorption of 2.4 dB/m at 979 nm. A core pumped configuration was therefore employed instead to reduce the active fibre length. A 27 cm-long 5M-RC-EDF was used in our experiment. As shown in Fig. 1(c), two single-mode pump laser diodes (27.5dBm each) were coupled in a bi-directional pump configuration (one coupled via the $LP_{11b}$ port of the input PL and the other similarly coupled through the $LP_{11b}$ port of the output PL). The total coupled pump power was estimated to be ~23 dBm due to the insertion loss of the PL and splice loss between the passive and active fibres.

First, we examined both the near- and far-field distributions of the amplified spatial modes by pumping through the input PL and without splicing the output PL. Clean modal amplification was confirmed at the output end of the 5M-RC-EDF using a CCD camera as shown

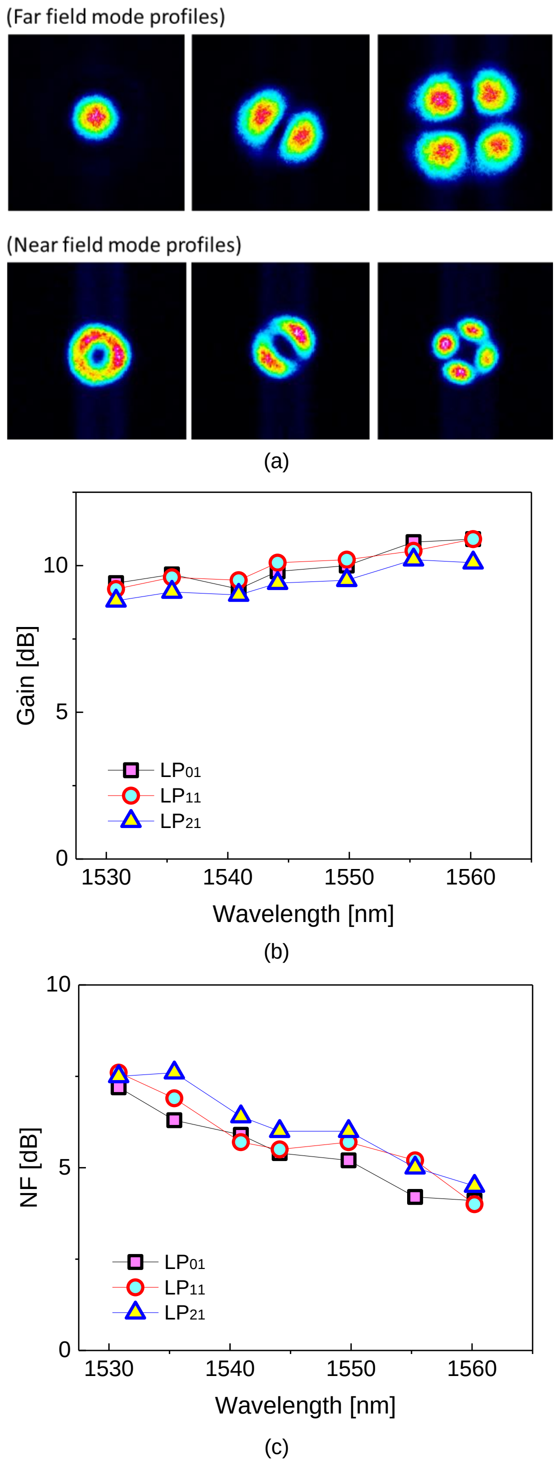


**Fig. 2:** (a) Far- and near-fields of the amplified signal modes and (b) measured modal gain and (c) noise figure as a function of wavelength at a fixed input signal power of -15dBm and launched pump power of 23dBm.

in Fig. 2(a). The detailed amplifier performance was then analyzed using the output PL as a mode demultiplexer. Fig. 2(b, c) shows the measured modal gain and noise figure (NF) as a function of wavelength at a fixed input signal power of -15 dBm per mode and a total launched pump power of 23 dBm. The average modal gain was relatively low (~10 dB) due primarily to the relatively low launched pump power and the short fibre length used to minimize the impact of fibre background loss. The increase in gain with wavelength signifies the lack of population inversion in the RC-EDF. Consequently the NF of the amplifier as plotted in Fig. 2(b) also shows an upward trend at the short wavelength edge reaching to 7.5 dB at 1530 nm. However, a very low DMG (less than 1 dB) was successfully achieved in the wavelength range of 1530-1560 nm. Note that this is the lowest experimentally measured DMG achieved so far from a FM-EDFA. The primary reason for the large observed RCF loss is associated with the relatively low index contrast between the core and cladding in this first generation of fabricated fibre which compromises the guidance strength (or core confinement) under single radial mode guidance conditions. We strongly believe that with realistic improvements in the index contrast that high performance FM-EDFAs (e.g. average gain >20 dB, DMG <1 dB) will be achievable with the proposed ring-core fibre amplifier.

## Conclusions

We have experimentally demonstrated a 5 spatial mode ring-core fibre amplifier for mode division multiplexed transmission. A very low differential modal gain of less than 1dB over the C-band with an average modal gain of ~10 dB was successfully achieved.

## Acknowledgements

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