Single-Polarization, Single-Longitudinal-Mode Erbium-Doped Fiber Laser Based on Twisting of Polarization-Maintaining Fiber Bragg Gratings

Feng Suchun Peng Jian Peng Wanjing Fan Yiyi Xie Qian Ren Wenhua

Institute of Lightwave Technology, Key Laboratory of All Optical Network and Advanced Telecommunication of Education Ministry of China, Beijing Jiaotong University, Beijing 100044, *China*

Abstract Single-polarization, single-longitudinal-mode (SLM) erbium-doped fiber laser based on the twisting of polarization-maintaining fiber Bragg gratings (PMFBGs) is proposed and demonstrated. Two uniform FBGs directly written in a homemade polarization-maintaining and photosensitive erbium-doped fiber (PMPEDF) without hydrogen loading by using ultraviolet light from a 248 nm KrF excimer laser as the wavelength-selective component are used in a linear cavity. Owing to the polarization-dependent loss enhanced by the PMFBGs, stable SLM and stable single-polarization operation of the fiber laser are achieved by controlling the birefringence through appropriately twisting the fiber laser cavity.

Key words lasers; single polarization; single longitudinal mode; fiber laser; polarization-maintaining fiber Bragg gratings

OCIS codes 060.2320; 060.2410; 060.2420; 060.3510; 060.3738

基于扭绞保偏光纤光栅的单纵模单偏振掺铒光纤激光器

冯素春 彭 健 彭万敬 范依依 谢 倩 任文华

北京交通大学光波技术研究所, 全光网络与现代通信网教育部重点实验室, 北京 100044

摘要 提出并实现了一种基于扭绞保偏光纤光栅的单纵模单偏振掺铒光纤激光器。光纤激光器的线型激光谐振腔由两个均匀保偏光纤光栅构成并作为激射波长和纵模模式选择器件,均匀保偏光纤光栅采用248 nm KrF准分子激光直接刻写在不需要氢载的自制保偏光敏掺铒光纤上。利用保偏光纤光栅引起的偏振依赖损耗效应,通过对光纤激光器谐振腔进行适当扭绞,成功实现了稳定输出的单纵模单偏振掺铒光纤激光器。

关键词 激光器; 掺铒光纤激光器; 单纵模; 单偏振; 保偏光纤光栅

中图分类号 TN248.1 **文献标识码** A

doi: 10.3788/CJL201643.0102002

1 Introduction

Single-longitudinal-mode (SLM) erbium-doped fiber (EDF) lasers are key devices for many applications, including distributed long-distance optical-fiber sensor systems, coherent optical communication, and coherent signal generation, owing to their various advantages, such as reduced production costs and perfect integration with fiber-optics-based systems[1-3]. Among the SLM technologies in fiber lasers, the short-linear-cavity structure is the simplest, and it makes the laser compact. Fiber Bragg gratings (FBGs) are good candidates for lasing-mode discrimination owing to their advantages such as low insertion loss, ease of use and fabrication, low cost, passiveness, and wavelength selectivity. In

收稿日期: 2015-05-10; **收到修改稿日期**: 2015-07-20

基金项目: 国家973计划(2010CB328206),国家自然科学基金(61107094),中央高校基本科研业务费(2013JBM017),北京交通大学青年英才计划

作者简介: 冯素春(1982—),男,博士,副教授,主要从事光纤通信、光纤激光器方面的研究。E-mail: fengsuchun@gmail.com

*通信联系人。E-mail: fengsuchun@gmail.com

conventional linear-type fiber lasers that utilize FBG reflectors to realize cavity feedback and wavelength selectivity, the laser cavity needs to be short, a few centimeters at most, such that the laser mode spacing is comparable with the grating bandwidth and SLM operation can be ensured. Both distributed Bragg reflectors (DBR) and distributed feedback (DFB) fiber lasers based on the FBG have been successfully realized in erbium-doped silica-based fiber, Er/Yb co-doped silica-based fiber, and Er/Yb co-doped phosphate glass fiber. The specially designed FBGs are always written on these fibers using 193, 244, or 248 nm ultraviolet light or 800 nm femtosecond laser pulses through the phase-mask method[4-10] or point-by-point technique[11]. Directly writing FBGs in the active fiber can provide a much lower threshold because it avoids intercavity splice loss and simplifies the fabrication process of the fiber laser. Note that the active fiber with FBG directly written using 244 nm or 248 nm ultraviolet light needs to be highly photosensitive (highly germanium-doped, hydrogen-loaded, or deuteron-loaded, but the hydrogen-loading process will lead to the excited-state lifetime reduction of Er^{3+} ions). In conventional ring-type fiber lasers, tens of meters of fibers exist in the laser cavity; hence, there are large numbers of equally spaced longitudinal modes operating in the wavelength passband of the filter of the fiber laser. Therefore, a narrow-bandwidth mode-selecting method is required to ensure SLM operation. Many methods have been proposed to obtain SLM fiber lasers, such as the integration of two cascaded fiber Fabry-Perot filters with different free spectral ranges into the fiber ring [12], incorporation of an equivalent phase-shifted FBG[13] or use of an FBG-based Fabry-Perot etalon[14] acting as an ultra-narrow bandpass filter in the laser cavity, addition of passive multiple rings[15] or multiple cavities[16] to achieve mode suppression, use of one section of a gain fiber as the saturable absorber acting as a very narrow filter[17], use of injection locking for SLM oscillation[18-20], and use of stimulated Rayleigh scattering in a nonuniform optical fiber[21]. Generally, most of these SLM fiber lasers operate in two eigenpolarization modes with slightly different resonant wavelengths owing to the random fiber birefringence. Conversely, power exchanges between the two eigenpolarization modes and laser-mode competition can limit their practical applications, in which case it will be necessary to ensure single-polarization-state operation in the fiber laser. Thus, various techniques are used to achieve the single-polarization operation of the SLM fiber laser, such as the utilization of polarization-dependent losses of the fiber laser[11,22], polarizing fiber[16], injection locking[18-19,23], and polarization-maintaining FBG (PMFBG)[23-24].

We demonstrate a single-polarization SLM EDF laser based on the twisting of the PMFBG. To our knowledge, two uniform FBGs directly written in a homemade polarization-maintaining and photosensitive erbium-doped fiber (PMPEDF) (highly germanium-doped, without hydrogen loading to photosensitize the fiber) by using ultraviolet light from a 248 nm KrF excimer laser as the wavelength-selective component are used in a linear cavity for the first time. Owing to the polarization-dependent loss enhanced by the PMFBG, stable SLM and stable single-polarization operation of the fiber laser are achieved by controlling the birefringence through appropriately twisting the fiber laser cavity.

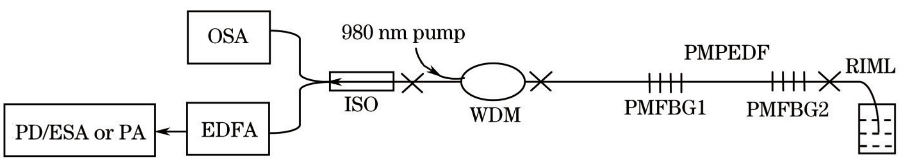

Fig.1 Schematic of proposed fiber laser

2 System configuration and principle

The configuration of the proposed fiber laser is schematically shown in Fig.1. The linear cavity laser consists of a pair of uniform PMFBGs (PMFBG1 and PMFBG2) with an interval of 30 mm that were directly written in a homemade PANDA PMPEDF (highly germanium-doped, without hydrogen loading to photosensitize the fiber, which improves the excited-state lifetime reduction of Er^{3+} ions by the hydrogen-loaded process), a 980/1550-nm wavelength-division multiplexer (WDM), and an optical isolator (ISO). The homemade PMPEDF was fabricated using the modified chemical vapor deposition (MCVD) technique (Optical Fiber Group in the Institute of Lightwave Technology, Beijing Jiaotong University) with an absorption coefficient of 25 dB/m at 1530 nm, and it was co-doped with aluminum ions to reduce the number of erbium ion pairs. The PMPEDF with a whole length of approximately 20 cm was pumped by a 980-nm laser diode through the 980/1550 nm WDM. The fiber end is placed in a refractive-index-matching liquid (RIML), which can prevent unnecessary light reflecting back to the laser cavity. The ISO at the output end is also used to prevent the light reflected from the fiber cut from returning to the laser cavity. The laser output is measured using an optical spectrum analyzer (OSA) (ANDO AQ6317C) with a wavelength resolution of 0.01 nm. The SLM operation of the fiber laser is monitored through an electrical spectrum analyzer (ESA) (Agilent N9010A, 9 kHz~26.5 GHz) connected to a photodetector (PD) (Tektronix CSA803A SD-48 PD Sub-unit, 33 GHz). In order to achieve sufficient optical power for detection by the PD and subsequent measurement by the ESA, the laser output is amplified by an EDF amplifier (EDFA) before it was injected into the PD. The single-polarization operation of the fiber laser is measured using a lightwave polarization analyzer (PA) (Agilent 8509).

Because of the different modal refractive indexes along the fast and slow axes, the PMFBG exhibits two reflection peaks: one for each polarization. The PMPEDF has a beat length of 9.09 mm, which corresponds to a wavelength separation of approximately 0.182 nm in the orthogonally polarized modes of the reflection peak from the PMFBG ($B = \Delta\lambda/2\Lambda$, where B is the beat length of the fiber, $\Delta\lambda$ is the wavelength spacing of the reflection peak, and 2Λ is the phase-mask period). The laser cavity is formed by PMFBG1 and PMFBG2, which were directly written in the PMPEDF with a 13-cm-long uniform phase mask (phase-mask period of 1068 nm) scanned by ultraviolet light from the 248 nm KrF excimer laser. The beam scanning technique was used during the fabrication process, in which the phase mask and fiber were fixed, while the laser beam was scanned along the fiber. The fiber laser is structurally simple and integrative, has low cavity loss, and is easy to be fabricated (no splicing point in the laser cavity; the fiber doesn't need to be hydrogen-loaded to increase the photosensitivity) compared with that previously reported Ref.[24]. PMFBG1 and PMFBG2, with an interval of approximately 30 mm, have the same length of 50 mm and were fabricated under the same fabricating conditions, including the beam intensity, scanning velocity, and phase-mask period. Therefore, the fabrication of the PMFBGs is simple, and the two PMFBGs have almost the same parameters (central wavelength, reflectivity, 3 dB bandwidth). The two reflection-peak wavelengths of the PMFBG were 1543.833 nm and 1544.016 nm, and each of the reflection bands has a 3 dB bandwidth of approximately 0.032 nm and reflectivity of approximately 90% for the corresponding polarizations. The transmission spectrum of the PMFBG1 measured using an amplified spontaneous emission (ASE) source is shown in Fig.2(a), and the overlap transmission spectrum of PMFBG1 and PMFBG2 is shown in Fig.2(b).

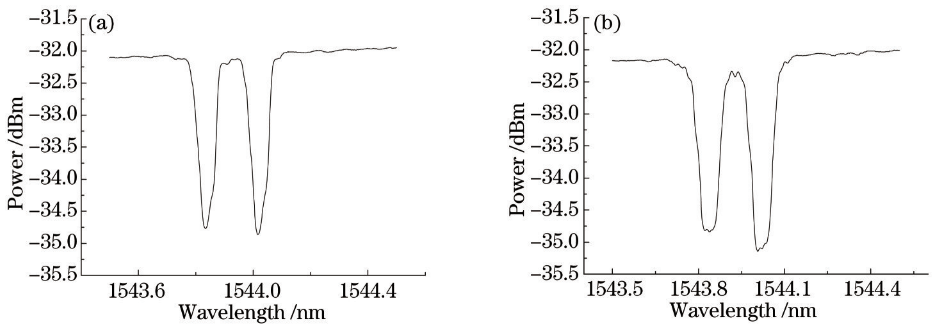

Fig.2 (a) Transmission spectrum of PMFBG and (b) overlap transmission spectrum of PMFBG1 and PMFGB2

According to the effective cavity length theory of the short Fabry-Perot cavity formed by the uniform FBGs [6,25], the longitudinal mode spacing is given by $\Delta\lambda = \lambda^2/2n_{eff}L_{eff}$, where λ is the wavelength of the FBG; n_{eff} is the effective index of the fiber core; and L_{eff} is the effective length of the laser cavity and is given by $L_{eff} = L_0 + L_{eff1} + L_{eff2}$, where L_0 is end-to-end spacing between the two FBGs and L_{eff1} and L_{eff2} are the effective lengths of the two FBGs and are given by $L_{eff} = L_g\sqrt{R}/2\mathrm{atanh}(\sqrt{R})$($L_g$ and R are the length and reflectivity of the FBG, respectively). Thus, the effective cavity length of the proposed fiber laser is calculated as approximately 55 mm. The calculated free spectral range (FSR) of the laser cavity is approximately 1.89 GHz, corresponding to a wavelength region of approximately 0.0151 nm, which is approximately half of the PMFBGs′ 3 dB bandwidth of 0.032 nm. Furthermore, in consideration of the FBG acting as feedback mirrors as well as laser longitudinal mode discriminators, which introduce different losses (by different reflectivity) to different modes, only one laser longitudinal mode can oscillate in the laser cavity; thus, SLM operation can be theoretically ensured. Additionally, SLM operation is verified by observing the electrical beating spectrum measured by the ESA, as described in the following section. Owing to the polarization-dependent loss enhanced by the PMFBG, the laser can be designed to operate in a stable single wavelength with a single polarization state by controlling the birefringence through appropriately twisting the fiber laser cavity.

3 Experimental results and discussion

The entire fiber laser system was placed on a vibration-isolation optical platform, and the experiment was performed at room temperature. When the 980 nm light of 75 mW pump power was coupled into the fiber laser, the laser began to exit stably on appropriately twisting the PMPEDF, which contains the PMFBGs. Fig.3 (a) shows the stable single-wavelength operation of the proposed fiber laser with a pump power of approximately 300 mW (maximum pump power). The output power is approximately 0.37 mW. The lasing wavelength of the fiber laser is 1543.843 nm, which corresponds to the left reflection peak of the PMFBG. The 3 dB bandwidth of the laser spectrum measured using an OSA with 0.01 nm wavelength resolution is 0.012 nm, and the optical signal-to-noise ratio (OSNR) of the laser is greater than 55 dB . Fig.3 (b) shows scans of the fiber laser repeated 16 times with 2 min intervals in nearly half an hour. The power-amplitude variation was measured to be less than 0.5 dB, which indicates that the stability of the fiber laser was very good. The measured slope efficiency of the fiber laser is approximately 0.15%, as shown in Fig.3 (c).

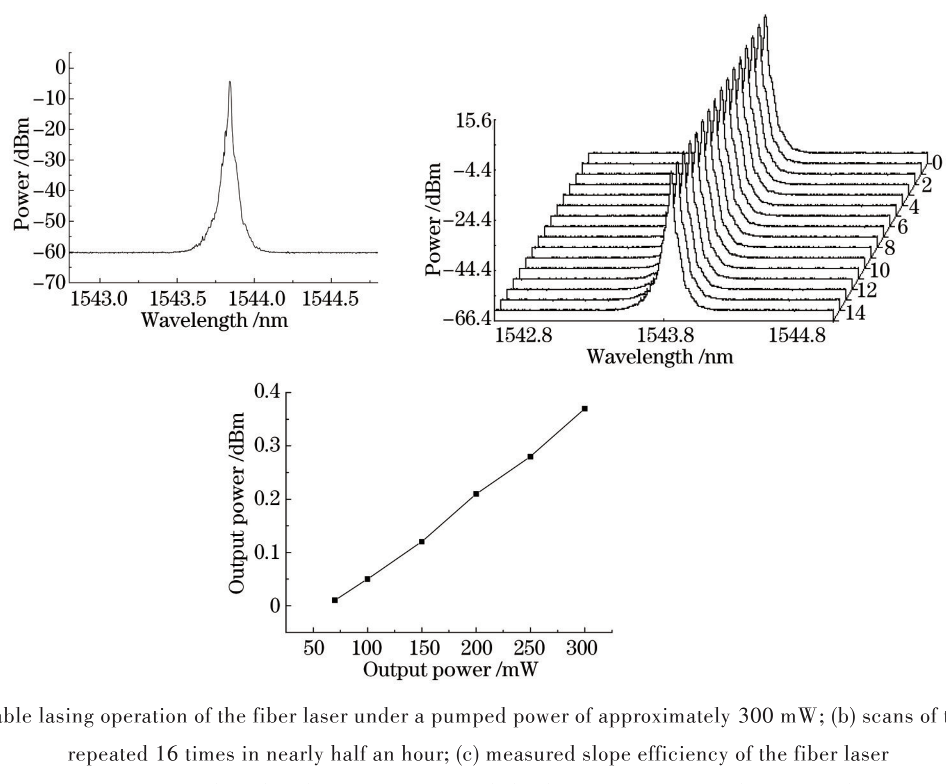

Fig.3 (a) Stable lasing operation of the fiber laser under a pumped power of approximately 300 mW; (b) scans of the fiber laser repeated 16 times in nearly half an hour; (c) measured slope efficiency of the fiber laser

To verify the SLM operation of the fiber laser, we injected the laser output into the PD and monitored the electrical beating spectrum through the ESA. To avoid the output power of the fiber laser being too low to be detected by the PD, the laser output was amplified by the EDFA before it was injected into the PD. When the pump power changes from 100 mW to 300 mW, the fiber laser operates with stable SLM and single polarization. It can be seen that there are no beating signals in the 4 GHz frequency range, as shown in Fig.4 (a), which implies that only one longitudinal lasing mode exists. As the effective cavity length of the fiber laser of approximately 55 mm corresponds to the FSR of the laser longitudinal mode of ~1.89 GHz, we believe that the fiber laser is well under SLM operation. A scanning Fabry−Perot interferometer (FPI) may also need to be used to examine the longitudinal−mode characteristics of the SLM fiber laser. However, in the current laboratory conditions, we do not have an FPI. The linewidth of the fiber laser was measured using the delayed self−heterodyne method. The delayed line is approximately 50 km long, corresponding to a nominal resolution of 4 kHz. The measured 3 dB linewidth of the fiber laser, as shown in Fig.4 (b), is approximately 6.7 kHz.

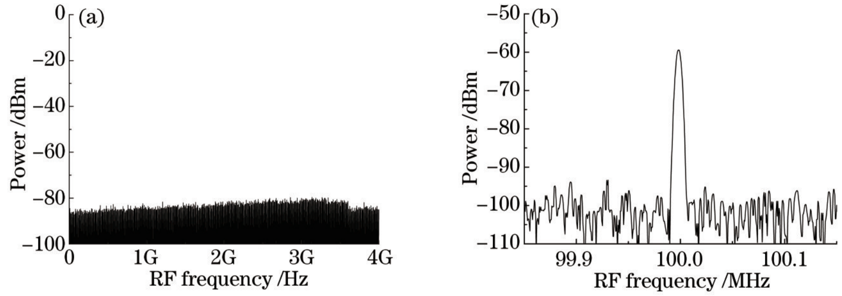

Fig.4 (a) Electrical beating spectrum of fiber laser measured by the ESA and (b) linewidth of fiber laser measured using the delayed self−heterodyne method

The polarization parameters of fiber laser were measured using a lightwave polarization analyzer (PA, HP 8509B). Through an 8 m segment of a commercial optical−fiber jumper, the laser output is connected to the PA. The polarization parameters of the fiber laser accumulated in 3 min without external disturbance is shown in Fig.5. The apparent degree of polarization (DOP) of the fiber laser in percentage is as high as 96.8%, which indicates that the laser output is almost in the stable single−polarization state.

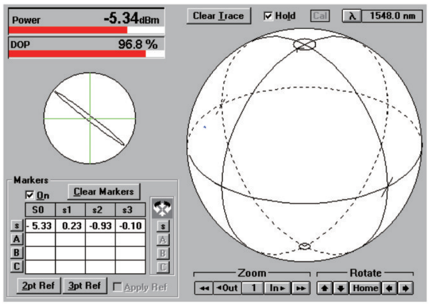

Fig.5 Polarization parameters of the fiber laser

Theoretically, feedback from the PMFBGs in the laser cavity results in different linearly polarized modes, which are separated in both wavelength and polarization. In our previous work[26−27], we achieved a switchable dual−wavelength erbium−doped fiber laser using the PMFBG in both linear and ring−type fiber laser cavities by adjusting the polarization controller (PC). Here, we qualitatively explain its operation. For stable dual−wavelength lasing operation, the amplitude discrepancy between the two different polarized modes is small when no perturbation−induced birefringence exists. For example, if we suppose that the x−polarization has a dominant position in lasing, then the y−polarization will achieve higher net gain than the x−polarization[28], which will weaken the mode competition and make them reach equilibrium gradually in lasing and vice versa. Lasers operating in different linearly polarized modes greatly enhance the PHB in the cavity and reduce the homogeneous broadening effect of the EDF. For stable single−wavelength lasing operation, owing to the polarization−dependent loss enhanced by the PMFBG, the amplitude discrepancy between the two different polarized modes becomes large when the PC is appropriately adjusted because perturbation−induced birefringence was used to change the polarization states of different wavelengths in the laser cavity, which allows only one of the two polarized modes to oscillate stably. In this paper, by controlling the birefringence through appropriately twisting the fiber laser cavity, stable SLM and stable single−polarization operation of the fiber laser were achieved. We had also unsuccessfully attempted to obtain another stable lasing operation with a lasing wavelength of orthogonal polarization through twisting. The attempt was unsuccessful because the gain and loss in the laser cavity related to the birefringence of the fiber cannot be precisely controlled by only twisting the fiber laser cavity roughly. The wavelength switching of the dual lasing wavelength of orthogonal polarization could be obtained using a precise, compact inline polarization controller for the short laser cavity.

4 Conclusion

We proposed and demonstrated a single-polarization SLM EDF laser based on the twisting of PMFBGs. Two uniform FBGs directly written in a homemade PMPEDF using ultraviolet light from a 248 nm KrF excimer laser as the wavelength-selective component are used in a linear cavity. The fiber laser is structurally simple and integrative, has low cavity loss, and is easy to be fabricated. Owing to the polarization-dependent loss enhanced by the PMFBG, stable SLM and stable single-polarization operation of the fiber laser are achieved by controlling the birefringence through appropriately twisting the fiber laser cavity.

Acknowledgments The authors would like to thank the Optical Fiber Group of Institute of Lightwave Technology for supplying the PMPEDF with high quality and Nan Jia for the DOP measurement.

参 考 文 献

1 Jia Qingsong, Wang Tianshu, Zhang Peng, *et al*.. Microwave signal generation based on dual-wavelength Brillouin fiber laser[J]. Chinese J Lasers, 2014, 41(7): 0705001.

贾青松, 王天枢, 张 鹏, 等. 基于双波长布里渊光纤激光器的微波信号产生[J]. 中国激光, 2014, 41(7): 0705001.

2 Yang Fei, Chen Dijun, Pan Zhengqing, *et al*.. Short linear cavity single-frequency fiber laser with active frequency stabilization by fiber Bragg grating[J]. Chinese J Lasers, 2012, 39(9): 0902005.

杨 飞, 陈迪俊, 潘政清, 等. 光纤光栅主动稳频的短直线腔单频光纤激光器[J]. 中国激光, 2012, 39(9): 0902005.

3 Hou Yunzhe, Wang Zhaoying, Qin Xuwei, *et al*.. Precisely tuning technology of multi-wavelength fiber laser by radio frequency signal based on single side band modulator[J]. Chinese J Lasers, 2014, 41(8): 0805001.

侯云哲, 王肇颖, 秦旭伟, 等. 利用单边带调制器实现对多波长光纤激光器的高精度射频控制调谐技术[J]. 中国激光, 2014, 41(8): 0805001.

4 Dianjie Jiang, Xiangfei Chen, Yitang Dai, *et al*.. A novel distributed feedback fiber laser based on equivalent phase shift[J]. IEEE Photon Technol Lett, 2004, 16(12): 2598-2600.

5 O Xu, S Lu, S Feng, *et al*.. Single-longitudinal-mode erbium-doped fiber laser with the fiber-Bragg-grating-based asymmetric two-cavity structure[J]. Opt Commun, 2009, 282: 962-965.

6 Yang Zhang, Bai-Ou Guan, and Hwa-Yaw Tam. Ultra-short distributed Bragg reflector fiber laser for sensing applications[J]. Opt Express, 2009, 17(12): 10050-10055.

7 Youngjae Kim, Serge Doucet, Sophie LaRochelle. 50-channel 100-GHz-spaced multiwavelength fiber lasers with single-frequency and single-polarization operation[J]. IEEE Photon Technol Lett, 2008, 20(20): 1718-1720.

8 S H Xu, Z M Yang, T Liu, *et al*.. An efficient compact 300 mW narrow-linewidth single frequency fiber laser at 1.5 μm[J]. Opt Express, 2010, 18(2): 1249-1254.

9 L Li, A Schülzgen, X Zhu, *et al*.. 1 W tunable dual-wavelength emission from cascaded distributed feedback fiber lasers[J]. Appl Phys Lett, 2008, 92: 051111.

10 Elodie Wikszak, Jens Thomas, Jonas Burghoff, *et al*.. Erbium fiber laser based on intracore femtosecond-written fiber Bragg grating[J]. Opt Lett, 2006, 31(16): 2390-2392.

11 Nemanja Jovanovic, Jens Thomas, Robert J. Williams, *et al*.. Polarization-dependent effects in point-by-point fiber Bragg gratings enable simple, linearly polarized fiber lasers[J]. Opt Express, 2009, 17(8): 6082-6095.

12 N Park, J W Dawson, K J Vahala, *et al*.. All fiber, low threshold, widely tunable single-frequency fiber ring laser with a tandem fiber Fabry-Perot filter[J]. Appl Phys Lett, 1991, 59: 2639-2671.

13 X F Chen, J P Yao, F Zeng, *et al*.. Single-longitudinal-mode fiber ring laser employing an equivalent phase-shifted fiber Bragg grating [J]. IEEE Photon Technol Lett, 2005, 17(7): 1390-1392.

14 X P Cheng, P Shum, C H Tse, *et al*.. Single-longitudinal-mode erbium-doped fiber laser based on high finesse fiber Bragg grating Fabry-Perot etalon[J]. IEEE Photon Technol Lett, 2008, 20(12): 976-978.

15 C C Lee, Y K Chen, and S K Liaw. Single-longitudinal-mode fiber laser with a passive multiple-ring cavity and its application for video transmission[J]. Opt Lett, 1998, 23(5): 358-360.

16 Alexander Polynkin, Pavel Polynkin, Masud Mansuripur, *et al.*. Single-frequency fiber ring laser with 1 W output power at 1.5 μm[J]. Opt Express, 2005, 13(8): 3179-3184.

17 Y Cheng, J T Kringlebotn, W H Loh, *et al.*. Stable single-frequency traveling-wave fiber loop laser with integral saturable-absorber-based tracking narrow-band filter[J]. Opt Lett, 1995, 20(8): 875-877.

18 Shinji Yamashita, Gregory J Cowle. Single-polarization operation of fiber distributed feedback (DFB) lasers by injection locking[J]. J Lightwave Technology, 1999, 17(3): 509-513.

19 X H Li, X M Liu, Y K Gong, *et al.*. A novel erbium/ytterbium co-doped distributed feedback fiber laser with single-polarization and unidirectional output[J]. Laser Phys Lett, 2010, 7(1): 55-59.

20 C C Lee and S Chi. Single-longitudinal-mode operation of a grating-based fiber-ring laser using self-injection feedback[J]. Opt Lett, 2000, 25(24): 1774-1776.

21 Tao Zhu, Xiaoyi Bao, and Liang Chen. A single-longitudinal-mode tunable fiber ring laser based on stimulated Rayleigh scattering in a nonuniform optical fiber[J]. J Lightwave Technol, 2011, 29(12): 1802-1807.

22 Z E Harutjunian, W H Loh, R I Laming, *et al.*. Single polarisation twisted distributed feedback fibre laser[J]. Electronics Letters, 1996, 32(4): 349-348.

23 Akihito suzuki, Youhei takahashi, Masato yoshida, *et al.*. An ultralow noise and narrow linewidth λ/4-shifted DFB Er-doped fiber laser with a ring cavity configuration[J]. IEEE Photon Technol Lett, 2007, 19(19): 1463-1465.

24 Z H Fu, Y X Wang, D Z Yang, *et al.*. Single-frequency linear cavity erbium-doped fiber laser for fiber-optic sensing applications[J]. Laser Phys Lett, 2009, 6(8): 594-597.

25 Y O Barmenkov, D Zalvidea, S T Peiro, *et al.*. Effective length of short Fabry-Perot cavity formed by uniform fiber Bragg gratings[J]. Opt Express, 2006, 14(14): 6394-6399.

26 S Feng, O Xu, S Lu, *et al.*. Single-polarization, switchable dual-wavelength erbium-doped fiber laser with two polarization maintaining fiber Bragg gratings[J]. Opt Express, 2008, 16(16): 11830-11835.

27 S Feng, O Xu, S Lu, *et al.*. Switchable dual-wavelength erbium-doped fiber ring laser based on one polarization maintaining fiber Bragg grating in a Sagnac loop interferometer[J]. Optics and Laser Technology, 2009, 41(3): 264-267.

28 R Leners, T Georges. Numerical and analytical modeling of polarization-dependent gain in erbium-doped fiber amplifiers[J]. Journal of the Optical Society of America B, 1995, 12(10): 1942-1954.

栏目编辑: 宋梅梅