Analysis of Inter-core Cross-gain Modulation in Cladding Pumped Multi-core Fiber Amplifiers

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Abstract

We numerically investigate pump-induced gain variations in eight-core fiber amplifiers. We compare two fibers with different erbium profiles by varying input power from -25 dBm to 0 dBm in one or four cores. Inter-core cross-gain modulation is < 0.6 dB.

Introduction

Cladding pumped multicore erbium doped fiber amplifiers (MC-EDFAs) show promising performance for future communication networks[1-4]. As a first application, single mode MC-EDFAs could replace multiple single core EDFAs to reduce cost and size. However, in the context of future flexible and reconfigurable networks, one concern that must be addressed regarding the use of these amplifiers is intercore cross-gain modulation[3-4]. In cladding pumped MC-EDFA, pump depletion is a function of the input signal condition in all cores. For example, increasing the input power in one core creates pump depletion that can reduce the gain in other cores. In this paper, we analyze intercore cross-gain modulation in cladding pumped amplifiers with eight cores in steady state. We consider two fiber designs that differ by their erbium ion doping profiles: a standard uniformly doped core and a doped ring located in the cladding in close proximity to the core. We compare inter-core cross-gain variations in steady state when the input signal power is changed in either one or four of the eight cores.

Fiber Parameters

We consider two different core designs for the multicore erbium doped fibers. Figure 1 shows the refractive index, *n*, and erbium ion concentration, ρ, profiles of both types of cores as a function of core radius, *r*. The cores of fiber A are step-index with uniform doping in the core (fig. 1a), i.e. $n = 1.4502$ and $\rho = 1.5 \times 10^{25}$ ions/m^3 for $r < 4.1$ µm. In fiber B, erbium doping is located in the cladding in order to increase the saturation input power and minimize gain compression[5]. Fig. 1b shows the refractive index profile of the cores of fiber B with $n = 1.4502$ for $r < 3.55$ µm, and $n = 1.446$ for 5 µm $< r <$ 7 µm. The erbium ion concentration is $\rho = 1.5 \times 10^{25}$ ions/m^3 in the annular region 5 µm $< r <$ 7 µm. Aluminium doping is also present in this region to increase the solubility of the erbium, which causes the increase of the refractive index. For both fibers, the cladding is silica with $n = 1.4440$ in the cladding. COMSOL was used to calculate the LP$_{01}$ mode overlap between both fibers, which are both single mode with similar mode profiles (overlap = 0.9969). The two fiber cores therefore only differ by their erbium doping profile.

Numerical simulation method

The optical fiber length is first optimized by considering that the optical amplifier is fully loaded with a total input signal power per core, P_{in}, of 0 dBm. For all simulations, we assume that P_{in} of each core is uniformly distributed over 31 channels in the C band (1530 nm to 1560 nm, 1 nm step). The pump is assumed to be uniformly distributed in the cladding, i.e. having the same overlap with all signal cores. The optimal fiber length is determined by maximizing the minimum gain over the spectrum of interest for a given pump power. With this optimal length, P_{in} of a subset of cores is swept and the maximum gain variation in the fully loaded cores is recorded.

The model used for the simulations is based on the standard EDFA set of power propagation and population rate equations, but with radial resolution[3,6]. The fiber cross-section is divided into 100 rings between $0 < r < 10$ µm. These rings are characterized by their own inversion level, signal and pump power confinements. The pump power, P_p, propagation equation is thus expressed as:

$$\frac{dP_p(z)}{dz} = -\left[\sigma_a\left(\sum_{i=1}^{8}\sum_{k=1}^{100} n_{1i,k}(z)\,\Gamma_{p,k}\right) - \alpha_p\right] P_p(z) \quad (1)$$

where σ_a is the pump absorption cross section, $n_{1i,k}$ is the lower level population of core i and ring k, and $\Gamma_{p,k}$ is the pump confinement in ring k. The summation is done over all rings and cores. Also, α_p is the pump background loss. Since the pump is considered uniformly distributed in the cladding, propagation of signals and population inversion in each core are calculated using standard models with radial resolution. Inter-core cross-gain modulation thus occurs through the pump as described by (1).

For the simulations, we consider that the amplifier is fully loaded when it has an input signal power of 0 dBm in each core (-14.91 dBm per channel). The total number of cores is 8, cladding radius of the fiber is 70 µm, pump background loss is 0.05 m^{-1}, signal background loss is negligible and the pump is copropagating with the signals. Emission and absorption cross sections used for the simulations correspond to typical values for alumino-silicate erbium doped fibers[7]. Three different scenarios are considered for each fiber: #1: P_p=15 W and one core has a variable input power; #2: P_p=20 W and one score has a variable input power; and #3: P_p=15 W and four cores have variable input powers. When varied, input signal power is swept between -25 dBm and 0 dBm, while it is kept constant at 0 dBm for all other cores. In the discussion below, the input power of the cores that are not fully loaded (unsaturated) is labeled $P_{in,un}$.

Fiber length and gain

The optimal lengths of fiber A and B are respectively 2.8 m and 24.5 m when P_p=15 W, and 3.05 m and 26.5 m when P_p=20 W. The remaining pump power at the fiber output was 11.9 W/1.6 W for fiber A/B and P_p=15 W, and 15.6 W/1.8 W for P_p=20 W. Figure 2 shows the gain calculated at these optimal lengths for both pump powers and under a fully loaded condition. The minimum gain is G=17.0 dB/19.7 dB for fiber A/B when P_p=15 W, and G=18.6 dB/21.7 dB for fiber A/B when P_p=20 W. The lower overlap of the signal mode field with the ring doping in Fiber B reduces saturation, which results in a higher gain. A longer fiber length is however needed and the low output pump power results in part from the significant pump propagation loss (>5 dB; note that in cladding pumping, the pump is guided by the silica cladding-low index polymer waveguide). In addition to providing higher gain, the lower saturation also leads to lower gain compression. Figure 3 shows the gain compression, ΔG, when the input signal power to all cores is changed from 0 dBm to -25 dBm with 15 W and 20 W pump for fibers A and B.

Inter-core cross-gain modulation results

Figures 4 shows spectral gain variation in the fully loaded cores under scenario#1 (seven cores fully loaded, P_p=15 W). The largest gain variation is observed at 1532 nm; it is 0.02 dB and 0.14 dB for fiber A and fiber B respectively. Simulations of gain variations were repeated for scenario#2 (P_p=20 W, input power varies in one core) and scenario#3 (P_p=15 W, input power varies in four cores). Figure 5 compares the results of the three scenarios by showing the gain variation at 1532 nm as a function of $P_{in,un}$ in either one or four cores. For scenario#2, the gain variation is 0.02 dB/0.16 dB for fiber A/B. For scenario#3 it is 0.06 dB/0.57 dB for fiber A/B. For fiber A, increasing P_p (scenario#2 vs scenario#1) does not produce any change and the curves are superimposed.

Discussion

Table 1 summarizes the results of maximum gain variation for each scenario and each fiber. Results indicate that fibers with annular doping in the cladding, while being beneficial to achieve higher minimum gain and lower gain compression, are more vulnerable to inter-core cross-gain modulation compared to standard fibers with uniformly doped cores. Considering the remaining pump power at the fiber outputs, this could be explained by the fact that fibre B uses more of the pump power and therefore is more sensitive to pump power variations when compared to fiber A, for which a large pump power remains available in any case. It should be noted that, in the present analysis, fiber length was chosen to maximize the minimum gain over the whole spectral band, which does result in a larger gain for fiber B compared to fiber A (19,7 dB vs 17,0 dB). Simulations of fiber B under scenario#3 (P_p=15 W, power varied in four cores) with a fiber length that aims to have the same gain as fiber A (17.0 dB) results in an optimum fiber length of 13.7 m, maximum compression of 4.83 dB and a maximum gain variation of 0.12 dB at 1532 nm.

Conclusion

We numerically investigated the sensitivity of MC-EDFA to inter-core cross-gain variations induced through the pump in steady state and compared two different erbium doping profiles. We explored different scenarios by varying input power between -25 dBm and 0 dBm in one or four cores. For all scenarios considered, gain variation was less than 0.6 dB. The MC-EDFA with annular doping operates in lower saturation offering a higher minimum gain and lower compression. However, results show that it is more sensitive to inter-core cross-gain modulation, which should therefore be considered when optimizing these designs.

Acknowledgements

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Tab. 1: Gain variation at 1532 nm in fully loaded cores when $P_{in,un}$ varies (-25 to 0 dBm) in one or four cores

	Fiber A	Fiber B
Scenario#1	0.02 dB	0.14 dB
Scenario#2	0.02 dB	0.16 dB
Scenario#3	0.06 dB	0.57 dB

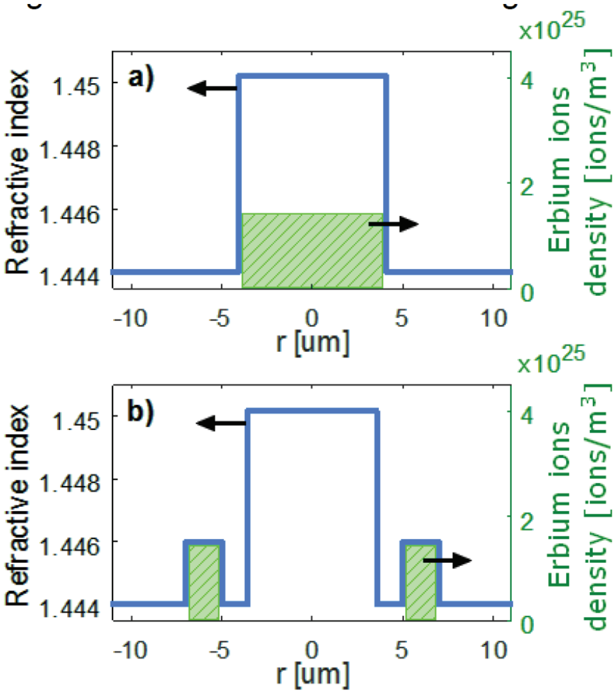

Fig. 1: Refractive index and erbium ion profiles for a) fiber A and b) fiber B.

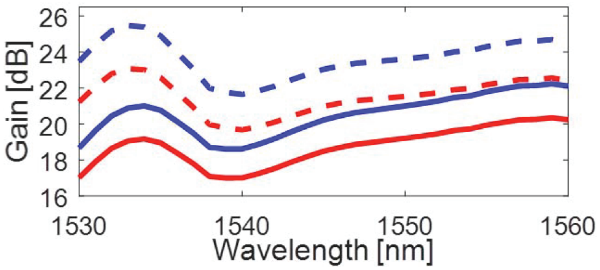

Fig. 2: Gain for P_{in}=0 dBm in each core, for fiber A (solid) and fiber B (dashed), and P_p of 15 W (red) and 20 W (blue).

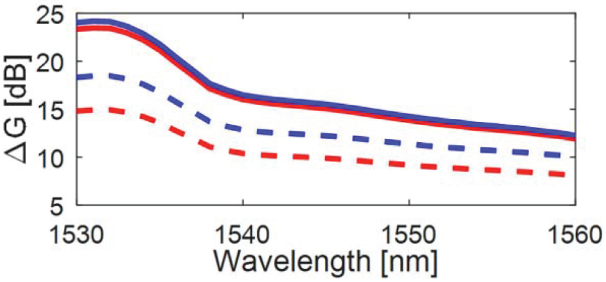

Fig. 3: Gain compression defined as ΔG=G(P_{in}=-25 dBm)-G(P_{in}=0 dBm) ; for fiber A (solid) and fiber B (dashed), and P_p of 15 W (red) and 20 W (blue).

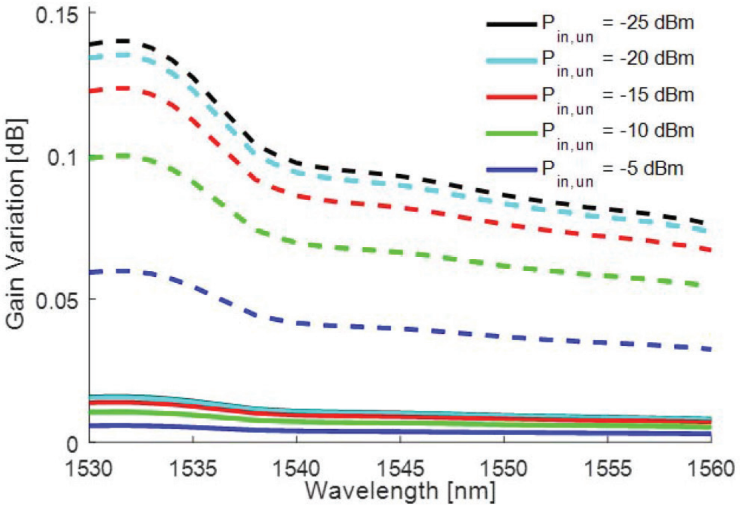

Fig. 4: Gain variation in fully loaded cores for fiber A/B (solid/dash) and P_p=15 W ($P_{in,un}$= -25 to -5 dBm in one core).

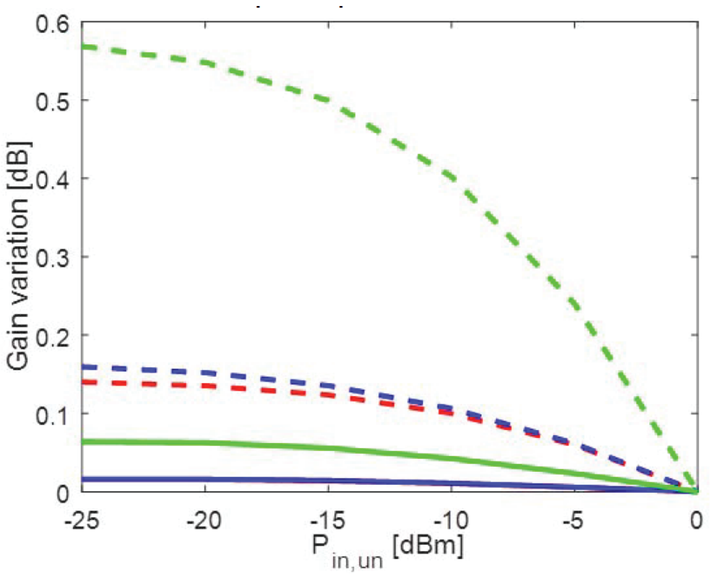

Fig. 5: Gain variation at 1532 nm in fully loaded cores as a function of $P_{in,un}$ for fiber A (solid) and fiber B (dashed), and for scenario#1(red), scenario#2(blue) and scenario#3(green)