Gain Equalization of a Six-Mode-Group Ring Core Multimode EDFA

Qiongyue Kang(1), Eeleong Lim(1), Yongmin Jun(1), Xianqing Jin(2), F. P. Payne(2), Shaiful Alam(1), and David J. Richardson(1)

(1) Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK
qk1g11@orc.soton.ac.uk
(2) University of Oxford, Parks Road, Oxford, OX1 3PJ, UK

Abstract We propose a 6-mode-group ring core multimode erbium doped fiber amplifier (RC-MM-EDFA) capable of providing almost identical gain among the six mode groups within the C band using either core- or cladding-pumped implementations.

Introduction

Space Division Multiplexing (SDM) has attracted considerable attention in the fiber-optic community as a radical approach to increase the per-fiber capacity by employing multiple distinguishable spatial information channels through the same glass strand[1]. One form of SDM uses Few Mode Fibers (FMFs) which guide a restricted number of modes to define the independent spatial channels. In the vast majority of FMF transmission systems[2], multiple-input, multiple-output processing (MIMO) is used to compensate for the linear cross-talk between optical modes due to mode coupling[2]. As the number of modes (information channels) increases, the complexity of MIMO processing necessarily increases rapidly for traditional multimode step index (SI) or graded index (GI) fibers. However, if the mode coupling can be minimized, the use of MIMO processing might be avoided (or perhaps more realistically simplified), thereby increasing the viability and scalability of the approach.

Ring-Core multimode fibers (RC-MMFs) that support radial modes have been reported theoretically to show great potential for improving the capacity of SDM systems with low complexity[3]. The RCF is designed to create a large effective index difference (Δn_{eff}) between the adjacent linearly polarized (LP) mode groups, in order to suppress mode coupling. As opposed to the SI-RC-MMF reported in ref. [3], we have established that a RC-MMF with a graded ring-index profile provides a larger fabrication tolerance to ring thickness variation. This graded index RC-MM-EDFA effectively guides LP_{01}, LP_{11}, LP_{21}, LP_{31}, LP_{41} and LP_{51} mode groups within the C band (1530 - 1565 nm). The modal gain performance of this RC-MM-EDFA is simulated under both core-pumped and cladding-pumped conditions with special consideration to macro-bending. Our simulation shows that under core-pumping conditions the RC-MM-EDFA can provide exceptionally equalized modal gain and which is largely insensitive to the modal content of the pump beam providing that the fiber is kept relatively straight. However, when the fiber is bent (with the current design to a bend radius of 5cm), use of the LP_{01} pump mode can create a significant preferential gain for the LP_{01} signal mode relative to the other higher order signal modes due to bend-induced modal distortion. However, if a high order mode pump (e.g. LP_{41}) is used then small modal gain differences can still be achieved on bending of the fiber. Finally, we simulate the RC-MM-EDFA under cladding-pumped operation. Not only can very small gain differences across all signal modes be achieved in these circumstances but also the performance is relatively immune to macro-bending (at least down to a bend radius of 5cm). Results showing modal amplifier performance under WDM operation are also presented.

Modeling of RC-MM-EDFA

Figure. 1 describes the refractive index profile (n) of the RC-MM-EDFA and the equivalent index n_{eq} (dashed, slanted index profile) defining our bent-fiber model[4].

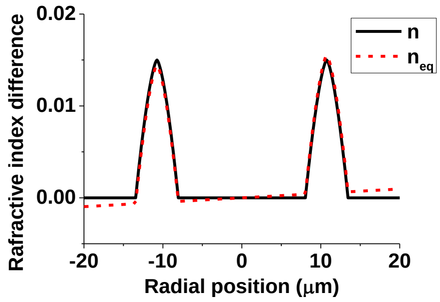
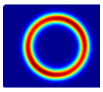
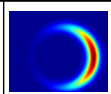
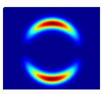
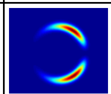
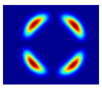
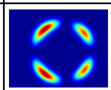
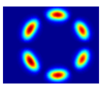
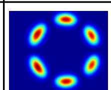
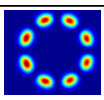
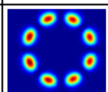
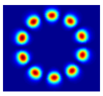
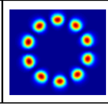


Fig.1 The refractive index of the RC-MM-EDFA when it is straight (black line) and bent with radius of 5cm

Our simulations show that this RC-MM-EDFA can be bent down to a radius of 5cm with negligible propagation losses for all the modes guided at 1550nm. The bend losses of the guided modes were calculated by using the imaginary part of the effective mode indices computed by the COMSOL Multiphysics® software. The mode intensity profiles of the guided modes at 1550nm for both straight fiber and bent fiber (R_{bend}=5cm) are shown in Table 1. The fiber index profile is raised at the outer side of the bent fiber yielding a shift of intensity of guided modes to that side due to the stronger guidance, as shown by the LP_{01}, LP_{11} and LP_{21} modes in Table 1. However, the higher order modes (i.e. LP_{31}, LP_{41} and LP_{51}) are found to preserve their intensity profiles. As long as the effective index of the higher order modes is still higher than the surrounding cladding-index (which is raised as a result of bending), the higher order modes are well guided in the fiber core. A detailed physical explanation of the bend-distortion resistance of higher order modes can be found in ref. [5].

Table 1: Modal properties of the RC-MM-EDFA

Signal Mode	Mode intensity profile (Straight)	Overlap integral with Er^{3+} (Straight)	Mode intensity profile (R_{bend}=5cm)	Overlap integral with Er^{3+} (R_{bend}=5cm)
LP01		0.9800		0.5286
LP11 odd		0.9822		0.6334
LP21 odd		0.9848		0.9214
LP31 odd		0.9867		0.9820
LP41 odd		0.9672		0.9658
LP51 odd		0.9795		0.9719

Modeling of core-pumped RC-MM-EDFA

The core-pumped RC-MM-EDFA is simulated using the simulation model described in our previous work[6]. In the simulations of this paper, we neglected the impact of ASE for simplicity. The erbium doping profile is assumed to follow the refractive index profile. The calculated overlap integrals of the normalized signal mode profiles and the erbium dopant distribution with and without bending are shown in Table 1. It is found that the overlap between signal and rare earth dopants are almost equal for each mode group when the fiber is straight. When the fiber is bent with R_{bend} of 5cm, the overlap between signal and the dopants is almost the same for LP_{31} mode and higher. We firstly analyze the performance of the RC-MM-EDFA under core-pumping conditions by using pure LP_{01} and pure LP_{41} pump modes at 980nm. For each investigation, a co-propagating pump power of 350mW and input signal power of -10 dBm per mode group were used. The modal gain evolution of each signal mode group against the fiber position along the z axis for pure LP_{01} and pure LP_{41} pumps for a straight fiber is illustrated in Fig. 2a.

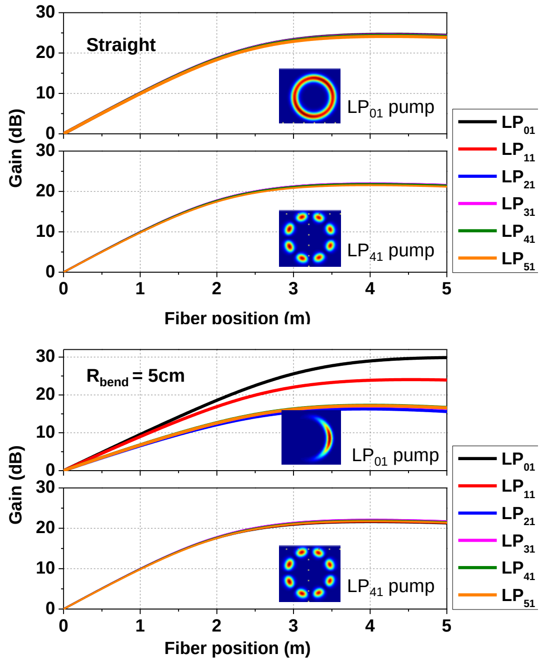


Fig. 2: The modal gain evolution against fiber position for LP_{01} pump and LP_{41} pump for (a) straight and (b) bent fibers.

The signal gains are nearly identical to each other, which reflects the almost equal overlap integrals between signal modes and the rare earth dopants shown in the third column of Table 1. The same gain curves, under the same simulation parameters but now with the fiber bent to a radius of 5cm, are plotted in Fig. 2b. In this case large gain differences among the signal modes (particularly between the LP_{01} mode and higher order modes) are observed due to the bend-induced distortion of the lower order modes (especially the LP_{01} mode). Therefore, the LP_{01} pump mode is unsuitable for core pumping due to its high sensitivity to bending. Our simulations also show that the LP_{51} and LP_{61} pump modes are equally as good as the LP_{41} mode as all of them are robust to bending down to a radius of 3cm, however pump modes higher than LP_{61} (e.g. LP_{71} and higher) suffer from bend-induced losses.

Modeling of cladding-pumped RC-MM-EDFA

In the cladding-pumping scheme, where a double-clad fiber (DCF) is usually used, the heavily multi-mode pump light is guided in the inner-cladding, which is intentionally made asymmetric (e.g. D-shaped) to promote mode-mixing for efficient pump absorption[7]. So in the modeling of cladding-pumped amplifiers, a simple but effective way to simulate the pump beam is to assume that the pump intensity profile is uniform across the doped core[7]. In the simulation, we used a 70μm inner cladding diameter (chosen with practical fabrication and power-coupling considerations in mind) and 2 W of co-propagating multimode pump power (at 980nm), which creates a uniform pump intensity of 5.2×10^{8} W/m^2 at the input end of the fiber. Figure 3 shows the simulated modal gain evolution against fiber position for all signal modes (input power of -10 dBm per mode) at 1550nm for the cladding-pumped RC-MM-EDFA with and without bending. Our numerical results suggest that at a fiber position of 5m, the maximum gain difference among the six mode groups is only 0.6 dB for the straight fiber, and 1.5 dB for a fiber with R_{bend} = 5cm. In conclusion, more than 20 dB gains for all the signal modes at 1550nm can be achieved after a 5m length of amplifier without much compromise due to bending.

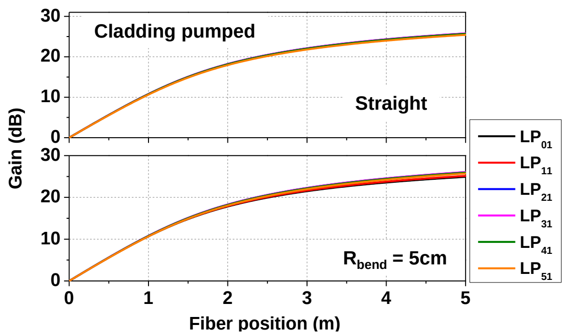


Fig. 3: The modal gain evolution against fiber position for cladding-pumping for (a) straight and (b) bent RC-MM-EDFA.

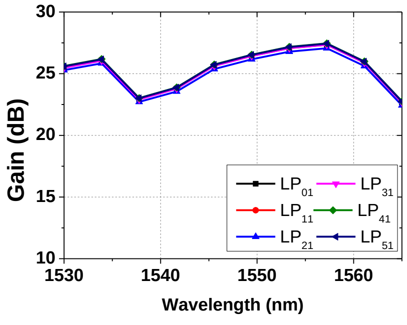


Fig. 4: The WDM signal gain profile of the cladding-pumped RC-MM-EDFA.

Finally, we simulated the WDM gain profiles of the cladding pumped RC-MM-EDFA. 10 wavelength channels spaced equally from 1530 nm to 1565 nm and 6 spatial modes at each wavelength with power of -20 dBm per mode per wavelength (in total -10 dBm per mode) were used as the input signals. The input multimode pump power was set to be 2 W, and the fiber length was chosen to be 5 m in order to balance the gain between short (i.e. 1530 - 1535 nm) and long (i.e. 1550 - 1565 nm) wavelengths. The WDM gain profiles are shown in Fig. 4. It can be seen that the gain curves for different spatial modes overlap with each other at all wavelengths within the C band illustrating excellent modal performance. The total gain difference across the whole band is about 5 dB. We found that the gain is relatively immune to bending down to R_{bend} of 5cm. The noise properties of the core- and cladding-pumped RC-MM-EDFA will be analyzed in future work.

Conclusions

We propose a 6-mode-group RC-MM-EDFA that features a high index-contrast ring index profile. It has advantages of providing nearly identical gain for all the guided signal modes and the performance is robust to macro-bending down to 5 cm when cladding-pumped, or core-pumped by higher order pump modes (e.g. LP_{41}). The proposed design has potential to be scaled up to a higher number of guided spatial modes whilst the cladding-pumped scheme will be the preferred choice for heavily multimoded RC-MM-EDFAs both from a cost and performance perspective.

Acknowledgements

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References

[1] D. J. Richardson et al., “Space-division multiplexing in optical fibers”, Nat. Photonics **7**, 354-362 (2013).
[2] R. Ryf et al., “Mode-division multiplexing over 96 km of Few-Mode Fiber Using Coherent 6×6 MIMO Proccessing” J. Lightwave Technol., Vol. **30**, Issue 4 (2012).
[3] X.Q. Jin et al, “Linearly Polarized Mode Division Mutliplexed Transmission over Ring-Index Multimode Fibres” *IEEE Summer Topicals 2013*, Paper. TuC4.3.
[4] D. Marcuse, “Influence of curvature on the losses of doubly clad fibers” Appl. Opt. Vol **21**, Issue 23 (1982).
[5] J. Fini et al., “Natural bend-distortion immunity of higher-order-mode large-mode-area fibers”, Opt. Letters, Vol **32**, no. 7 (2007).
[6] Q. Kang et al., “Accurate modal gain control in a multimode erbium doped fiber amplifier incorporating ring doping and a simple LP_{01} pump configuration”, Opt. Express Vol **20**, Issue 19, p. 20835-20843 (2012).
[7] A. Hardy, "Signal Amplification in Strongly Pumped Fiber Amplifiers", IEEE J. of Quantum Electron. Vol. **33**, NO. (3) (1997).