Design and Analysis of Annulus Core Few Mode EDFA for Modal Gain Equalization
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Abstract—A few mode (FM) fiber amplifier is widely under study to overcome the issue of Internet traffic in optical communication. This letter proposes annulus core FM erbium-doped fiber (EDF) with annulus or extra annulus doping for the amplification of the LP_{01}, LP_{11}, LP_{21}, and LP_{31} signal mode groups with low differential modal gain (DMG). Our simulations confirm that extra annulus doping helps in reducing DMG of higher order mode groups. We have achieved less than 2.2-dB DMG over C-band for four-mode groups using extra annulus doping. The proposed EDF would be useful for the space division multiplexing (SDM)-based optical communication system.

Index Terms—Space division multiplexing, optical fiber amplifier, erbium, optical fiber communication.

I. INTRODUCTION

S TATISTICS of capacity with time suggest that increase in internet traffic may soon lead to capacity crunch as we are approaching to capacity limits of the single mode optical fiber systems. SDM is an effective way of increasing transmission capacity of optical fiber communication by increasing the number of channels [1]. There are two ways to incorporate SDM in optical communication system: multicore fiber (MCF) and few-mode fiber (FMF). Recently 112 Tb/s transmission capacity using a seven-core fiber [2] and 57.6 Tb/s net capacity using few mode fiber [3] have been reported. In addition to this, the development of SDM requires SDM integration based transmitter, receiver and optical amplifier. The most commonly used optical amplifier for optical communication is erbium doped fiber amplifier (EDFA). An aggregate capacity of 1.2 Tbit/s over a 250-GHz bandwidth using a three-core microstructured fiber with inline amplification via parallel single-mode EDFAs was demonstrated in [4] with maximum transmission distance of 4200 km. For cost reduction, SDM requires simultaneous amplification of the individual guided modes within the amplifier.

To enable few-mode fiber based SDM optical communication system, it is necessary to develop FM-EDFA which could provide high gain, low DMG and mode number scaling. Control over DMG mainly depends on erbium-doping profile and pump intensity distribution [5]. A system of multimode pump configuration has been demonstrated for controlled mode dependent gain at 1530 nm with DMG less than ±0.5 dB for two mode groups using uniformly-doped FM-EDF [6]. Several FM-EDFs using various controlled erbium doping profiles have been proposed. The ring-doped step-index fibers have been studied to minimize the DMG of the signal mode groups [7], [8]. The extra-annulus doping has also been studied for step-index fiber with or without trench and for graded-index fiber with or without trench to minimize DMG [9]. The improvement of DMG in FM-EDFA by employing graded-index ring-core erbium-doped fiber instead of conventional step-index fiber has been studied [10], [11].

Recently, a ring core FMF which supports three mode groups LP_{01}, LP_{11}, LP_{21} and does not support LP_{02} and LP_{22} mode groups (to avoid mode conversion between LP_{01} and LP_{02} at discontinuity point) has been studied to minimize the differential mode delay (DMD) [12]. In this letter, we have studied an annulus core EDFA which supports LP_{01}, LP_{11}, LP_{21} and LP_{31} mode groups only. The proposed EDF is studied with annulus and extra-annulus doping. The design parameters dependence of effective index (n_{eff}) has been studied. The LP_{01} pump mode has good overlaps with the ring-shaped signal modes of FM-EDF. We have introduced extra-annulus doping in annulus core fiber and have shown that extra annulus doping helps in reducing DMG. In this work, we have scaled up the signal mode groups of annulus core EDFA to 4 while maintaining effective indices separation between adjacent mode groups (Δn_{eff}) greater than 5.5×10^{-4}. We have achieved less than 2.2 dB DMG over C-band using extra annulus doping. The proposed fiber could be useful in FMF based optical communication system.

II. FIBER DESIGN

The proposed FM-EDF structure is schematically shown in Fig. 1. It consists of two core segments: one is uniform low index core (r < a) and other is annulus high index core (a < r < b). The central low-index core segment and the
Matrix Method [13]. The power confinement in Er profiles of the fiber have been calculated by using Transfer in Fig. 2. Mode effective indices and corresponding mode \( \Delta_1 \) used are:

\[
\Delta = \frac{(n_1^2 - n_{\text{silica}}^2)}{2n_1^2}
\]

The proposed design has been studied with annulus and extra annulus Er\(^{3+} \) doping as shown in Fig. 1. We have chosen LP01 mode at 980 nm wavelength as pump mode. The standard techniques of phase mask or spatial light modulator could be used for pump excitation. The mode profiles of different signal mode groups and LP01 pump mode of FM-EDF with \( \Delta = 1\% \), \( a = 5.2 \ \mu \text{m} \), \( d = 2.7 \ \mu \text{m} \), \( e = 0.5 \ \mu \text{m} \) are shown in Fig. 2. Mode effective indices and corresponding mode profiles of the fiber have been calculated by using Transfer Matrix Method [13]. The power confinement in Er\(^{3+} \) doped region and nearly equal overlap of the chosen pump mode with different signal mode groups enable to achieve high gain and low DMG. We can see that LP01 pump mode will have equal overlaps with even and odd modes of the same mode group. Our calculations also show that it has similar overlaps with different signal mode groups.

### III. Numerical Simulation and Result

The gains of FM-EDFA have been calculated by using mathematical modeling given in Ref. [6]. For the calculation of gain, the input signal power in each orientation and polarization of signal mode groups has been chosen as 30 \( \mu \)W and erbium ion concentration used is \( N_0 = 1 \times 10^{25} \text{ m}^{-3} \). The absorption and emission cross-sections used at 1530 nm are \( 4.68 \times 10^{-25} \text{ m}^2 \) and \( 5.54 \times 10^{-25} \text{ m}^2 \) respectively and the pump absorption cross-section used at 980 nm is \( 1.879 \times 10^{-25} \text{ m}^2 \) [14]. The simulations have been performed for annulus and extra annulus doping.

Recently, a ring core FMF has been studied for three mode groups to reduce DMD for SDM communication system [12]. To incorporate such fiber in SDM optical system, the design of corresponding ring core FM-EDFA is required. We have designed 3-mode group ring core FM-EDFA for such FMF. Fig. 3 (a) shows the variation of gains of LP01, LP11, and LP21 mode groups of FM-EDF with its length. The parameters used are: \( \Delta = 1\% \), \( a = 3.5 \ \mu \text{m} \), \( d = 2.7 \ \mu \text{m} \) and \( e = 0.5 \ \mu \text{m} \). The modes of the fiber corresponding to these parameters have sufficient mode spacing (\( > 1.1 \times 10^{-3} \)) in order to avoid mode coupling due to macro-bending [15]. For annulus doping, overlaps of pump with LP01, LP11 and LP21 signal mode groups of FM-EDF at 1530 nm wavelength are \( 8.38 \times 10^9 \), \( 8.53 \times 10^9 \) and \( 8.19 \times 10^9 \) respectively and for extra annulus doping, overlaps of pump with LP01, LP11 and LP21 signal mode groups of FM-EDF at 1530 nm wavelength are \( 8.51 \times 10^9 \), \( 8.68 \times 10^9 \) and \( 8.38 \times 10^9 \) respectively. The result shows that more than 20 dB gain for each mode group and less than 0.8 dB DMG have been achieved using input pump power of 150 mW and amplifier of length longer than 2 m with annulus doping. This is due to almost equal overlaps of pump with signal mode groups. Fig. 3 (b) shows that using extra annulus doping, DMG of 3 mode groups becomes less than 0.6 dB. This indicates that DMG could be further reduced using extra annulus doping. This happens because signal mode profiles of higher-order mode groups extend more towards extra annulus region as shown in the inset of Fig. 3 (b), so extra annulus doping enhances the gains of higher-order mode groups in comparison to those of lower-order mode groups, which results in decrease of DMG. The work could be extended to even higher mode groups. Fig 3 (c) shows the gain of 4 mode groups LP01, LP11, LP21 and LP31 with FM-EDFA length using extra annulus doping and input pump power of 200 mW. The fiber parameters used are \( \Delta = 1\% \), \( a = 5.2 \ \mu \text{m} \), \( d = 2.7 \ \mu \text{m} \), \( e = 0.5 \ \mu \text{m} \). The overlaps of pump with LP01, LP11, LP21 and LP31 signal mode groups of
FM-EDF at 1530 nm wavelength using extra annulus doping are \(6.25 \times 10^9\), \(6.32 \times 10^9\), \(6.33 \times 10^9\) and \(6.16 \times 10^9\) respectively. The results show more than 20 dB gain with less than 0.5 dB DMG for fiber length greater than 2 m. The results and parameters corresponding to Figs. 3 (b) and (c) suggest that the number of supported modes and DMG control depends on various parameters of the EDF. So, the parameters of amplifier should be optimized for minimum DMG while maintaining sufficient mode spacing \(\Delta n_{\text{eff}}\) between adjacent mode groups. Therefore, we have studied the effect of different parameters on DMG of signal mode groups.

The variation of DMG with central core radius \(a\) is shown in Fig. 4 (a). The variation of mode effective indices with \(a\) is shown in Fig. 4 (b) at 1530 nm wavelength. The other parameters used in calculation are: \(\Delta = 1\%\), \(d = 2.7 \mu m\), \(e = 0.5 \mu m\). The results show that DMG and mode spacing \(\Delta n_{\text{eff}}\) decrease with increase in \(a\). For \(a = 3.5 \mu m\), 3-signal mode groups are supported and their DMG is 0.76 dB with annulus doping and 0.66 dB with extra annulus doping while the value of \(\Delta n_{\text{eff}}\) is more than \(1.1 \times 10^{-3}\). For \(a = 5 \mu m\), there are 4-mode groups and their DMG is 0.72 dB with annulus doping and 0.51 dB with extra annulus doping while effective index spacing is greater than \(6 \times 10^{-4}\). For \(a = 6.5 \mu m\), DMG of five mode groups is 0.72 dB with annulus doping and 0.49 dB with extra annulus doping and effective index spacing is greater than \(3.5 \times 10^{-4}\). The results also show that there is a decrease in DMG with extra annulus doping in comparison to annulus doping.

Figs. 5 (a) and (b) show the effect of \(\Delta\) on DMG and mode effective indices. The other parameters used in calculation are: \(\Delta = 0.9\%\), \(a = 5.2 \mu m\), \(d = 2.7 \mu m\), \(e = 0.5 \mu m\). The results show that DMG decreases with increase in \(\Delta\) and there is no significant change in \(\Delta n_{\text{eff}}\). The results also show the significant effect of extra annulus doping. For \(\Delta = 0.9\%\) and extra annulus doping, DMG of 4 mode groups is 0.71 dB with \(\Delta n_{\text{eff}}\) greater than \(5.7 \times 10^{-4}\). Using \(\Delta = 1.3\%\), the DMG of 4 mode groups can be brought down to 0.21 dB. However, a higher value of \(\Delta\) would also result in propagation loss due to high Ge concentration. Thus, \(\Delta = 1\%\) is optimum from point of view of DMG control and fiber manufacturing.

Figs. 6 (a) and (b) show the tolerance of annulus core width \(d\) on DMG and mode indices. The other parameters used in calculation are: \(\Delta = 1\%\), \(a = 5.2 \mu m\), \(e = 0.5 \mu m\).
The results show that DMG decreases with increase in $d$ and $\Delta n_{\text{eff}}$ also decreases with increase in $d$. However, in the range $2.6 \mu m < d < 2.7 \mu m$, DMG of 4 mode groups varies from 0.46 dB to 0.42 dB with extra annulus doping and $\Delta n_{\text{eff}}$ is greater than $5.5 \times 10^{-4}$. It means, there is only a small variation of 0.04 dB in DMG of 4 mode groups with 0.1 $\mu m$ change in $d$.

The variation of pump power on gains of different signal mode groups is shown in Fig. 7 (a). The optimized parameters used in calculation are: $\Lambda = 1\%$, $a = 5.2 \mu m$, $d = 2.7 \mu m$ and $e = 0.5 \mu m$. The results show that for pump power $P_{\text{pump}} \geq 150$ mW, more than 20 dB gain for each mode group and less than 0.5 dB differential modal gain (DMG) with sufficient mode spacing $> 5.5 \times 10^{-4}$ to avoid mode coupling have been achieved using amplifier of length 3 m. DMG varies from 0.3 dB to 0.5 dB with pump power variation from 150 mW to 350 mW, which shows that any fluctuation in pump power does not significantly affect the DMG. Fig. 7 (b) shows the convergence of noise figures towards 3.3 dB with increase in modal gain.

The study of modal gains and noise figures (NF) of LP$_{01}$, LP$_{11}$, LP$_{21}$ and LP$_{31}$ mode groups of FM-EDFA is shown in Fig. 8. The study shows that DMG between the four mode groups corresponding to single wavelength is below 0.45 dB and the gain difference for a mode group over C-band is less than 1.75 dB. Thus, overall DMG is below 2.2 dB over entire C-band with $\Delta n_{\text{eff}} > 5.5 \times 10^{-4}$ and noise figure less than 3.5 dB. The gain difference can be further minimized by using gain equalization filter [16].

IV. CONCLUSION

We have studied an annulus core FM-EDF with extra annulus doping for applications in SDM optical communication system. We have shown that DMG of 3 mode groups is less than 0.6 dB with effective indices separation greater than $1.1 \times 10^{-3}$. We have also investigated the effect of annular core width, relative index difference and central core radius on DMG and mode spacing using annulus and extra annulus doping. Extra annulus doping plays a significant role in minimizing DMG. The study shows that less than 2.2 dB DMG over C-band for 4 mode groups EDF could be achieved with mode spacing $> 5.5 \times 10^{-4}$. The proposed configuration would be useful for SDM system.

REFERENCES