Switchable dual-mode all-fiber laser with few-mode fiber Bragg grating

Wenxing Jin\textsuperscript{1,2}, Yanhui Qi\textsuperscript{1,2}, Yuguang Yang\textsuperscript{1,2}, Youchao Jiang\textsuperscript{1,2}, Yue Wu\textsuperscript{1,2}, Yao Xu\textsuperscript{1,2}, Shuzhi Yao\textsuperscript{1,2} and Shuisheng Jian\textsuperscript{1,2}

\textsuperscript{1} Key Lab of All Optical Network & Advanced Telecommunication Network of EMC, Beijing Jiaotong University, Beijing 100044, People’s Republic of China
\textsuperscript{2} Institute of Lightwave Technology, Beijing Jiaotong University, Beijing 100044, People’s Republic of China

E-mail: 13111011@bjtu.edu.cn

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Abstract

We propose a new approach to realize switchable mode operation in a few-mode erbium-doped fiber laser. The ring fiber laser structure is constructed with a core-offset splicing between single-mode fiber and dual-mode fiber. Stable operating on the fundamental mode laser and second-order mode laser individually or simultaneously is realized by appropriately adjusting the state of the polarization controller and bending status of the few-mode fiber Bragg grating. The narrow 3 dB linewidth less than 0.02 nm and high optical signal to noise ratio more than 42 dB are obtained for both modes in either separate laser or simultaneous laser operating conditions.

Keywords: dual-mode, switchable laser, few-mode fiber, fiber Bragg grating

(Some figures may appear in colour only in the online journal)

1. Introduction

The fundamental capacity limit of the single-mode optical fiber transmission network is approaching, due to the exponential increasing data demand driven by the Internet [1, 2]. It is not enough to fulfill the current transmission data demand except for using wavelength division multiplexing (WDM), time division multiplexing (TDM) and polarization division multiplexing (PDM) [3]. Recently great attention has been paid to spatial division multiplexing (SDM) because of its potential to dramatically increase the capacity of a single-mode fiber (SMF) as another dimension freedom [4, 5]. SDM transmission could be achieved by employing either a multicore fiber (MCF) or a few-mode fiber (FMF) [6–8].

FMF, as one means to realize SDM, has already received considerable attention [9]. Good performance of high transmission efficiency has been reported in the experiment, which enhances the possibility of practically trying to overcome current capacity bottleneck [10–12]. Except for transmission exploration on SDM, FMF has also find its application in higher-order mode fiber laser fields with the combination of fiber Bragg gratings (FBG). Daniel et al used a FBG and a volume Bragg grating to achieve mode selection in a multimode fiber laser [13], and electronically controllable transverse mode selection was also realised through acousto-optic tunable-filters and FBG [14]. It is inevitable to increase the operating system complexity by introducing the volume Bragg grating and acousto-optic tunable-filters. At the same time, multiwavelength fiber lasers based on FMF-FBG were demonstrated [15–18]. However, these methods producing multiwavelength lasers did not figure out the corresponding transverse modes of each peak wavelength. Selective transverse mode fiber lasers of second-order mode with FMF-FBG were also obtained employing ytterbium optical fiber [19–21]. In addition, mode-locked all-fiber lasers operating on a second-order mode were available with the assistance of FMF-FBG [22–24], which made a valuable contribution to construction of higher-order mode fiber lasers.

In this letter, we present a new approach to realize switchable mode operation in a few-mode erbium-doped fiber (EDF) laser. Separate or simultaneous laser operation on LP\textsubscript{01}
mode and LP\textsubscript{11} mode can be achieved by utilizing the ring fiber structure and carefully bending FMF-FBG. The lateral offset splicing between SMF and FMF is applied to make effective coupling from the fundamental mode to second-order mode. The narrow 3 dB linewidth less than 0.02 nm and high optical signal to noise ratio (OSNR) more than 42 dB are obtained for both modes in either separate laser or simultaneous laser operating conditions. Meanwhile, the stable laser emission for both the single mode condition and dual-mode condition is confirmed in the experiment. The proposed switchable dual-mode all-fiber laser has the advantages of simple configuration, easy control and stable operation.

2. Few-mode fiber Bragg grating property

The few-mode fiber perform is manufactured by the modified chemical vapor deposition (MCVD) method, then the fiber perform is drawn to a desirable fiber cladding diameter in order to support the few core-guided modes, including LP\textsubscript{01} mode and LP\textsubscript{11} mode here. The measured refractive index (RI) profile of the designed dual-mode fiber is shown in figure 1. The inset in figure 1 displays the microscope photograph of the home-made dual-mode fiber. The maximum index difference of the designed fiber is about 1.00%, and the outer diameter is about 115 \( \mu \text{m} \).

The mode supported by the fiber can be calculated using a full-vector finite element method (Comsol Multiphysics) based on the RI profile of the designed fiber. The effective RI of the supporting modes with respect to the wavelength is illustrated in figure 2. Only two degenerate mode groups, including LP\textsubscript{01} mode and LP\textsubscript{11} mode, can be supported with a wavelength ranging from 1530 nm to 1565 nm. So, we also call the fiber ‘dual-mode fiber’ (DMF).

The FMF-FBG was fabricated by ultraviolet illumination through a phase mask. The period of the phase mask is 1068 nm, and the length of FMF-FBG is about 3 cm. The reflection spectrum of the FMF-FBG was measured using an ASE light source and an optical spectral analyzer (OSA) with 0.01 nm resolution. To ensure efficient excitation of the second order mode (LP\textsubscript{11}), the core-offset splicing between SMF and DMF is adopted \[25\]. For FMF-FBG, the Bragg wavelengths are determined by the grating function \( \beta_1 - \beta_2 = 2\pi/\Lambda \), where \( \beta_1 \) and \( \beta_2 \) are the propagation constants of forward and backward propagating modes, and \( \Lambda \) represents the FMF grating period \[26, 27\]. In the FMF-FBG, reflection occurs not only between the same order mode, but also between the neighboring modes \[28, 29\]. Figure 3 shows the measured reflection spectrum of the fabricated FMF-FBG. As depicted in figure 3, there are not only a LP\textsubscript{01} reflection peak (1546.5 nm) and a LP\textsubscript{11} reflection peak (1543.6 nm), but also a mode-conversion peak (1545.1 nm) arising from the intermodal coupling between the LP\textsubscript{01} peak and LP\textsubscript{11} peak. The lateral offset splicing remaining immovable is employed.

Figure 1. The refractive index profile of the designed FMF. The inset shows the microscope photograph of the FMF.

Figure 2. Effective RI of core-guided modes with respect to different wavelength of FMF.

Figure 3. Reflection spectra of the FMF-FBG used in the experiment. The peaks corresponding to the LP\textsubscript{01} and LP\textsubscript{11} modes are indicated by the arrows.
through bending the FMF-FBG to achieve the desired mode operation during the experiment.

3. Experiment and result

The experimental schematic of the proposed switchable dual-mode fiber laser based on few-mode fiber Bragg grating is presented in figure 4. It consists of a 980 nm semiconductor laser, a 980/1550 nm wavelength division multiplexing (WDM), one section of EDF about 2 m length, an optical isolator (ISO), a 90/10 optical coupler with 10% power coupled out at the output, a polarization controller (PC) and an optical circulator. The circulator is connected between the PC and WDM to form the ring laser structure. There is also a lateral offset splicing spot (OSS) between the circulator and the DMF Bragg grating, as shown in figure 4. The OSS here could assist the efficient coupling from the LP01 mode to the LP11 mode. The 980 nm semiconductor laser is used as the pump, and WDM used for leading the pump power into the laser cavity and the signal power circulating in the cavity. The EDF here serves as the gain medium. The ISO is operating at 1550 nm in order to keep the ring laser unidirectional operation. The 90/10 optical coupler is employed to couple out 10% signal power into the optical spectrum analyzer (OSA) in order to monitor the status of output laser. The PC is used to control the polarization state in the fiber laser cavity and the coupling efficiency between the two modes. The circulator is able to ensure the unidirectional propagation of the laser cavity.

The whole experiment process is operating at the vibration isolation platform. The pump power is fixed at 200 mW throughout the whole experiment. It is found that the mode status is deeply affected by the bending status of the FMF-FBG, while changing the states of PC has less effect on the laser operation on the different mode. So the state of PC remains unchanged when the output laser realizes the desired mode operation on output laser. The laser output spectrum is monitored with an OSA (Ando AQ6317C) with the resolution of 0.01 nm. The maximum intensity and its wavelength could be got through the screen of OSA in real time. The laser can operate in the LP11 mode and the LP01 mode separately or simultaneously by bending the FMF-FBG carefully at room temperature.

The stable LP11 mode fiber laser is achieved in the experiment by cautiously adjusting the PC and carefully bending the FMF-FBG. Figure 5(a) shows the single-wavelength laser emission of the LP11 mode based on the ring fiber laser structure and bending the FMF-FBG condition. The operating wavelength is around 1542.964 nm, and 3 dB spectral linewidth is about 0.02 nm. As can be seen in figure 5(a), there is a small power peak around 1545.9 nm representing the depressed LP01 mode. The OSNR is over 42 dB. Figure 5(b) shows the results of the repeated output maximum power I and peak wavelength $\lambda_p$ fluctuations’ measurements of LP11 mode laser operation. A total number of 12 measurements were made at 90 second intervals. The peak wavelength fluctuation of the LP11 mode is less than 0.01 nm, and the maximum intensity fluctuation is less than 1 dB in the experiment. The results indicate stable laser operation on LP11 mode at room temperature of the proposed fiber laser structure.

When changing the bending condition of the FMF-FBG appropriately, the single LP01 mode fiber laser is achieved, as depicted in figure 6. Figure 6(a) illustrates the laser output spectrum of the LP01 mode and figure 6(b) shows the peak wavelength fluctuation and the maximum intensity fluctuation of the single mode. The depressed LP11 mode around 1542.9 nm could be still seen in figure 6(a). The operating wavelength of LP01 mode is around 1545.936 nm with a less than 0.02 nm 3 dB linewidth and more than 46 dB OSNR. The stable LP01 mode laser operation is ensured by the fluctuations of $\lambda_p$ less than 0.01 nm and that of I lower than 1 dB, as shown in figure 6(b).

The dual-mode laser operation could be realized simultaneously through adjusting the bending status of FMF-FBG carefully while keeping PC state unchanged. The laser spectrum of the LP11 mode and the LP01 mode is presented in figure 7(a). Both modes achieve a narrow 3 dB linewidth about 0.02 nm, and a high OSNR, more than 44 dB. The operation wavelengths of the LP11 mode and the LP01 mode are around 1542.958 nm and 1545.904 nm, separately. Both modes' wavelengths differ a little from the previous experiments, which only operate on one mode. It is noticed that the peak wavelengths of both modes have the same change tendency, which, when induced by bending stress, is inevitable. The temporal stabilities of both modes operation are shown in figures 7(b) and 7(c), separately. The peak wavelength fluctuations of both modes are less than 0.01 nm. In addition, the maximum intensity fluctuation of the LP11 mode is less than 1 dB, and that of the LP01 mode is less than 1.2 dB in the experiment. These results demonstrate the stable simultaneous laser operation of the LP11 mode and the LP01 mode.

The stable operating on the fundamental mode laser and second-order mode laser individually or simultaneously is realized in the experiment. The whole experimental setup is

![Figure 4](image-url)
Figure 5. Single emission of LP_{11} mode. (a) Optical spectra of LP_{11} mode of the proposed fiber laser. (b) The stability of LP_{11} mode.

Figure 6. Single emission of LP_{01} mode. (a) Optical spectra of LP_{01} mode of the proposed fiber laser. (b) The stability of LP_{01} mode.

Figure 7. Simultaneous emission of the LP_{01} mode and the LP_{11} mode. (a) Optical spectra of the LP_{01} mode and the LP_{11} mode of the proposed fiber laser. (b) The stability of the LP_{01} mode and the LP_{11} mode.
operated on the vibration isolation platform to avoid any environmental influence. Different from simply changing the state of the PC to get various coupling efficiencies from the fundamental mode to high-order mode, so as to control the production of high-order mode as previous works indicated [16, 19, 25], we change the Bragg gratings resonance condition of each mode by bending the FMF-FBG in the experiment. As stated in section 2, the forward propagating and backward propagating modes of the same order or neighboring order could produce self-coupling and cross-coupling when fitting the Bragg resonance condition. The backward propagating mode of the fundamental mode or second-order mode caused by FMF-FBG reflection scatters out even vanishes when bending the FMF-FBG. Additionally, different bending statuses of FMF-FBG could cause different reflection mode operations. That is to say, various coupling conditions are affected by the bending status of FMF-FBG, leading to different mode lasing operations. In addition, FMF-FBG has a strong polarization dependence because of the damage cracks formed on one side of the core, during the process of grating fabrication [18, 30]. Changing the bending status of FMF-FBG could get the different polarization state resonance mode at Bragg wavelength. At the same time, the PC is employed to control the polarization state and allow continuous adjustment of birefringence within the cavity to balance gain and loss in the fiber laser cavity [31], which helps to overcome the homogeneous gain broadening in EDF. It is worth noting that in the experiment the state of PC keeps unchanged when bending the FMF-FBG. After getting the desired mode lasing operation, the PC is used to get the maximum intensity value.

4. Conclusion

In this paper, we proposed a switchable dual-mode all-fiber laser based on few-mode fiber Bragg grating. The stable laser operation of the LP_{11} mode and the LP_{01} mode could be realized separately or simultaneously by properly adjusting the state of PC and bending condition of FMF-FBG at room temperature during the experiment. The narrow 3 dB linewidth of laser output for both modes is less than 0.02 nm. The high OSNR, more than 42 dB, is available either in single mode operation or in dual-mode operation. The proposed all-fiber laser structure has the advantages of simple configuration, easy control and stable operation.

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References

[1] Essiambre R J, Kramer G, Winzer P J, Foschini G J and Goebel B 2010 IEEE J. Lightwave Technol. 28 662
[2] Essiambre R J and Tkach R W 2012 Proc. IEEE 100 1035
[3] Winzer P J 2014 Nat. Photon 8 345
[4] Richardson D J, Fini J M and Nelson L E 2013 Nat. Photon 7 354
[5] Li G, Bai N, Zhao N and Xia C 2014 Adv. Opt. Photon. 6 413
[6] Saitoh K and Matsuo S 2013 J. Nanophotonics 2 441
[7] Benyuan Z, Fini J M, Yan M F, Xiang L, Chandrasekhar S, Taunay T F, Fishelyen M, Monberg E M and DiMarcello F V 2012 IEEE J. Lightwave Technol. 30 486
[8] Sakaguchi J et al 2016 IEEE J. Lightwave Technol. 34 93
[9] Essiambre R J, Ryf R, Fontaine N K and Randel S 2013 IEEE Photon. J. 5 0701307
[10] Ryf R et al 2012 IEEE J. Lightwave Technol. 30 521
[11] van Uden R G H, Correa R A, Lopez E A, Huijskens F M, Xia C, Li G, Schltzen A, de Wardt H, Koonen A M J and Okonkwo C M 2014 Nat. Photon 8 865
[12] Mizuno T, Takara H, Sano A and Miyamoto Y 2016 IEEE J. Lightwave Technol. 34 582
[13] Daniel J M O, Chan J S P, Kim J W, Sahu J K, Ibsen M and Clarkson W A 2011 Opt. Express 19 12434
[14] Daniel J M O and Clarkson W A 2013 Opt. Express 21 29442
[15] Han Y-G, Lee S B, Moon D S and Chung Y 2005 Opt. Lett. 30 2200
[16] Moon D S, Paek U-C and Chung Y 2004 Opt. Express 12 6147
[17] Lei S, Chao L, Jianzhong H, Zhihong L and Yixin W 2005 IEEE Photon. Technol. Lett. 17 315
[18] Xinhuang F, Yang L, Shengguif F, Shuzhong Y and Xiaoyi D 2004 Photon. Technol. Lett. 16 762
[19] Sun B, Wang A, Xu L, Gu C, Lin Z, Ming H and Zhan Q 2012 Opt. Lett. 37 464
[20] Sun B, Wang A, Xu L, Gu C, Zhou Y, Lin Z, Ming H and Zhan Q 2013 Opt. Lett. 38 667
[21] Liu T, Chen S-P and Hou J 2016 Opt. Lett. 41 5692
[22] Dong J and Chiang K S 2014 IEEE Photon. Technol. Lett. 26 1766
[23] Sun B, Wang A, Gu C, Chen G, Xu L, Chun D and Zhan Q 2015 Opt. Lett. 40 1691
[24] Zhou Y, Wang A, Gu C, Sun B, Xu L, Li F, Chun D and Zhan Q 2016 Opt. Lett. 41 548
[25] Grosjean T, Courjon D and Spajer M 2002 Opt. Commun. 203 1
[26] Mizunami T, Djambova T V, Niibio T and Gupta S 2000 IEEE J. Lightwave Technol. 18 230
[27] Changgui L and Yiping C 2006 IEEE J. Lightwave Technol. 24 598
[28] Huang T, Fu S, Ke C, Shumi P and Liu D 2014 IEEE Photon. Technol. Lett. 26 1908
[29] Ali M M, Jung Y, Lim K-S, Islam M R, Shaif-Ul A, Richardson D J and Ahmad H 2015 IEEE Photon. Technol. Lett. 27 1713
[30] Moon D S, Paek U-C and Chung Y 2005 Opt. Express 13 5614
[31] Qi Y, Sun J, Kang Z, Ma L, Jin W and Jian S 2016 Opt. Fiber Technol. 29 70