Weakly-Coupled Few-Mode Gain-Flattening Filter Using Long-Period Fiber Grating in Double-Cladding FMF

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Abstract: A weakly-coupled few-mode gain-flattening filter (FM-GFF) based on long-period fiber gratings (LPFGs) in double-cladding few-mode fiber is proposed. Utilizing the FM-GFF, we demonstrate that the gain spectra of each core mode can be independently flattened.

OCIS codes: (060.2330) Fiber optics communications; (230.2285) Fiber devices and optical amplifiers

1. Introduction

Mode-division multiplexing (MDM) [1] has been proposed and widely investigated as an alternative technique for capacity enhancement. Recently, weakly-coupled MDM has received much attention [2], in which the signal in each guided mode can be independently received without complex multiple-input-multiple-output (MIMO) processing. Weakly-coupled MDM transmission over more than 100-km few-mode fiber (FMF) has been experimentally demonstrated [2], which indicates that weakly-coupled MDM can be utilized not only in short-reach applications, but also possibly extended in metro area networks (MAN) for several hundred kilometers transmission. Thus, few-mode Erbium doped fiber amplifier (FM-EDFA) is a key component which can simultaneously amplify all modal channels [3]. In our previous work, we have firstly experimentally demonstrated weakly-coupled MDM-WDM amplification and transmission employing intensity modulation and simple direct detection (IM-DD) [4]. However, we find that the gain of guided modes varies with the operating wavelength and the mode pattern, which is unfriendly in MDM-DWDM transmissions and switching scenarios. Therefore, for furtherly enlarging applications of FM-EDFA, a few-mode gain-flattening filter (FM-GFF) that can independently flatten the output power of each guided mode in C-band is necessary.

Recently, the FM-GFF based on spatial light modulator (SLM) has been proposed [5]. However, such a scheme is for strongly-coupled MDM and will introduce high extra insertion loss. In single-mode erbium-doped fiber amplifier (SM-EDFA), long-period fiber gratings (LPFGs) are particularly attractive as single-mode gain-flattening filter (SM-GFF) for its many advantages, such as compact size and low insertion loss. SM-GFF based on LPFGs usually can couple the core mode to the forward propagating cladding modes, inducing resonant dips in the transmission spectra, and the gain spectra can be flattened through cascading multiple LPFGs with different resonant dips. For a FM-EDFA, the influence factors of gain spectra are more complex than that in SM-EDFA. However, as far as we know, FM-GFF based on LPFGs has not been studied until now.

In this paper, a novel structure for FM-GFF based on LPFGs in double-cladding FMF (DC-FMF) is proposed. The DC-FMF is specially designed to control the number and effective refractive index of inner-cladding modes. Therefore, each core mode can couple its power to a corresponding inner-cladding mode utilizing a LPFG without affecting other core modes in C-band. The output power of all core modes can be independently flattened by cascading the LPFGs. To demonstrate the feasibility of our method, a 4-mode weakly-coupled FM-GFF is designed and the output power of all modes can be easily flattened to 0.47 dB in C-band.

2. Principle of the proposed FM-GFF

The proposed structure of DC-FMF is shown in Fig 1(a). For the DC-FMF, the number and effective refractive index of inner-cladding modes can be controlled through designing the radius and effective refractive index of inner-cladding, which can ensure that only one core mode LP_{lm}^{core} is coupled to one inner-cladding mode $LP_{l'm'}^{clad}$ in C-band every time. This is the key point to realize the power spectra of each core mode can be independently adjusted. For LP_{lm}^{core} and $LP_{l'm'}^{clad}$, l and l' are the azimuthal order, and m and m' are the radial order, respectively. Because we utilize simple structure of LPFGs for mode coupling, the mode LP_{lm}^{core} can be coupled to mode $LP_{l'm'}^{clad}$ only when $l=l'$.

For LPFGs, mode coupling is caused by irregularities of refractive index (RI) profile within the fiber, as is shown in Fig. 1(b). The fiber consists of segments of constant RI distributions, in each of which the modes can be calculated using standard mode solvers or iterative method. These can be distributed along the fiber or be locally confined yielding single or multiple coupling events. We can theoretically describe mode coupling by thinking of the RI distribution as sliced in constant pieces, each having a different transverse profile and consequently a separate mode set. The coupling comes from the non-zero overlap integral of modes from the one and the other basis at the point of the index interface, whereas within the constant RI slice the respective modes are orthogonal and merely have relative phase shifts. Utilizing this theory, we can design the transmittance of each mode to flatten the FM-EDFA, as shown in Fig. 1(c). The all-fiber structure of FM-EDFA is our firstly proposed for weakly-coupled MDM amplification, which is characterized by weakly-coupled EDF, cascaded mode-selective couplers (MSCs) for pump light injection and weakly-coupled few-mode wavelength multiplexer (FM-WMUX) for pump/signal coupling.

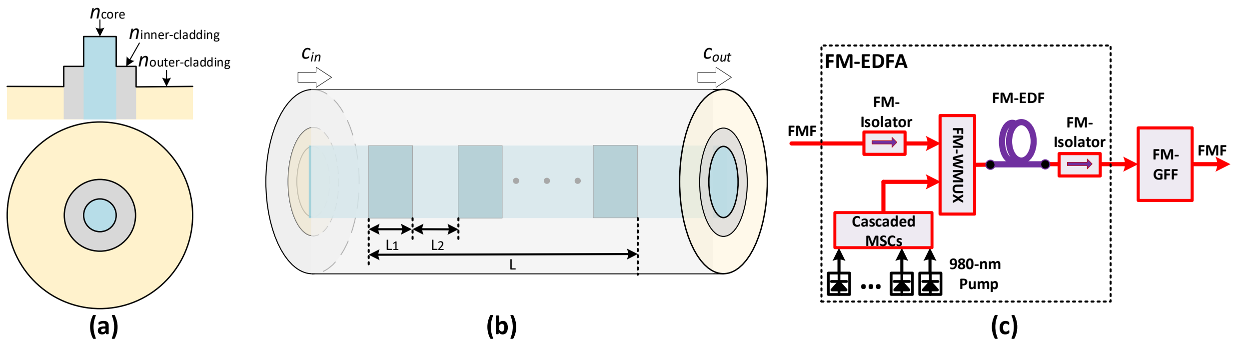

Fig. 1. (a) The proposed design of weakly-coupled DC-FMF, (b) The schematic diagram of LPFG in DC-FMF, (c) The schematic diagram of using FM-GFF to flatten the gain spectra of FM-EDFA. C_{in}: Input signal, C_{out}: Input signal, L_1 and L_2: Length of one period, L: Total length.

3. Simulation Results

In order to demonstrate the feasibility of the proposed method, a 4-mode weakly-coupled FM-GFF is designed and demonstrated. The radii of the core, inner-cladding, and outer-cladding for 4-mode DC-FMF are 6.8-µm, 12.5-µm, and 62.5-µm, respectively. While the effective refractive indices of these layers are 1.45952, 1.44782, and 1.44402, respectively. The FMF supports four core modes (LP_{01}, LP_{11}, LP_{21}, and LP_{02}) and four inner-cladding modes (LP_{31}, LP_{12}, LP_{03}, and LP_{22}). The minimum mode effective refractive index difference (Δneff) among all core modes is 1.03×10^{-3}, which can minimize modal crosstalk between adjacent modes according to coupled-mode theory. The change of effective refractive index in core for LPFG is 0.0383×10^{-3}. Simulation parameters are shown in Table 2.

Firstly, we evaluate the characters of transmittance spectra of single FM-LPFG in mode dimension. Fig. 2(a)~(d) shows the transmittance of all core modes in C-band with a fixed resonant wavelength of 1550-nm versus different resonant modes of LP_{01}, LP_{11}, LP_{21}, and LP_{02}, respectively. N is the number of periods of the FM-LPFG. From the results, we can see that only the resonant mode has a large insertion loss while other core modes can hardly be affected when the resonant wavelength is confirmed. Besides, we also simulate the transmittance of all core modes in C-band versus different resonant wavelengths. Figure 3(a) shows the result when resonant mode is LP_{11} mode and N is 48. We can see, for different resonant wavelength, only LP_{11} mode has a large insertion loss while other core modes can hardly be affected. In order to demonstrate that arbitrary insertion losses of resonant modes at the resonant wavelength can be realized, we simulate the transmittance of all core modes versus N, as shown in Fig. 3(b). From the result, we can see the insertion loss of resonant mode LP_{11} get larger with the increasing of N. It should be noted that the similar results have also been got when resonant modes are LP_{01}, LP_{21}, and LP_{02} modes, respectively. From the above results, we can see the transmittance spectra of each core mode can be independently designed while other core modes are hardly affected utilizing the proposed FM-LPFG. This is a great advantage because we can easily design FM-GFF where each mode can be independently flattened like that done in SM-EDFA.

Then, in order to evaluate the feasibility of flattening all modes power in C-band, we successfully flatten gain spectra of four modes using cascaded FM-LPFGs as FM-GFF. The gain spectra before and after the FM-GFF are shown in Fig. 4 (a) and (b), respectively. From the results, we can see the spectra of each core mode can be flatten to within 0.47-dB in C-band and the power loss is about 2.4-dB at the lowest point of gain spectra. Fig. 5 gives the structure of the designed FM-GFF using cascaded LPFGs. The power of inner-cladding modes coming from core modes coupling in each LPFG can be quickly eliminated by slicing a segment 4-mode single-cladding FMF to void generating interference in next LPFG.

Table 2 Simulation parameters

Core Mode	Mode Coupling	L_1 (mm)				L_2 (mm)			
		1530 nm	1540 nm	1550 nm	1560 nm	1530 nm	1540 nm	1550 nm	1560 nm
LP01	LP01→LP03	0.061236	0.061544	0.061851	0.062158	0.059655	0.059960	0.060264	0.060568
LP11	LP11→LP12	0.272367	0.273634	0.274955	0.276328	0.265383	0.266491	0.267655	0.268875
LP21	LP21→LP22	0.347425	0.351925	0.356504	0.361157	0.332845	0.337107	0.3414461	0.345857
LP02	LP02→LP03	0.741477	0.753068	0.764832	0.776754	0.706433	0.717489	0.728721	0.740117

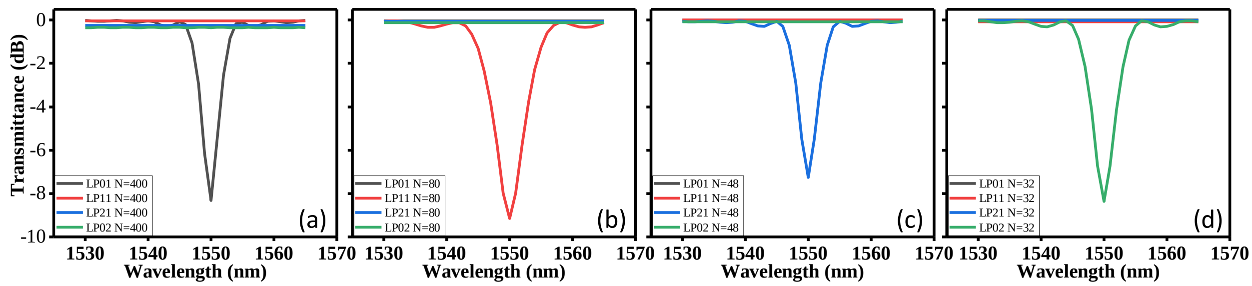

Fig. 2 The transmittance of the FM-LPFG versus different resonant modes: (a) LP_{01}; (b) LP_{11}; (c) LP_{21}; (d) LP_{02} at a fixed resonant wavelength of 1550-nm.

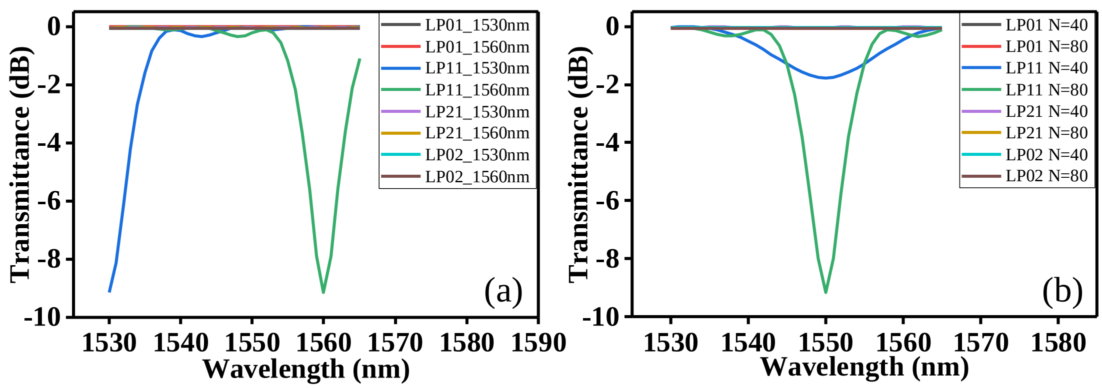

Fig. 3 The transmittance of the FM-LPFG versus: (a) different resonant wavelengths at N=48; (b) different N at a fixed wavelength of 1550-nm when the resonant mode is LP_{11} mode.

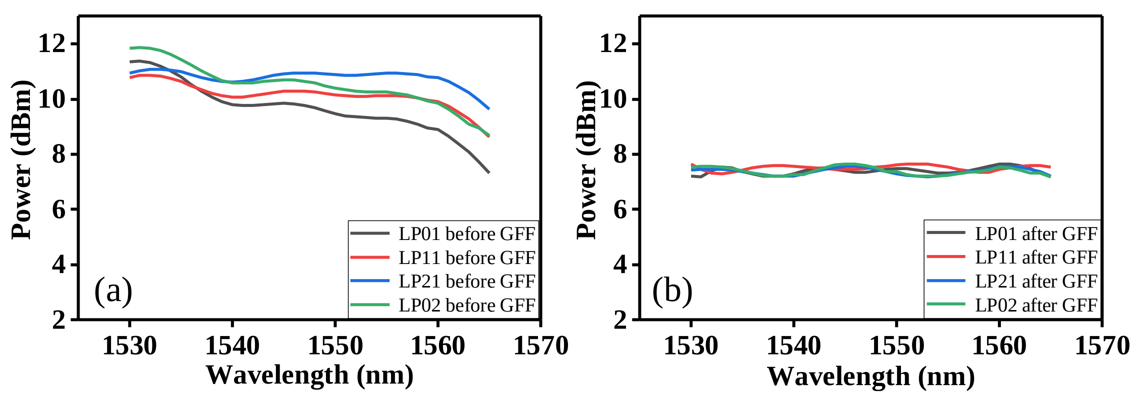

Fig. 4 The gain spectra of 4-mode (a) before and (b) after designed FM-GFF.

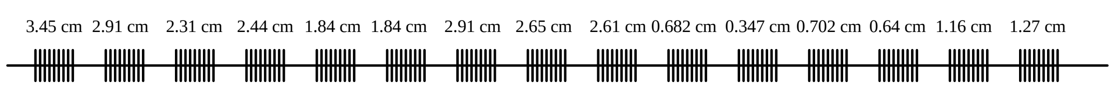

Fig. 5 The designed FM-GFF using cascaded LPFGs.

4. Conclusions

In this paper, a novel structure to realize FM-GFF based on LPFGs in DC-FMF is proposed. The DC-FMF is specially designed, where each core mode can be coupled to a particular inner-cladding mode using a LPFG while other core modes can hardly be affected. Utilizing this method, we evaluate a 4-mode weakly-coupled FM-GFF. Thanks to the advantages that transmittance spectra of each core mode can be independently designed, we easily flatten the output power of a 4-mode EDFA to 0.47 dB in C-band. *This work was supported by the NSFC (61771024, 61627814, 61505002, 61690194 and 61605004), Shenzhen Science and Technology Plan (JCYJ 20170412153729436, 20180227175348359, 20170817113844300), and Projects Foundation of YOFC (SKLD1708)*.

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