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Mode-dependent dynamic gain of all-fiber FM-EDFA under various pump manipulation

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The dynamic gain of a few-mode erbium-doped fiber amplifier (FM-EDFA) is vital for the long-haul mode division multiplexing (MDM) transmission. Here, we investigate the mode-dependent dynamic gain of an FM-EDFA under various manipulations of the pump mode. First, we numerically calculate the gain variation with respect to the input signal power, where a mode-dependent saturation input power occurs under different pump modes. Even under the fixed intensity profile of the pump laser, the saturation input power of each spatial mode is different. Moreover, high-order mode pumping leads to a compression of the linear amplification region, even though it is beneficial for the mitigation of the differential modal gain (DMG) arising in all guided modes. Then, we develop an all-fiber 3-mode EDFA, where the fundamental mode of the pump laser can be efficiently converted to the LP_{11} mode using the all-fiber mode-selective coupler (MSC). In comparison with the traditional LP_{01} pumping scheme, the DMG at 1550 nm can be mitigated from 1.61 dB to 0.97 dB under the LP_{11} mode pumping, while both an average gain of 19.93 dB and a DMG of less than 1 dB can be achieved from 1530 nm to 1560 nm. However, the corresponding signal input saturation powers are reduced by 0.3 dB for the LP_{01} mode and 1.6 dB for the LP_{11} mode, respectively. Both theoretical and experimental results indicate that a trade-off occurs between the DMG mitigation and the extension of the linear amplification range when the intensity profile of pump laser is manipulated.

Keywords: few-mode erbium-doped fiber amplifier; differential modal gain; saturation input power.
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1. Introduction

As a promising technique to overcome the capacity crunch of a standard single-mode fiber (SSMF), mode division multiplexing (MDM) has attracted worldwide research interests, as it can carry different data information over individual spatial modes[1]. The few-mode erbium-doped fiber amplifier (FM-EDFA), as a crucial component in compensating for the loss of long-haul MDM transmission, has been actively explored during the past few years[2–6]. The FM-EDFA employs one pump laser to simultaneously amplify multiple guided modes arising in the few-mode fiber (FMF). One of the main challenges for the FM-EDFA is realizing the low differential modal gain (DMG) among all guided modes with a sufficient small-signal gain (SSG). It has been identified that the DMG is determined by the overlap integral between the intensity profiles of both the specific guided mode and the pump mode within the erbium-ion-doped region[7]. Thus, all existing schemes of DMG mitigation can be generally divided into three categories.

First, researchers start to optimize the DMG performance with respect to the intensity profile of the guided modes[8–12]. Using a ring refractive index (RI) structure, both a DMG of 0.8 dB between LP_{01} and LP_{11} modes and an average gain of about 17 dB can be secured, when the input signal power at 1550 nm is −10 dBm per mode[13]. Second, researchers have proposed several FM-EDFs with novel erbium doping distributions. Using annular doping, researchers realized the maximum gain of the LP_{11} and the LP_{21} signal modes close to 20 dB and a DMG of less than 1 dB when the input signal power is −10 dBm per mode at 1550 nm[14]. Then, using ‘Batman’ doping, the researchers achieved an average gain of 15 dB and 2.5 dB DMG for the 6 LP modes when the input signal power is −13 dBm per mode at 1550 nm[15]. Since realizing either the RI distribution or the erbium doping profile needs a sophisticated fiber fabrication process, a performance penalty always exists between the experimental verification and the theoretical prediction. Moreover, the mode-field matching between the EDF and the commercial FMF needs to be further considered. Third, the FM-EDFA with a small DMG can be achieved by manipulating the intensity profile of the pump laser[16]. By converting the pump laser from the LP_{01} to the LP_{21} mode through a photonic lantern (PL), both a DMG of about 0.5 dB among the 6 LP modes and a gain of about 16 dB can be secured when the input signal power at 1550 nm is −10 dBm per mode[17].

In addition, once the pumping mode varies, the dynamic gain of the FM-EDFA will also be affected. In fact, the signal saturation input power is a key indicator of the dynamic gain for the EDFA. It is known that the operation of a traditional single-mode EDFA (SM-EDFA) above the input saturation power will lead to gain compression[17]. In particular, when the input signal power is higher than the input saturation power, the gain decreases faster with the growing input signal power[18]. When the FM-EDFA is operated at the saturated region, the fluctuation of the input power will cause severe gain fluctuation, leading to the DMG variation of the FM-EDFA. Thus, the linear amplification range determined by the input saturation power is particularly critical for the reconfigurable optical network, where large input power variations of all guided modes occur. It is highly desired that the optical amplifier has a wider range of linear amplification. However, current FM-EDFA investigations are mainly focused on the statistic gain and the DMG performances under a specific input signal power without considering its dynamic gain. Therefore, the input saturation power of the FM-EDFA needs to be clarified under the intensity profile manipulation of the pump laser together with the DMG mitigation.

In this work, an all-fiber FM-EDFA supporting three modes under various manipulations of the pump mode is comprehensively investigated. We numerically identify that higher-order pumping is helpful for mitigating the DMG. However, in terms of the input saturation power, it leads to a reduction of the linear amplification range. When a mode selective coupler (MSC) is used to convert the LP_{01} mode to the LP_{11} mode for a 976-nm pump laser, in comparison with the fundamental mode pumping, the DMG can be mitigated from 2 dB to 1 dB under the condition of the LP_{11} mode pumping. However, the input saturation powers of the LP_{01} and the LP_{11} signals are reduced by 0.3 dB and 1.6 dB, respectively. Therefore, there occurs a trade-off between the DMG mitigation and an extension of linear amplification range.

2. Numerical Simulations

We start to numerically investigate the impact of different pumping schemes on the FM-EDFA performance in terms of the DMG and the input saturation power. As shown in Fig. 1, the experimentally used FM-EDF has a core radius of about 7 μm and a cladding radius of 62.5 μm with a numerical aperture (NA) of around 0.19. By calculating the normalized depth (ND)[19], we can find that the ND is lower than 0.3, and the width of the RI drop is lower than 15% of the core diameter. Thus, there exists almost no impact on the mode profile of the pump and signal. It can be reasonably approximated as the RI structure shown in Fig. 1(b), leading to a guidance of the LP_{01}, LP_{11a}, and LP_{11b} modes over the C-band. Erbium ions are uniformly doped at the core region with a doping concentration of about $4 \times 10^{24}\ m^{-3}$. Based on the above parameters, according to Ref. [20], we maintain that the difference values of the overlapping factors are 2.6×10^9 and 5.4×10^7 when the pump modes are LP_{01} and LP_{11}, respectively. We can see that the difference of the overlapping factor is smaller than the condition of the LP_{11} pumping, leading to a lower DMG. For this EDF, we have performed the modeling of the FM-EDFA as a three-level system[20,21].

When the length of the used FM-EDF is 5 m and the pump power is 210 mW, we can obtain the gain as a function of the input power for both the LP_{01} and the LP_{11} pumping. As shown in Fig. 2, the gain values of the three guided modes remain constant and then rapidly decrease when the input signal power

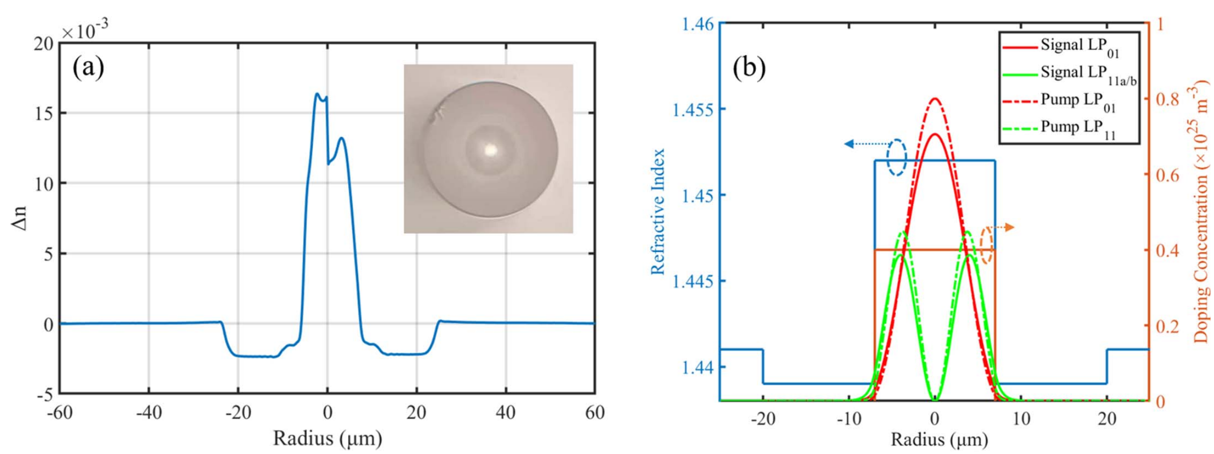

Fig. 1. (a) Refractive index distribution of the FM-EDF. (b) Intensity profiles of LP_{01} and LP_{11} at 1550 nm and 980 nm.

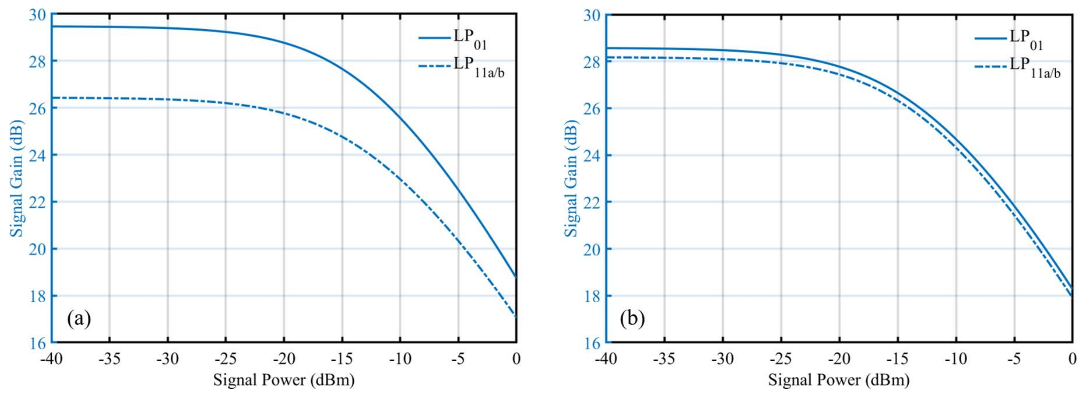

Fig. 2. Gain variation of each guided mode with respect to the signal power when the pump modes are (a) LP_{01} and (b) LP_{11} modes, respectively.

Table 1. The Saturation Input Power for Each Signal Mode with a Different Pump Scheme in Simulation.

	Saturation Input Power (dBm)	
	LP_{01} Signal Mode	$LP_{11a/b}$ Signal Mode
Under LP_{01} mode pumping	−11.8	−11.1
Under LP_{11} mode pumping	−12	−11.7

gradually increases. In particular, when the pump laser is operated at the LP_{01} mode and the input signal power is −10 dBm per mode, the gain values of the LP_{01} and the LP_{11} modes are 25.56 dB and 22.95 dB, respectively, leading to a DMG of 2.61 dB. However, when the intensity profile of the pump laser is in the LP_{11} mode, the corresponding gain values are 24.68 dB and 24.32 dB, respectively, leading to a DMG of 0.36 dB. Normally, the input power corresponding to a 3-dB drop of its SSG is defined as the input saturation power[18]. For the proposed FM-EDFA, the input saturation power values of the three guided modes under different pumping schemes can be obtained, as shown in Table 1. For the same pump mode, the saturation input powers of the LP_{11} mode are 0.7 dB and 0.3 dB higher than that of the LP_{01} mode, respectively, implying a wider range of linear amplification for the higher-order signal mode, which is consistent with the findings of previous studies[21]. This is due to the fact that the intensity profile of the LP_{11} signal mode is more divergent than that of the LP_{01} signal mode. Thus, the higher order signal modes consume the upper-level population more slowly. However, after manipulating the intensity profile of the pump laser for the purpose of DMG mitigation, the saturation input power drops by 0.2 dB for the LP_{01} mode and 0.6 dB for the LP_{11} mode, respectively. Since the intensity profile of the higher-order pump mode is less concentrated at the central region of the core, the excited populations into the upper energy level are not enough to satisfy the consumption of the signal, leading to faster amplifier saturation compared to the LP_{01} pumping. Thus, not only does the FM-EDFA have different saturation input power for different signal modes but also there occurs a trade-off between the pump manipulation induced by the DMG mitigation and the extension of the linear amplification range.

3. Experiment and Discussion

Next, we start to develop an all-fiber FM-EDFA, for the ease of experimental verification. As shown in Fig. 3, the signal to be amplified is generated by a C-band tunable laser source (TLS) with the SSMF pigtail. We connect the SSMF pigtail with the

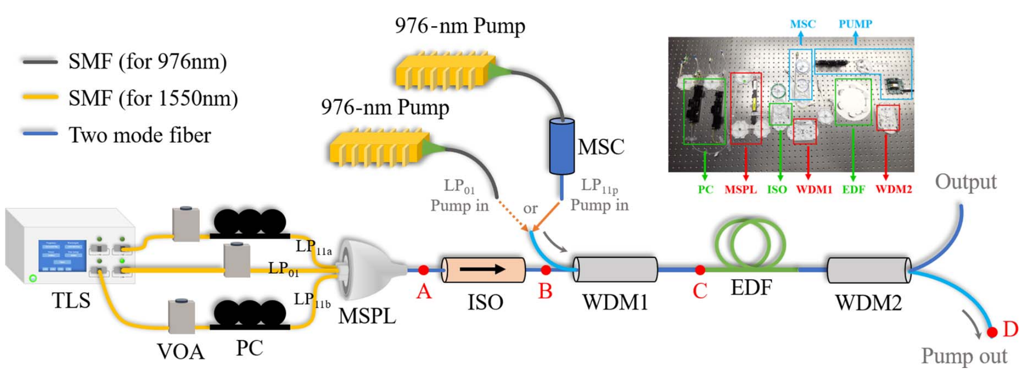

Fig. 3. Experimental setup of the all-fiber FM-EDFA. TLS, tunable laser source; VOA, variable optical attenuator; PC, polarization controller; MSPL, mode-selective photonic lantern; ISO, isolator; WDM, wavelength division multiplexer; MSC, mode-selective coupler; OSA, optical spectrum analyzer.

input port of the mode-selective photonic lantern (MSPL, Phoenix Photonics 3PL-0160153), so that either the LP_{11a} or the LP_{11b} mode can be separately excited and multiplexed with the LP_{01} mode. Polarization controllers (PCs) are used to manage the intensity profile of the higher-order modes, and the variable optical attenuator (VOA) is used to equalize the mode dependent loss (MDL) arising in the mode selective conversion in order to fix the input power of each mode. To prevent the unwanted reflections, an isolator with a two-mode fiber (TMF) pigtail is used after the MSPL. The used commercial TMF (YOFC FM SI-2) has a core radius of about 7 μm and the core refractive index of 1.4485, respectively. Meanwhile, we experimentally implement two pumping schemes. The first one is to directly introduce the 976-nm laser with the LP_{01} mode into wavelength division multiplexer 1 (WDM1) as the pump source. The other pumping scheme is used to convert the LP_{01} mode to the LP_{11} mode by using an all-fiber MSC with conversion efficiency of 85.2%. Here, we place a PC after the 976-nm pump laser in order to ensure the high mode purity. With the help of WDM1, the pump laser and three-mode division multiplexing signals can be successfully introduced into a 5-m FM-EDF. The FM-EDF has the same parameters in the numerical investigation. After the FM-EDF, WDM2 is applied to filter out the residual pump, whose intensity profile can be monitored. Meanwhile, the amplified 1550-nm signal can be characterized by a charge-coupled device camera (CCD, SP928-1550-OSI), an optical spectrum analyzer (OSA, AQ6370D), and a power meter (PM100D), respectively.

In order to monitor the evolution of the signal mode, we record its intensity profile at the output port of each passive device denoted as points A, B, and C in Fig. 3, as shown in Fig. 4(a). From those results, we can conclude that the intensity profile of each guided mode is well preserved. Meanwhile, the MDL of each passive device is provided in Table 2. Here, we measure the output power P_1 of the previous device and then fuse the device under test with the output pigtail of the previous device. Next, we measure the output power P_2 of the device under test to obtain the insertion loss as $\text{Loss} = P_1 - P_2$. Thus, the splicing

Table 2. Insertion Losses of the Passive Fiber-Optic Device.

	Insertion Losses (dB)		
	LP_{01}	$LP11_a$	$LP11_b$
ISO	0.64	1.32	1.17
MSPL@1550 nm	2.75	4.21	3.51
WDM2@1550 nm	0.47	0.78	0.64
MSC@976 nm	/	1.7	
WDM1@1550 nm	0.57	0.9	1
WDM1@976 nm	0.61	0.74	

loss is taken into account during the device loss measurement. According to this result, we can adjust the VOA to manage the launch power of each spatial mode at the FM-EDF input. Furthermore, the mode profile of 976-nm pump laser is also recorded by another CCD (GS3-U3-32S4C), as shown in Fig. 4(b). Before introducing the pump into the FM-EDF, denoted as point C in Fig. 3, we can observe either the LP_{01} or the LP_{11} mode profile of the pump laser. After co-propagation with the 1550-nm signal over the FM-EDF, the mode profile of the residual pump at the WDM2 output, denoted as point D in Fig. 3, is recorded as well. It can be seen that the intensity profile is well preserved for either the LP_{01} or the LP_{11} pump mode, and the MDL of WDM1 at 976 nm is summarized in Table 2 as well.

Initially, we examine both the gain and the DMG characteristics of the FM-EDFA. Figure 5 shows the DMG as a function of the pump power for two different pumping schemes. Here, the signal power of each mode at the FM-EDF input is fixed at −10 dBm. As shown in Fig. 5, the pump power, no matter the pump mode is either LP_{01} or LP_{11}, ranges from 50 to 250 mW. When the pump mode is LP_{01}, the average gain eventually reaches about 19.57 dB. However, when the pump mode is

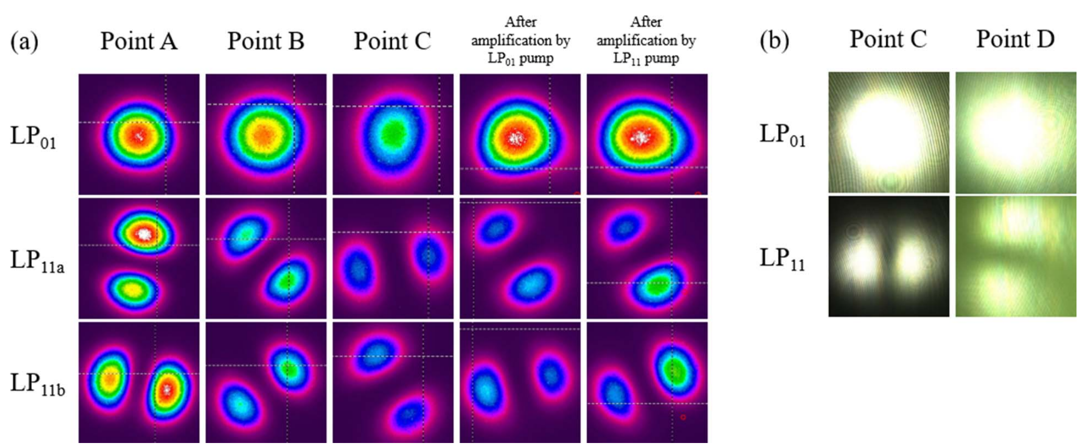

Fig. 4. Near-field mode profiles of (a) the signal modes measured at points A, B, and C after amplification and (b) the pump modes at points C and D.

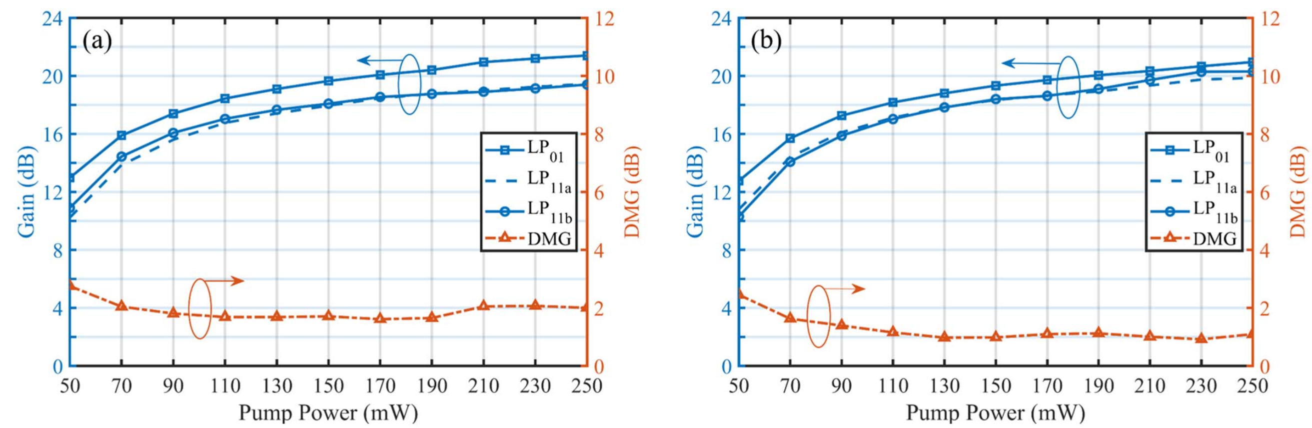

Fig. 5. Variations of the gains and the DMGs with respect to (a) LP_{01} pump power and (b) LP_{11} pump power when the input signal power is −10 dBm per mode.

LP_{11}, the average gain can be more than 20.34 dB. Furthermore, as for the LP_{01} pumping scheme, the DMG is about 1.61 dB, while for the LP_{11} pump scheme, the DMG can decrease to about 0.97 dB when the pump power is fixed at 210 mW. Here, the NF values of the LP_{01}, LP_{11a}, and LP_{11b} signal modes are 4.9 dB, 10.1 dB, and 9.4 dB, respectively, under the condition of the LP_{01} pumping scheme, while the NF values become 5.2 dB, 8.8 dB, and 8.7 dB, respectively, under the LP_{11} pumping scheme. Moreover, the gain and the DMG of the FM-EDFA with respect to the operation wavelength of the input signal are also characterized. The operation wavelength of the input signal is tuned over the C-band from 1530 nm to 1565 nm with a resolution of 2.5 nm when the signal and pump powers are fixed at −10 dBm and 210 mW, respectively. Overall, both an average gain of 19.93 dB and a DMG of less than 1 dB can be achieved from 1530 nm to 1560 nm, as shown in Fig. 6. This is in line with the simulation results.

Second, we investigate the dynamic gain under different pumping schemes. When the pump power is 210 mW, the gain variations with respect to the input signal power are shown in Fig. 7. Similar to the simulation analysis, the gain first remains constant and then gradually decreases as the signal power increases. As shown in Table 3, the saturation input powers of the LP_{01} and the LP_{11} models are −12.7 dBm and −7.2 dBm, respectively, when the LP_{01} pumping scheme is chosen. However, when the pumping scheme is converted to the LP_{11} mode, the saturation input powers of the two spatial modes are −13.0 dBm and −8.8 dBm, respectively. For each pumping scheme, the saturation input power of the LP_{01} mode is 5.5 dB and 4.2 dB lower than the saturation input power of the LP_{11} mode, respectively. A mode-dependent difference of the saturated input power among the guided modes can be clearly summarized. Moreover, although the mode selective conversion of the pump laser from the LP_{01} mode to the LP_{11} mode leads to a low DMG of 0.97 dB under an input signal power of −10 dBm, it reduces the saturation input power by 0.3 dB for the LP_{01} signal mode and 1.6 dB for the LP_{11} signal mode, respectively. Thus, the high-order pumping results in a small range of linear amplification. A trade-off between the DMG mitigation and the extension of the linear amplification range for

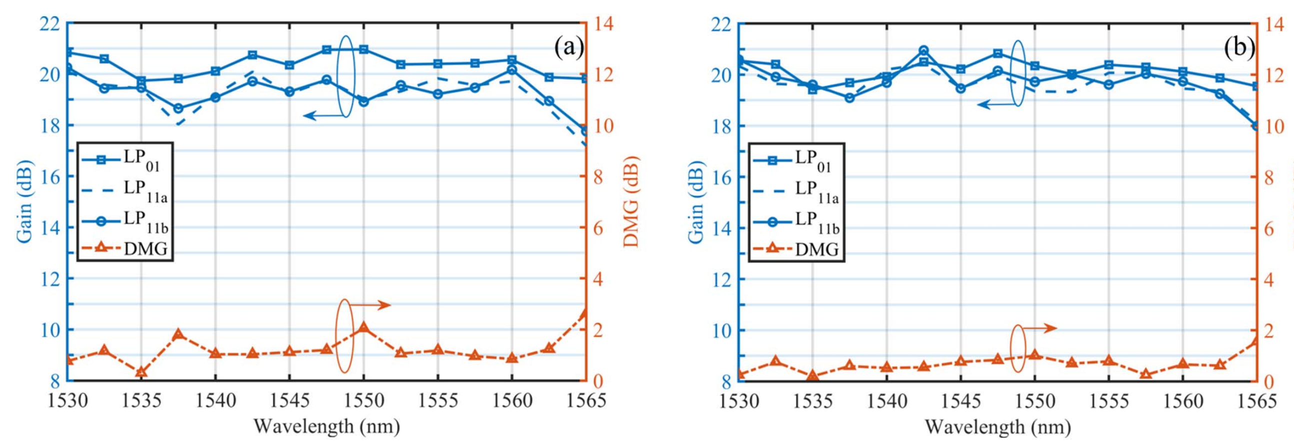

Fig. 6. Variations of the gains and the DMGs over the C-band with (a) the LP_{01} pumping scheme and (b) the LP_{11} pumping scheme, when the pump power is 210 mW and the input signal power is −10 dBm per mode.

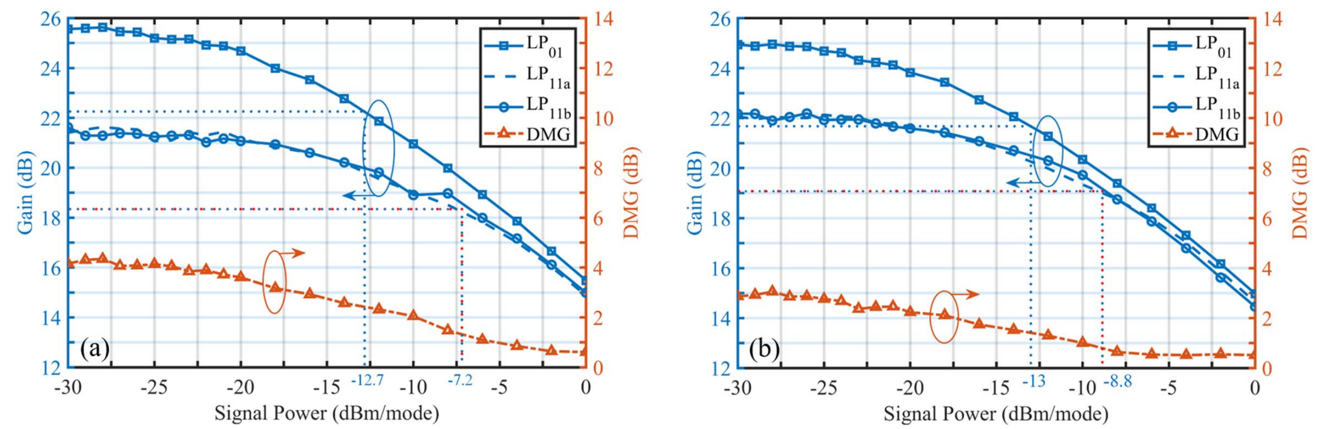

Fig. 7. Dynamic gain of the three guided modes as a function of the input signal power when the pump modes are (a) LP_{01} and (b) LP_{11}, respectively, with the fixed pump power of 210 mW.

Table 3. Saturation Input Power for Each Signal Mode with Different Pump Schemes in Experiment.

	Saturation Input Power (dBm)	
	LP_{01} Signal Mode	$LP_{11a/b}$ Signal Mode
Under LP_{01} mode pumping	−12.7	−7.2
Under LP_{11} mode pumping	−13.0	−8.8

the all-fiber FM-EDFA is experimentally verified when the intensity profile of pump laser is manipulated.

4. Conclusions

We have examined the dynamic gain of an all-fiber FM-EDFA in terms of the DMG and the input saturation power when the intensity profile of the pump laser is manipulated. During the numerical simulation, we found that not only the mode-dependent difference of the saturated input power occurs for all guided modes but also the implementation of higher-order pumping. The ease of DMG mitigation results in a reduction of the saturation input power for each guided mode. In the experiment, the gain of the all-fiber FM-EDFA at 1550 nm is more than 20 dB and the DMG can be reduced to be 0.97 dB. In particular, both an average gain of 19.93 dB and a DMG of less than 1 dB can be achieved from 1530 nm to 1560 nm. However, the saturation input powers of the LP_{01} and the LP_{11} modes are −12.7 dBm and −7.2 dBm, respectively, when the pump laser is operated at the fundamental mode. The corresponding saturation input powers drop to −13.0 dBm and −8.8 dBm, respectively, under the LP_{11} pumping scheme. Furthermore, the saturation input power of the LP_{11} mode is 5.5 dB and 4.2 dB higher than that of the LP_{01} mode, respectively, under the fixed pumping scheme. The manipulation of the pump intensity profile results in the reduced saturation input powers by 0.3 dB and 1.6 dB, respectively. There occurs a mode-dependent dynamic gain and a trade-off between the DMG mitigation and the extension of the linear amplification range under the high-order pumping scheme.

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