Strongly Coupled Few-mode Erbium-doped Fiber Amplifiers with Ultralow Differential Modal Gain

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Abstract: We propose new few-mode EDFAs based on strong mode coupling, which can be realized by distributed long-period gratings. As a result, an ultralow differential modal gain of 0.5 dB can be achieved with layered doping.

1. Introduction

Space division multiplexing (SDM) technology has been studied as a promising approach to overcome the capacity limit of single-mode fiber network [1,2] by using multiple spatial channels in few-mode fibers (FMFs) and/or multi-core fibers (MCFs). One of the key building blocks in such a long-haul SDM system is its matching optical fiber amplifiers to amplify all spatial channels simultaneously. Various few-mode erbium-doped fiber amplifiers (FM-EDFAs) and multi-core EDFAs [3-5] have been developed. These amplifiers are cost effective and power efficient compared to multiple single-mode EDFAs [3], and SDM amplification itself has become a major research topic.

A key factor in designing SDM amplifiers is gain equalization for all spatial channels. The differential modal gain (DMG) of a FM-EDFA has a direct impact on system performance. Advanced amplifier designs have been proposed to minimize the DMG [3-7]. In principle, DMG depends on the spatial overlap among signal and pump mode profiles, and Er-dopant distribution, which is effectively reduced by parameter optimization. FM-EDFAs have been reported to amplify 6, 10 and 21 spatial modes [8-10], with DMG of typically 2~3 dB. However, it is difficult to realize very low DMG of <1 dB. Moreover, FM-EDFAs for a large number of modes through the above parameter optimization would suffer from the complexity of design and fabrication.

As an alternative way to reduce DMG, a FM-EDFA can be built with intentionally enhanced mode coupling (MC) in a fiber core. This has two main advantages: 1) reduced DMG by sufficiently scrambling signal modes, and 2) reduced design complexity as the number of modes increases. In particular, it is noted that strong MC in long-haul few-mode transmission links is viewed as an effective way to greatly reduce MIMO complexity [11,12]. The use of strong coupling in FM-EDFAs naturally matches fiber links. Recently, a mode scrambler is inserted into a FM-EDFA, resulting in DMG reduction by 1.8 dB on average [13]. It would be highly desirable to explore how to greatly reduce the DMG of a FM-EDFA via inducing strong coupling.

In this paper, we propose strongly coupled FM-EDFAs for the first time to greatly reduce DMG by wisely choosing coupling strength (CS) and the number of coupling points (NCPs). It is shown that DMG can be reduced by 7.6 dB in a uniformly doped FM-EDFA. Moreover, with an optimized doping profile, the DMG can be as low as 0.5 dB. We find that strong MC in FM-EDFAs would not sacrifice the gain flatness in C-band while reducing DMG. Finally, the feasibility of the proposed FM-EDFAs is discussed.

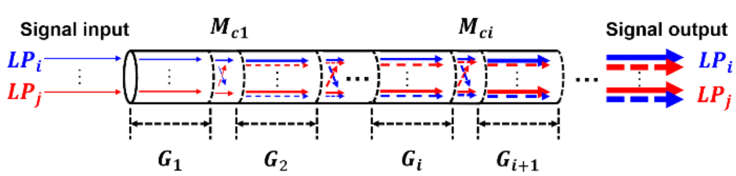

Fig. 1. The proposed strongly coupled FM-EDFA.

2. Principle of a strongly coupled FM-EDFA

In Fig. 1, an Er-doped fiber (EDF) is divided into $\boldsymbol{K}$ independent sections, each modeled as an amplification process. Distributed MC can be treated as random matrices before and after each independent section. The fiber transfer matrix (TM) of the proposed FM-EDFA is written by

$$M = G_K \cdots G_{i+1} M_{ci} G_i \cdots G_2 M_{c1} G_1 \quad (1)$$

where $\boldsymbol{M}$ is the TM, $\boldsymbol{G_i}$ is the gain matrix in the i-th section, $\boldsymbol{M_{ci}}$ is the random coupling matrix among modes. $\boldsymbol{M}$ includes all possible paths through the fully coupled amplifier, from which the overall MG and DMG are obtained by SVD technique at any frequency [14].

Here, EDFs are divided into 1000 pieces with the same length, each modeled using 4[th]-order Runge-Kutta method, with a step of 1.2 cm. Mode coupling is randomly inserted between the pieces. The linearly polarized signals (LP_{01}, LP_{11}, LP_{21}, LP_{02}), each with a power of 0.1 mW, and a 980-nm pump (LP_{01}) are used. Two types of EDFs are considered in terms of their transverse feature: Type A with uniform doping (100 ppm) and Type B with layered doping (65 ppm @ radius<b, b=3 μm & 115 ppm @ radius>c, c=4.8 μm), as shown in Fig. 2 (a)&(b), whose core radii are both 8 μm.

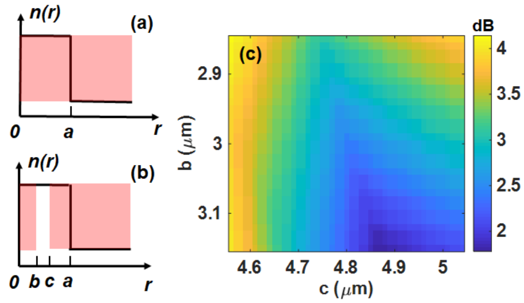

Fig. 2. Schematic of 6-mode EDFA (a) Type A and (b) Type B (shaded part represents Er doping); (c) DMG vs. b & c in Type-B EDFA

3. Significant reduction of differential mode gain

Figure 3 shows DMG as a function of both NCP and CS for a 6-mode Type-A or Type-B EDFA. NCP and CS are ranged from 100 to 600 and from -25 to -5 dB/pt, respectively. However, even if NCP and CS are fixed, DMG still varies due to the randomness of single-point coupling matrix and the location of coupling point. Thus, we calculate DMG for 100 times at each NCP and CS and then average them, as shown in Fig. 3. We note that DMG of Type B EDFAs in uncoupled case is 2.4 dB, much lower than that of Type A. In Fig. 3, reduction in DMG is significant, due to strong mode mixing. Moreover, compared with NCP, increasing CS is more effective for DMG reduction. For Type A, DMG can be reduced dramatically by 7.6 dB, from 9.3 to 1.7 dB, while, for Type B, the minimum DMG can be even as low as 0.5 dB, which is jointly contributed by EDF structural improvement in both transverse and longitudinal directions. In addition, from Fig.2(c), when Er-dopant distribution for Type-B EDF varies, i.e., b and c have an error of ±2.5% in real fabrication, DMG in the uncoupled case fluctuates within 1 dB, and thus DMG of the 6-mode EDFA with strong coupling can still be expected to be <1 dB.

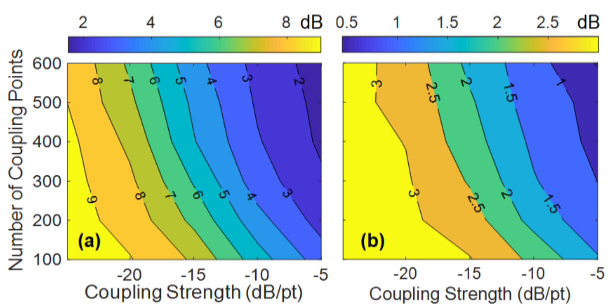

Fig. 3. DMG vs. NCP and CS in (a) Type A and (b) Type B.

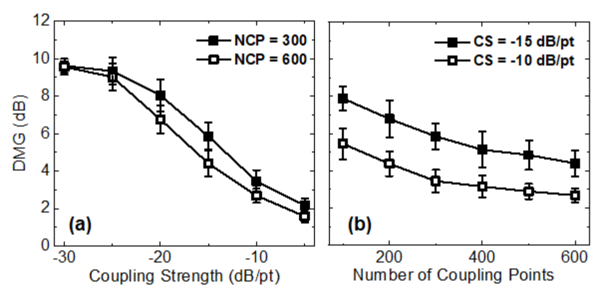

Fig. 4. DMG vs. (a) CS at NCP = 300 and 600; (b) NCP at CS = -15 dB/pt and -10 dB/pt.

As described above, NCP and CS are the key to reduce DMG. Due to the randomness of single-point coupling matrix and coupling locations, we need to evaluate DMG fluctuation after 100 repeated calculations. Note that, in Fig. 3, DMG of the two types of FM-EDFAs has a similar trend vs. NCP and CS. Thus, we choose the Type A for analysis below. As shown in Fig. 4(a), DMG decreases with CS, from 9.6 ± 0.3 to 2.1 ± 0.3 dB, with 7.5-dB reduction, when NCP is fixed to 300. Similarly, 8.3-dB reduction is found for NCP = 600. It is important to note that the standard deviation of DMG first increases and then decreases with CS from -30 dB/pt to -5 dB/pt. This is because the overall randomness is quite weak when CS is around -30 dB/pt, and on the other hand it is also weak as CS increases to be >-10 dB/pt with modes fully scrambled. Figure 4(b) shows that DMG decreases from 7.9 ± 0.6 to 4.4 ± 0.7 dB with NCP, when CS is fixed at -15 dB/pt. DMG variation decreases as a whole with CS, especially for a large NCP.

Figure 5(a) shows the average MG and DMG as a function of pump power in uncoupled and strongly coupled FM-EDFAs. The average MGs of uncoupled and strongly coupled FM-EDFAs are almost the same. And, DMG and its standard derivation also remain constant at 3.5 ± 0.5 dB with a pump power from 200 to 1000 mW, i.e., the pump power does not degrade the DMG of the strongly coupled FM-EDFA as in the uncoupled case. We can see that the pumping behavior of strongly coupled FM-EDFAs are basically the same as that of the uncoupled case, except that DMG is greatly reduced.

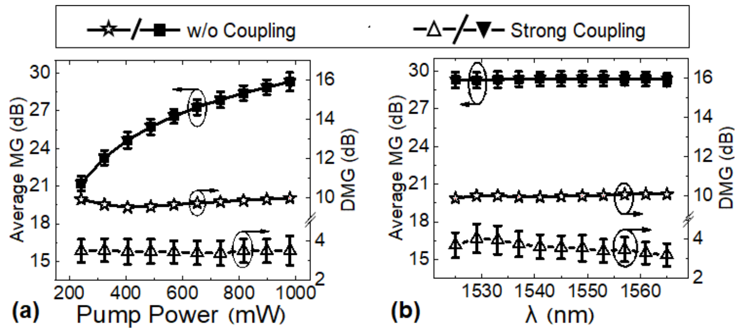

Fig. 5. Average modal gain and DMG vs. (a) pump power and (b) wavelength across the C-band in uncoupled and strongly coupled 6-mode EDFAs (CS = -10 dB/pt; NCP =300).

In addition to low DMG, the wideband operation is also important for FM-EDFAs. Also, we calculate the average MG and corresponding DMG across the C-band shown in Fig. 5(b). The spontaneous emission spectrum of the amplifier that we use is measured experimentally. We find that the average MGs of uncoupled and strongly coupled FM-EDFAs are the same in the C-band. DMG of strongly coupled FM-EDFA is much lower than that in the uncoupled case, although having a negligible variation. Therefore, strong mode mixing in FM-EDFAs does not sacrifice the C-band gain flatness, while reducing DMG.

4. Implementation of strongly coupled few-mode EDFAs

It is important to verify the feasibility of the proposed FM-EDFAs. Long-period gratings (LPGs) have been used as an effective way to induce strong MC in fiber for a low differential mode delay [11,15]. We propose to apply this to FM-EDFAs to realize a low DMG. Importantly, the grating strength Δn_g is the key parameter and directly determines CS. It can be realized by controlling the exposure power of a CO_2 laser. When Δn_g equals 2.5×10^{-5}, we calculate the coupling length, which is found to be 20 cm, meaning that complete mode conversion can be achieved after a 20-cm-long fiber [15]. Thus, when the fiber length is 4 cm, 10% power transfer, i.e., CS = -10 dB, can be realized. In our work, EDF length is set to be 12 m, which can accommodate 300 pieces of the LPGs, i.e., NCP = 300. In addition, the loss caused by grating writing is negligible (e.g., <0.1 dB) due to the short fiber length. Thus, we believe that the proposed strongly coupled FM-EFDA with CS = -10 dB/pt and NCP = 300 is practical.

5. Conclusions

For the first time, we have proposed a strongly coupled FM-EDFA and developed a new gain model for it. Low DMG can be obtained in strongly coupled FM-EDFAs with great DMG reduction of 7.5 dB in a uniformly doped 6-mode EDFA, while 0.5-dB DMG has been made feasible in an optimized doping profile. Wideband operation over C band is also achieved. Importantly, it is shown that strongly coupled EDFAs can be realized using distributed LPGs.

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