Minimizing Differential Modal Gain in Cladding Pumped EDFAs Supporting Four and Six Mode Groups

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Abstract: We employ a Genetic Algorithm for the purpose of minimization of maximum differential modal gain (DMG) over all the supported signal modes (at the same wavelength) of cladding pumped four-mode and six-mode-group EDFAs. The optimal EDFA designs found through the algorithm provide less than 1dB DMG across the C-band (1530-1565 nm) and L-band (1565- 1600 nm) whilst achieving more than 20dB gain per mode in the C-band. We then analyze the sensitivity of the DMG to small variations from the optimal value of the erbium doping concentration and the structural parameters, and estimate the fabrication tolerance for the reliable amplifier performance.

1. Introduction

Space Division Multiplexing (SDM) has attracted considerable attention in high-capacity fiber-optic communication systems as a radical approach to increase the capacity per-fiber by employing multiple distinguishable spatial information channels through the same fiber [1, 2]. One form of SDM uses Few Mode Fibers (FMFs) which guide a restricted number of modes to define the independent spatial channels. So far, both 2 and 4-mode group systems have been reported, including both transmission fibers and a compatible associated inline Few-Mode Erbium Doped Fiber Amplifier (FM-EDFA) [3-4]. The majority of the demonstrated FM-EDFAs have been core-pumped with either one or two single-mode pump diodes [3-5]. Obviously, as the number of modes supported by a single fiber is increased, the total signal output power (and hence the required pump power needed for high gain, low noise amplification) increases significantly, dictating the use of multiple, expensive single mode pumps. Reduction in the cost per transmitted bit is essential for SDM to be seriously considered for commercial deployment and cladding-pumping using high-power multimode pump diodes (which has already been demonstrated for multi-core EDFAs [6]) provides a more practical and potentially much cheaper way to provide the pump radiation. The first demonstration of cladding pumped Erbium Doped Fiber Amplifier supporting four mode groups (4M-EDFA) reported a DMG (i.e. the maximum gain difference among all the signal modes at the same wavelength) of around 4 dB [7]. When developing FM EDFAs minimizing DMG is of paramount importance in ensuring the best overall system performance and the DMG fundamentally arises from difference in the overlap between pump, signal and rare earth dopants between modes. 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 (i.e. D-shaped) to promote mode mixing for efficient pump absorption [8]. So in the modeling of cladding-pumped amplifiers, a simple but effective way to simulate the pump is to assume that the pump intensity profile is uniform across the doped core [9]. Careful tailoring of the erbium doping profile in an active multimode fiber is therefore central to minimizing the DMG in cladding-pumped FM-EDFAs.

In this work, we employ a Genetic Algorithm (GA) [10] to help optimize the rare earth doping profile of a cladding-pumped EDFA, supporting more than two propagating mode groups, in order to reduce the DMG. The optimum fiber designs provide less than 1 dB DMG across the wavelength range (1530-1600nm). The sensitivity of the DMG to variations in the erbium doping concentration and the structural parameters is also presented.

2. Simulation

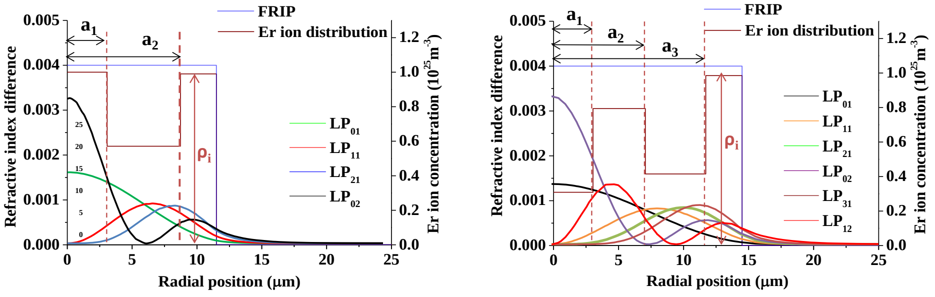
The FM-EDFA was simulated using the simulation model described in our previous work [11]. For the noise calculation, we split the wavelength band from 1490nm to 1630nm into 140 equal-width (1nm) wavelength slots. In order to manipulate the erbium ion distribution, we chose to divide the erbium-doped core into several layers whilst keeping the FRIP unchanged, so that the optimal dopant concentration in each core layer can be numerically investigated for minimization of the DMG. For the purpose of reducing fabrication complexity, the number of erbium-doped layers should be as few as possible. Through trials, we have found that at least three-layer and a four-layer doping structures (shown in Fig. 1) are required in order to achieve a DMG of less than 1 dB in the C- band (1530-1565 nm) for the 4M-EDFA and 6M-EDFA respectively. Thus for the 4M-EDFA, there are two structural parameters (i.e. a_1, a_2 shown in Fig. 1a) determining the dimensions of the three-core layers and three doping concentration parameters (i.e. ρ_1, ρ_2, ρ_3) describing the erbium ion concentration of each core layer to be optimized. Similarly, there are three structural parameters (i.e. a_1, a_2, a_3 shown in Fig. 1b) and four doping concentration parameters (i.e. ρ_1, ρ_2, ρ_3, ρ_4) to be optimized for the 6M-EDFA. Due to the involvement of more than 5 free parameters, we implemented a GA to establish the optimum choice of the dopant concentration and the dimension of each core layer for the minimization of the DMG. The GA is a generic optimization tool for optimizing multiple parameters simultaneously based on a natural selection process that mimics biological evolution. The GA has been successfully applied to several fiber designs, for example ref. [12]. In the GA implemented here, the fitness function, “F”, that is used to evaluate the ‘quality’ of a given structure and minimized by the algorithm, is defined as:

$$F = \sum_{\lambda_i = 1530nm}^{1565nm} DMG(\lambda_i) \tag{1}$$

where DMG(λ_i) is the differential modal gain calculated at wavelength λ_i and the sum is performed over 5 uniformly spaced points in the interval. For all modeling work in this paper, a total input signal power of 0 dBm at a single wavelength, co-propagating with a pump input power of 2.5W are assumed. It is to be noted here that the total input signal power is equally split into the 6 spatially distinct signal modes in the case of 4M-EDFA (i.e. LP_{01}, LP_{11a}, LP_{11b}, LP_{21a}, LP_{21b} and LP_{02}), i.e. -7.78 dBm per mode; and 10 spatially distinct signal modes in the case of the 6M-EDFA (i.e. LP_{01}, LP_{11a}, LP_{11b}, LP_{21a}, LP_{21b}, LP_{02}, LP_{31a}, LP_{31b}, LP_{12a}, LP_{12b}), i.e. -10 dBm per mode. The amplifier model is run five times (to obtain the DMG values needed at different signal wavelengths) to calculate the fitness function ‘F’ for a given fiber structure. The free parameters (or the ‘genes’ of the algorithm) are the structural parameters a_i (i.e. a_1, a_2, …) and the doping concentration ρ_i (i.e. ρ_1, ρ_2, …) of the i-th core layer.

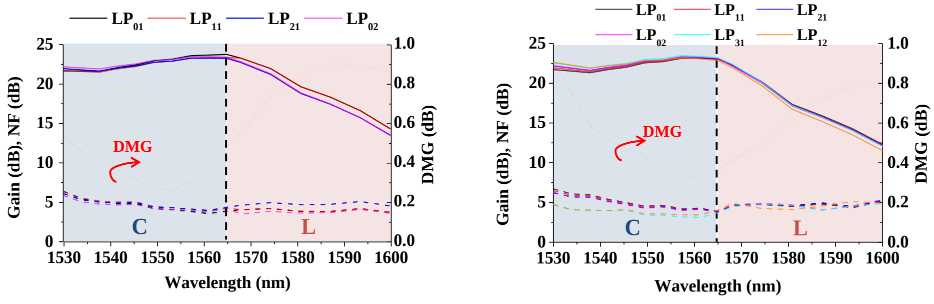
3. Optimized fiber

(1) Four-mode-group EDFA



(a) (b)

Figure 1. The fiber refractive index profile (FRIP), the signal mode intensity distributions, and the doping profile of (a) 4M-EDFA, denoted as ‘F1’ and (b) 6M- EDFA, denoted as ‘F2’, to be optimized through the GA; where ρ_i (m^{-3}) is the doping concentration of the i-th core layer.



(a) (b)

Figure 2. The modal gain (continuous line), noise figure (dashed line) and DMG (red dotted line) characteristics of the best (a) 4-mode-group EDFA and (b) 6-mode-group EDFA calculated by the GA. The blue (pink) shaded region indicates the C-band (L-band).

We have chosen to study a double-clad, step-index erbium doped fiber (EDF) with a core-to-inner clad refractive index difference of 0.004 and a core diameter of 23μm. We assume that the fiber is weakly guiding and supports the lowest four transverse mode groups from 1530 nm to 1565 nm, whose modal intensity profiles are shown in Fig. 1a. The diameter of the inner cladding was chosen to be 100µm, compatible with our preferred choice of pigtailed pump diode, and results in a core-to-cladding ratio of about 1: 4.3. The best fiber design (a_1 = 3.074 µm, a_2 = 8.730 µm, ρ_1 = 1.00e+25 m^{-3}, ρ_2 = 5.71e+24 m^{-3}, ρ_3 = 9.98e+24 m^{-3}) found through the GA is shown in Fig. 1a, here denoted as 'F1'. This 'W' shaped erbium dopant distribution provides similar amounts of overlap between the dopants and the signal modes. The gain and noise characteristics of the best fiber design are plotted in Fig. 2a. A fiber length of 13 m is used to ensure minimal gain tilt across the C-band, as indicated by the blue-shaded region in Fig. 2a. The gain and noise properties in the L-band is also plotted in the pink-shaded region as shown in Fig. 2a. The DMG (shown in red dotted line in Fig. 2a) is controlled to better than 1 dB from 1530 nm to 1600 nm, with a minimum of 0.26dB at 1553 nm and maximum of 0.90 dB at 1587 nm. In the C band, the modal gains are found to be more than 20 dB with a maximum gain of 23.37 dB for the LP_{01} mode at around 1565 nm and a minimal gain of 21.51 dB for the LP_{11} mode at around 1538 nm, for the input signal/pump power conditions described in section 2. The NFs shown in Fig. 2a are relatively high (i.e. between 5 to 7 dB) at the short wavelength region (1530-1542 nm) where the gain is relatively low. When the gain is relatively high, in the wavelength region of 1545 nm - 1565 nm, the NFs are found to be below 5 dB. In the L-band, the modal gains are much lower than those in the C-band, because the amplifier length is not optimized to achieve high gain in the L-band.

(2) Six-mode-group EDFA

In this instance the core diameter of the EDF is scaled up to 29 µm so as to support six-mode-groups while keeping the core-to-inner clad refractive index difference and the inner cladding diameter exactly the same as in the previous case. The FRIP and signal intensity profiles of the 6M-EDFA (denoted as 'F2') and its optimal erbium dopant profile (a_1 = 3.030 µm, a_2 = 7.059 µm, a_3 = 11.703 µm, ρ_1 = 3.09e+24 m^{-3}, ρ_2 = 7.94e+24 m^{-3}, ρ_3 = 4.15e+24 m^{-3}, ρ_4 = 9.85e+24 m^{-3}) obtained from the GA are shown in Fig. 1b. A fiber length of 12 m is used to ensure minimal gain tilt across the C band, as shown in the blue-shaded region in Fig. 2b. The gain and noise properties in the L-band are also plotted in the pink-shaded region in Fig. 2b. As shown in Fig. 2b, the DMGs (the red dotted line) are found to be below 1 dB with a lowest value of 0.31 dB at 1561 nm and a highest value of 0.91 dB at 1530 nm. The gain and noise characteristics of F2 are similar to that of F1. In the C-band, the modal gains are well above 20 dB with a maximum of 23.47 dB for the LP_{31} mode at around 1557 nm and a minimum of 21.38 dB for the LP_{01} mode at around 1538 nm. The NFs of the LP_{01}, LP_{11} and LP_{21} modes are relatively high (larger than 5dB) at the short wavelength region (i.e. 1530 - 1540 nm) but again become less than 5dB for wavelengths longer than 1545 nm. Again, the modal gains in the L-band are not optimum. However, the optimization of gains in the L-band is beyond the scope of this paper.

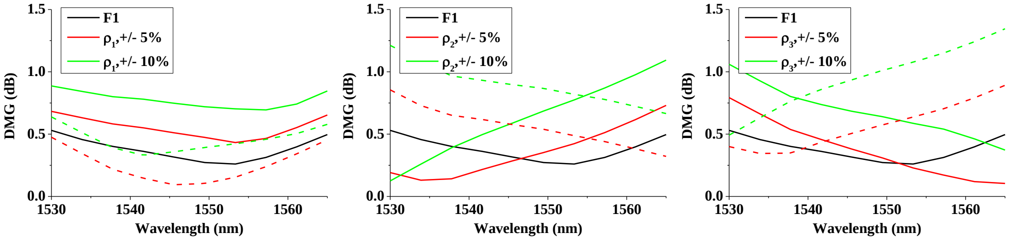
From more extensive simulations, we have also found that the changes in length or pump powers (in order to optimize gain, NF at certain signal wavelengths) of the amplifiers based on fibers F1 or F2 in general only result in a very small variation of the DMGs (less than 5%).

3. Fabrication tolerance discussion

Having demonstrated that very low DMG in both 4M and 6M cladding-pumped EDFAs can be theoretically realized, we went on to investigate how the inevitable imperfections introduced during the fabrication process of EDF affects the EDFA performance. In this section, we focused our tolerance discussion on the C-band using the optimized fiber lengths (i.e. 13m for the F1, 12 m for the F2) from the previous section. Firstly, a tolerance check on the doping concentration of each erbium-doped layer is studied in this section to assess the fabrication challenge in achieving the predicted levels of amplifier performance. We have run a set of simulations on both F1 and F2, in which we modified the doping concentration of each core layer (ρ_1, ρ_2 …) by ± 5% and ± 10% from the optimum value. Results for F1 and F2 are presented in Fig. 3 and Fig. 4 respectively.

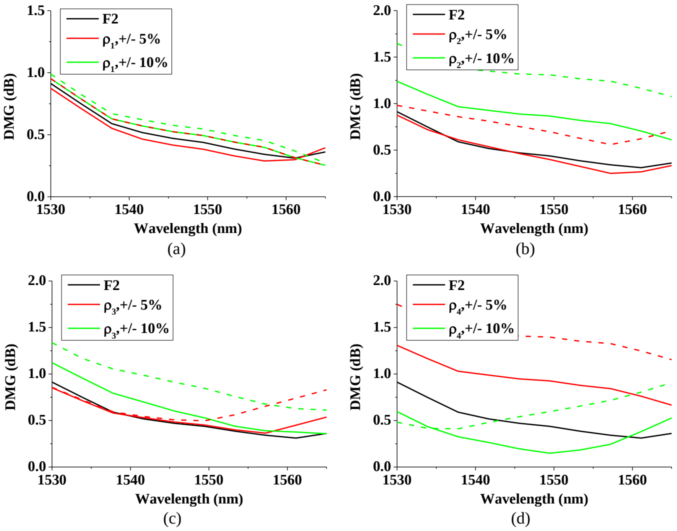
From Fig. 3a, it is evident that less than 1 dB DMG can be achieved over the full C-band with up to ±10% variation in ρ_1 (doping concentration of the 1st layer of F1). However, increasing the ρ_2, brings about a rise in the DMG at longer wavelengths whilst the DMG values at short wavelengths are more or less unaffected. On the contrary, decreasing ρ_2, results in an increase in the DMG at shorter wavelengths. However, decreasing ρ_3 results in increases the DMG in the longer wavelengths because the gain for the LP_{01} mode increase faster relative to other signal modes, as the dashed lines shown in Fig. 3c. In general, the performance of F1 is robust for up to ±5% changes in erbium concentration of the 2nd and 3rd core layers.

Fig. 4a and 4b show that the performance of F2 is robust for up to ±10% changes in the ρ_1 and +10% variations for the ρ_2. However, even a small reduction in ρ_2 from its optimum value result in the DMG becoming larger than 1dB at the short wavelength edge of the C-band. Down to -5% variation of the ρ_2 is acceptable for wavelengths longer than 1535nm. As shown in Fig. 4c, the DMGs are acceptable when the ρ_3 changes from -5% to +10%. Finally, Fig. 4d shows that ρ_4 is the most critical parameter of the four. The physical reason behind that is if ρ_4 increases by +10%, the gain of the LP_{01} mode slightly decreases and the gain of the LP_{31} mode increases. This results in a larger DMG (i.e. 1.8 dB). However, if ρ_4 decreases by -10% from its optimum position, the gain of the LP_{01} mode increases and the gain of the LP_{31} mode decreases, which allows the DMG to remain below 1 dB.



(a) (b) (c)

Figure 3. Variation of the DMG versus signal wavelength as (a) ρ_1, (b) ρ_2 (c) ρ_3 is changed for fiber F1. Continuous (dashed) lines represent a "+" ("-") variation.



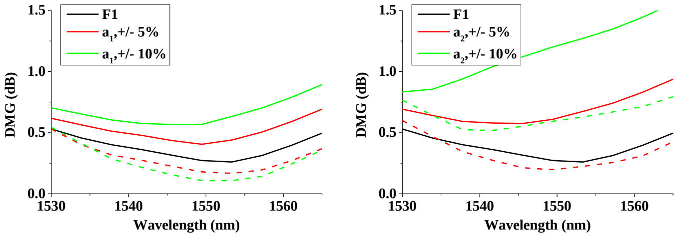
(c) (d)

Figure 4. Variation of the DMG versus signal wavelength as (a) ρ_1, (b) ρ_2 (c) ρ_3 is changed for the fiber F2. Continuous (dashed) lines represent a "+" ("-") variation.

Apart from the doping concentration, the structural parameters (i.e. a_1, a_2 ...) are another key set of parameters that also determines the final amplifier performance. A tolerance check of the structural parameters (i.e. a_1, a_2 ...) of both F1 and F2 were studied accordingly. Once again we run a set of simulations on both F1 and F2, in which we modified the structural parameters (i.e. a_1, a_2 ...) by ±5% and ±10% from the optimum value. Results for F1 and F2 are presented in Fig. 5 and Fig. 6 respectively.

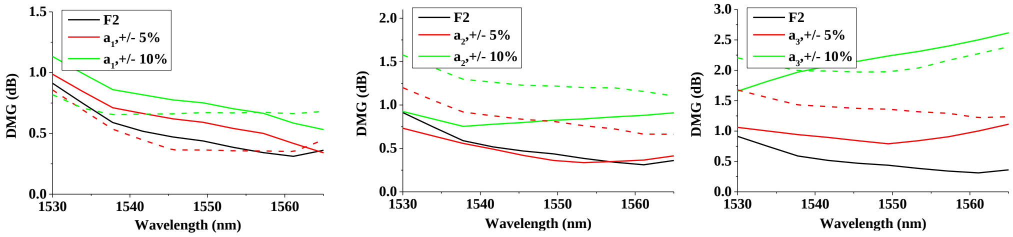
From Fig. 5a, it is evident that the DMG values for the full C-band are all below 1 dB with up to ±10% variation in a_1 for F1. However, increasing the a_2 of F1 to +10%, results in a large rise (above 1.5dB) in the DMG at longer wavelengths (1560 - 1565nm), as shown by the green solid line in Fig. 5b. If a performance of DMG< 1 dB for the full C bands is required, the variation of a_2 in F1 should be controlled to within -10% to +5%.

Fig. 6(a) and 6(b) show that the performance of F2 is robust to ±10% changes in the a_1 and +10% variations for the a_2. However, there is very little tolerance to reductions in a_2. a_3 determines the thickness of the 3rd and the 4th core layers of F2, so that any changes in a_3 mostly impacts the overlap between the erbium dopants and the LP_{31}, LP_{12} modes. Simulations shows that the gains for the LP_{12} and LP_{01} modes become the largest amongst all modes when a_3 is increased; while the gain for the LP_{31} mode becomes the highest when a_3 is decreased. Only a minimal variation of a_3 in the positive direction is tolerable, and particular care must be applied to try and match the optimum value, if a low DMG profile is required.



(a) (b)

Figure 5. Variation of the DMG against signal wavelength as the structural parameter (a) a_1, (b) a_2 is changed for the fiber F1. Continuous (dashed) lines represent a “+” (“-”) variation.



(a) (b) (c)

Figure 6. Variation of the DMG versus signal wavelength as the structural parameter (a) a_1, (b) a_2, (c) a_3 is changed for the fiber F2. Continuous (dashed) lines represent a “+” (“-”) variation.

4. Conclusion

We applied a Genetic Algorithm to minimize the differential modal gain in cladding pumped EDFAs supporting four and six-mode-groups. The optimum 4M-EDFA and 6M-EDFA designs, exhibiting three-layer and four-layer core structures (denoted as ‘F1’ and ‘F2) respectively, provide less than 1 dB DMG across the C- and L-band. Over 20 dB gain across the C-band is obtained for both F1 and F2 using a forward pump power of 2.5W and EDF lengths of 13m and 12m respectively. The amplifier performance in the L-band can be further improved by optimizing the fiber length and pump power. We have also studied the impact on DMGs due to the variation in doping concentration and physical dimension of each core layer of F1 and F2, and estimated the fabrication tolerance for a reliable amplifier performance.

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