Stable single longitudinal mode erbium-doped silica fiber laser based on an asymmetric linear three-cavity structure*

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(Received 23 April 2012; revised manuscript received 11 June 2012)

We present a stable linear-cavity single longitudinal mode (SLM) erbium-doped silica fiber laser. It consists of four fiber Bragg gratings (FBGs) directly written in a section of photosensitive erbium-doped fiber (EDF) to form an asymmetric three-cavity structure. The stable SLM operation at a wavelength of 1545.112 nm with a 3-dB bandwidth of 0.012 nm and an optical signal-to-noise ratio (OSNR) of about 60 dB is verified experimentally. Under laboratory conditions, the performance of a power fluctuation of less than 0.05 dB observed from the power meter for 6 h and a wavelength variation of less than 0.01 nm obtained from the optical spectrum analyzer (OSA) for about 1.5 h are demonstrated. The gain fiber length is no longer limited to only several centimeters for SLM operation because of the excellent mode-selecting ability of the asymmetric three-cavity structure. The proposed scheme provides a simple and cost-effective approach to realizing a stable SLM fiber laser.

Keywords: asymmetric three-cavity structure, single longitudinal mode, erbium-doped fiber laser, linear cavity

PACS: 42.55.Wd, 42.81.–I, 42.60.–v **DOI:** 10.1088/1674-1056/22/1/014208

1. Introduction

Fiber lasers have been developed intensively over the last ten years.[1–11] Single longitudinal mode (SLM) erbium-doped fiber lasers (EDFLs) are of great interest due to their applications in optical sensors where long coherence lengths are required, such as lidar, high-resolution spectroscopy, optical metrology, pollution monitoring, atom frequency standard, etc.[3–10] Among the SLM technologies of fiber lasers, using the structure of a short linear cavity is the simplest method, and the best reflection mirror of the cavity is fiber Bragg grating (FBG) due to its superior advantages of low insertion loss, low cost, passiveness, and high selectivity. For conventional short linear-type lasers in which two FBG-based reflectors are utilized to realize cavity feedback and wavelength selectivity, the laser cavity needs to be as short as several centimeters at most, so that the laser mode spacing becomes comparable to the grating bandwidth and SLM operation can be ensured. Short SLM fiber laser of about 1550 nm using FBGs as reflectors has been demonstrated first by Ball *et al.*[12] in erbium-doped silicate fibers. However, a cavity that is too short restricts the output power substantially,[8] and even leads to unlasing because there are not enough erbium ions inside the fiber to provide sufficient gain to overcome the losses of the cavity.[13] A single-mode fiber made of erbium/ytterbium co-doped phosphate glass exhibits extremely high optical gain and suitability for short linear-cavity SLM fiber lasers,[14–16] but the erbium/ytterbium co-doped phosphate fiber with photosensitivity is very expensive and the spliced joints between the two different fibers may cause high loss. In addition, mechanical fragility may occur because phosphate and silica glass have different optical, mechanical, and thermal properties. Another method to control the longitudinal mode is to use multiple-cavity laser structures, which have been successfully employed in semiconductor laser technology[17,18] and some fiber laser technologies. Zhang *et al.*[19] proposed an SLM EDFL with multiple ring cavities, which has a low optical signal-to-noise ratio (OSNR) and a complicated configuration. Wang *et al.*[20] introduced a common resonant cavity technology that can provide good longitudinal mode-selecting performance, but they did not use this technology in the SLM EDFL. Xu *et al.*[21] reported on an SLM fiber laser with two asymmetric cavities consisting of three FBGs directly written in a section of photosensitive erbium-doped fiber (EDF). It has, however, a relatively large wavelength and power fluctuation, as well as short gain fiber tolerated in the cavity.

In the present paper, an asymmetric three-cavity EDFL containing four FBGs is proposed. Since four FBGs are directly written into a section of photosensitive EDF, the laser presented here has advantages such as no fusion splice point, simplicity and compactness, and ease of fabrication. The stable SLM operation is verified experimentally without mode competition and hopping. The whole cavity length is no longer

*Project supported by the National Natural Science Foundation of China (Grant Nos. 61077069 and 61107094) and the Innovation Foundation for Excellent Doctoral Candidates of Beijing Jiaotong University, China (Grant No. 2011YJS202).

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restricted only to several centimeters as in the case of those conventional short linear-type fiber lasers.

2. Experimental setup

The experimental configuration of the proposed fiber laser is shown in Fig. 1. This apparatus comprises of a basic linear cavity composed of a section of photosensitive EDF with four FBGs (FBG1, FBG2, FBG3, and FBG4), a 980-nm laser diode (LD), a 980/1550-nm wavelength diversion multiplexer (WDM), and an isolator (ISO). The residual pump light is absorbed by the refractive index matching liquid (RIML) which can also avoid useless light from reflecting back to the laser cavity. The photosensitive EDF is fabricated by our optical fiber group in the Institute of Lightwave Technology, Beijing Jiaotong University with an absorption peak of 25 dB/m at 1530 nm, and is co-doped with aluminum ions to reduce the number of erbium ion pairs. The ISO at the output end is used to prevent the light reflected from the fiber cut from returning to the laser cavity. Finally, the laser output is measured by using an ANDO AQ6317C optical spectrum analyzer (OSA) with a 0.01-nm resolution, a radio frequency (RF) electrical spectrum analyzer (ESA) (Agilent N9010A, 9 kHz–26.5 GHz), and a laser power meter (PM), separately. In order to be detected by a photodetector (PD) (Tektronix SD-48, 33 GHz) and finally monitored as an electrical signal by the RF ESA, the laser output is amplified first by an EDF amplifier (EDFA) before it enters the PD.

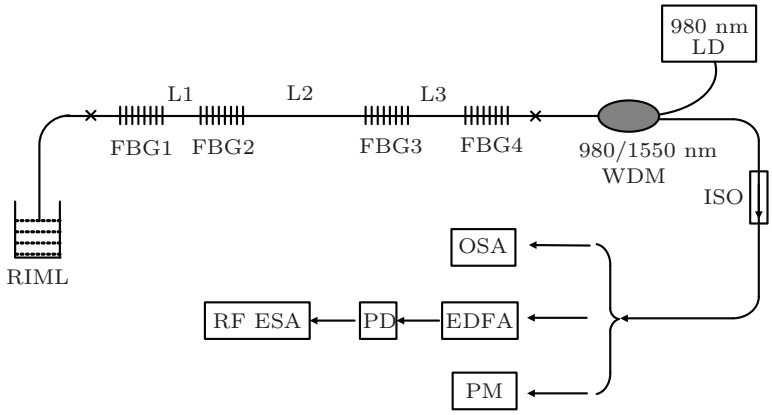


Fig. 1. Experimental configuration.

The laser cavity is formed by four identical FBGs: FBG1, FBG2, FBG3 and FBG4. Each FBG is directly written in the photosensitive EDF by being exposed to ultraviolet (UV) radiation from a KrF excimer laser with an energy of 65 mJ per pulse at 248 nm and a repetition rate of 6 Hz for 8 min. A 14-cm-long uniform phase mask with its pitch period of 1068 nm is employed in the FBG-written process. The four FBGs have the same length of 10 mm, and are fabricated under the same conditions. During the fabrication of the four FBGs, the photosensitive EDF and the phase mask are fixed without any shifting. Therefore, there is no splicing point in the whole cavity. The four FBGs have almost the same 3-dB bandwidth of 0.192 nm and the same peak reflectivity of about 87% (transmission depth of 9 dB) at the Bragg wavelength of 1545.091 nm. The reflection spectrum and transmission spectrum of FBG1, measured by the OSA, are shown in Figs. 2(a) and 2(b), respectively. Four FBGs are written successively within the central 10-cm region of a 30-cm photosensitive EDF. In total three cavities (L1, L2, and L3) are formed, and the lengths of cavities L1, L2, and L3 are 3, 50, and 7 mm, respectively.

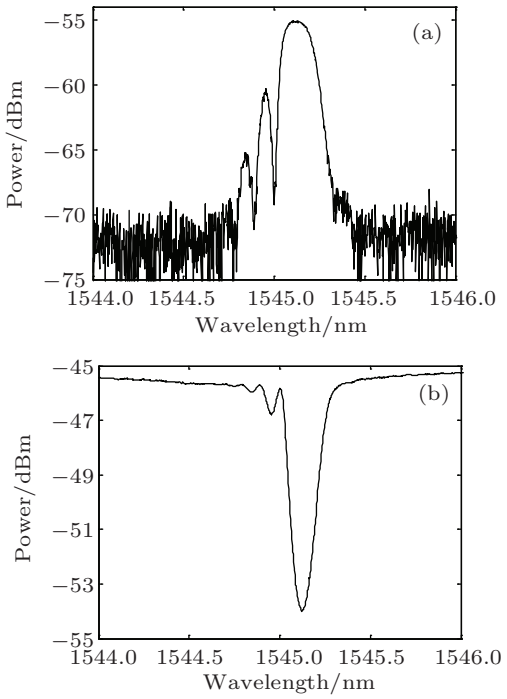


Fig. 2. (a) Reflectivity spectrum of FBG1; (b) transmission spectrum of FBG1.

In the three cavities, there are two Fabry–Perot (F–P) filters formed by FBG1 and FBG2, and FBG3 and FBG4, respectively. Figure 3(a) shows the transmission spectrum with all the four FBGs in the EDF written. We can see that only one transmission peak remains there, which, however, is not in the centre of the transmission spectrum of FBG1. This is mainly because the main transmission peaks of the two F-P filters are not overlapping. Therefore, we expose the F–P filter formed by FBG1 and FBG2 to the UV radiation from the KrF excimer laser with its energy of 65 mJ per pulse at 248 nm and its repetition rate of 1 Hz for 16 sec in the centre of the filter but without the phase mask, which can adjust its transmission spectrum by changing the refractive index of the EDF where the F–P filter is fabricated. After that, the transmission spectrum of the asymmetric three-cavity structure, measured by the OSA, is shown in Fig. 3(b), which shows that almost all the transmission side-lobes are suppressed, and only the main transmission peak remains at a wavelength of 1545.112 nm.

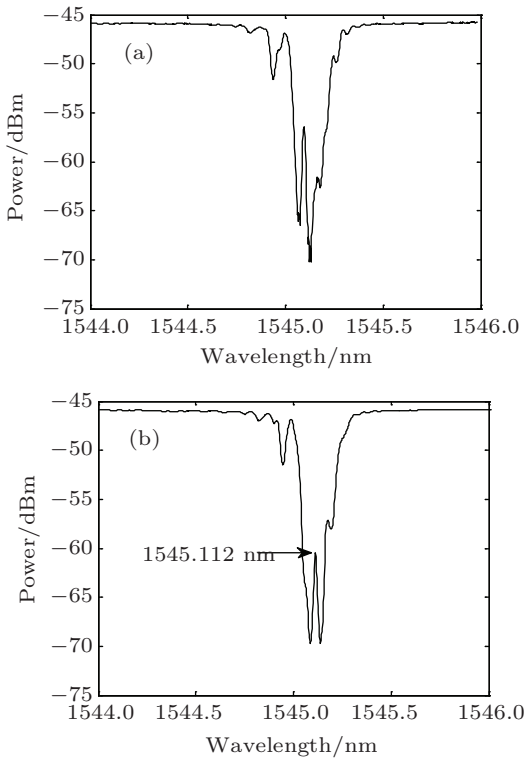


Fig. 3. Transmission spectra of the asymmetric three-cavity structure (a) without and (b) with exposure to the UV radiation without the phase mask in the centre of the F–P filter formed by FBG1 and FBG2.

According to the effective cavity length theory,[22] the three effective cavity lengths are calculated to be about 8, 55, and 12 mm, respectively. According to the vernier effect,[23] the free spectral range (FSR) of the compound cavity of the fiber laser is calculated to be about 26 GHz, corresponding to a wavelength region of roughly 0.21 nm, which is wider than the 3-dB bandwidth of 0.192 nm of the FBGs. Therefore, there is only one longitudinal mode that can oscillate in the three cavities simultaneously, and the SLM operation can be ensured theoretically. Additionally, the SLM operation is also verified by observing the RF beating spectrum measured by the RF ESA in the following section.

Actually, the length of L2 is not limited to 50 mm because of the good mode-selecting property of the asymmetric three-cavity structure. However, in view of the fact that the phase mask length is 14 cm and the position of the EDF cannot be shifted for writing four identical FBGs, we adopt an L2 length of 50 mm. We verify the SLM operation at an L2 length of about 15 cm experimentally, as shown below.

3. Results and discussion

The bare three-cavity laser is placed on a vibration isolation optical platform and the experiment is carried out at room temperature. Figure 4 shows a typical emission spectrum of the laser, measured by the OSA with a resolution of 0.01 nm. The lasing wavelength is 1545.112 nm, the 3-dB bandwidth is 0.012 nm which is less than the minimum resolution of the OSA used, and the OSNR is about 60 dB.

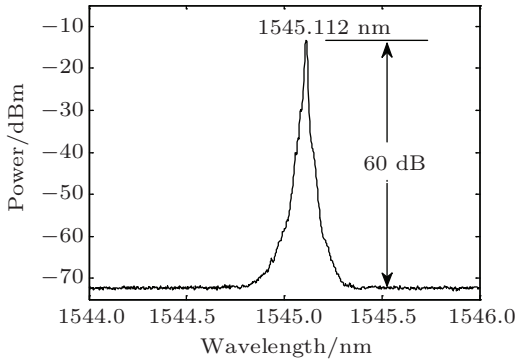


Fig. 4. Optical spectrum of the laser emission measured by the OSA.

To verify the SLM operation of the fiber laser proposed, we inject the laser output into a 33-GHz PD and monitor the electrical signals through the RF ESA. To avoid the fact that the output power is too low to be detected by the PD, the laser output is amplified by the EDFA first before it is injected into the RF ESA. The amplified laser output at the wavelength of 1545.112 nm is shown in Fig. 5, indicating that the output power increases to 3.9 dBm. The RF beating spectra are measured in different frequency ranges, as shown in Figs. 6(a) and 6(b). It can be seen in Fig. 6(a) that there is no obvious beating signal between the main lasing mode and the side-modes in a 10-GHz frequency range. Because the longest effective cavity of 55 mm corresponds to the FSR of about 1.9 GHz, we can believe that the fiber laser is under a good SLM operation. In Fig. 6(b), however, we can see a small beating signal at an RF frequency of 85 MHz, which is induced by two orthogonal polarization modes in the EDF. This problem can be

eliminated easily by appropriately twisting the EDF containing FBGs, and the RF beating spectrum after the EDF was twisted appropriately is shown in Fig. 7 in a frequency range of 0–500 MHz, in which no beating signal is found. Therefore, the SLM operation condition for the fiber laser proposed is well verified. The linewidth of the laser should be measured using the delayed self-heterodyne method. However, according to the present laboratory conditions, we do not have an acousto–optical modulator.

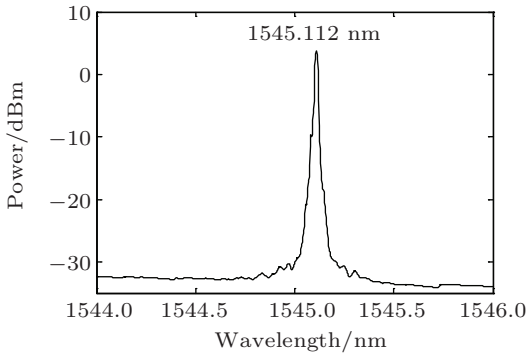


Fig. 5. Optical spectrum of the amplified laser output measured by the OSA.

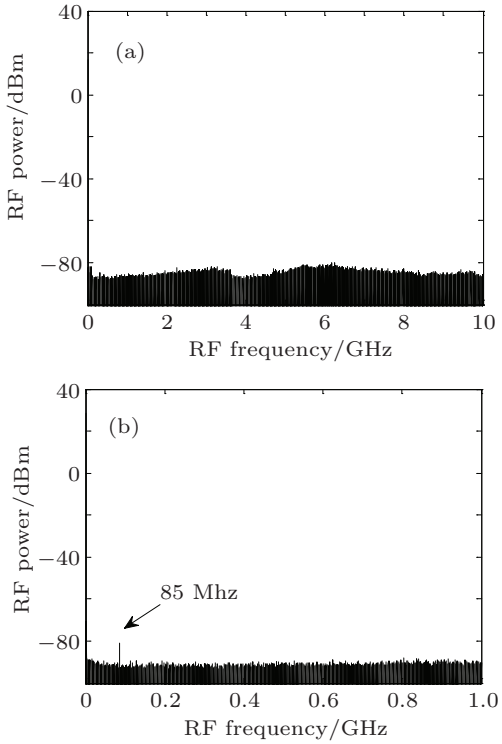


Fig. 6. RF beating spectra of the amplified laser output measured by the RF ESA in two different frequency ranges: (a) 10 GHz, (b) 1 GHz.

Figure 8 shows the laser output power as a function of the pump power. It can be found that the threshold is about 45 mW and the slope efficiency is 0.3%. The relatively high threshold is mainly due to the fact that the remainder 20-cm EDF outside of the three-cavity absorbs a large proportion of pump power and some pump power leaking out through the short EDF. The low slope efficiency is mainly due to the relatively low concentration of erbium ions doping in the EDF. It can also be seen in Fig. 8 that the output power reaches its maximum of 330 μW when the pump power increases to 171 mW, which indicates that the erbium ions in the EDF have reached a maximal quantum efficiency. Therefore, if the concentration of erbium ions increases, the gain fiber is changed into high-concentration erbium/ytterbium co-doped silica fiber, or if the L2 length increases appropriately, the output power and slope efficiency can be improved to a higher order of magnitude.

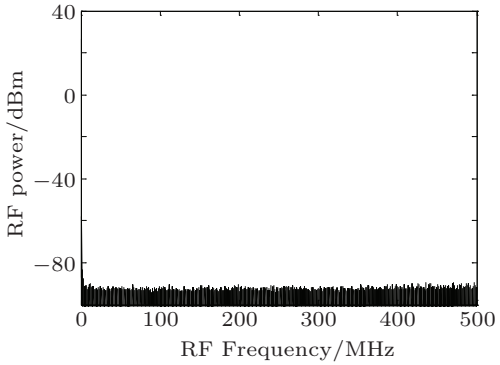


Fig. 7. RF beating spectrum of the amplified laser output, measured by the RF ESA after the EDF was twisted appropriately.

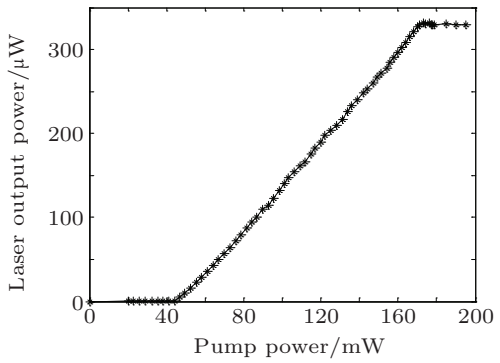


Fig. 8. Laser output power as a function of pump power.

Under a pump power of 68 mW at 980 nm, continuous scans of the lasing spectrum at the wavelength of 1545.112 nm in about 150 min are shown in Fig. 9. The output power is about −13 dBm and the OSNR is about 60 dB. In the situation of room temperature and a vibration isolation optical platform, the maximum power fluctuation at the wavelength operation is recorded to be less than 0.05 dB by observing the power meter for 6 h. The wavelength fluctuation is less than the resolution limit of 0.01, which is obtained by observing the OSA for 1.5 h. The stability may benefit from the good mode-selecting ability of the asymmetric three-cavity structure and the fine laboratory environment. Also, the stability can be improved by using special grating packaging technology and effective temperature compensation technology. Additionally, the wavelength tuning can be achieved by adjusting the temperatures of the FBGs or changing the phase mask period when writing the FBGs.

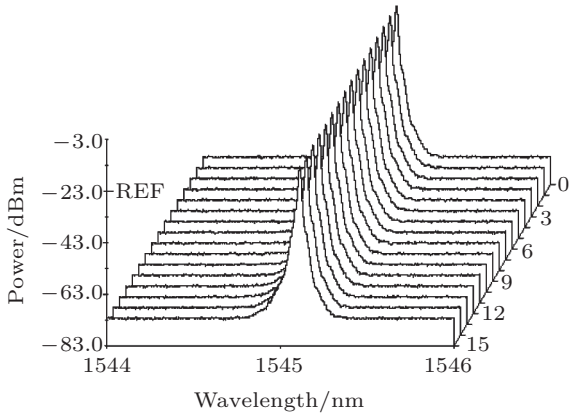


Fig. 9. The lasing spectrum scanned by the OSA for 16 times in about 150 min.

Finally, to verify the excellent mode-selecting property of the asymmetric three-cavity structure, we cut off the EDF in the centre of cavity L2, and a 10-cm identical EDF is spliced in the cavity to increase the length of cavity L2 to 15 cm. Then we measure the laser output spectrum and the RF beating spectrum by using the OSA and the RF ESA, respectively (see Figs. 10(a) and 10(b)). The lasing wavelength of 1545.113 nm with a 3-dB bandwidth of 0.013 nm and an OSNR of 63 dB is measured, and there is no beating signal in a 5-GHz frequency range. Therefore, the asymmetric three-cavity structure can improve the laser output stability and increase the tolerated gain fiber length for SLM operation of the short cavity linear fiber laser.

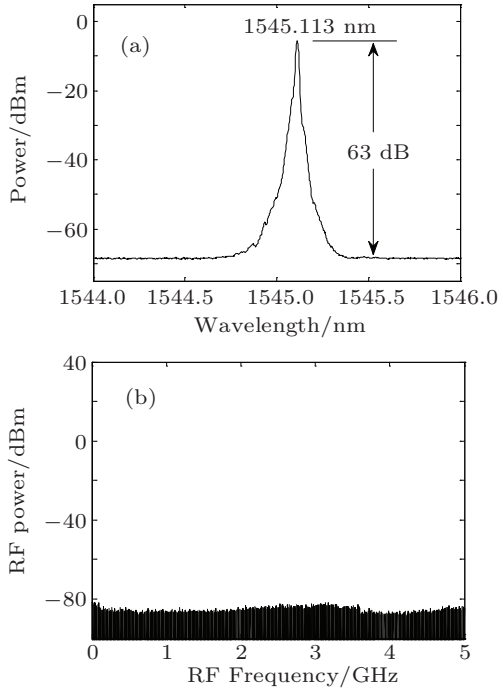


Fig. 10. (a) Optical spectrum of the laser emission, measured by the OSA. (b) RF beating spectrum of the laser output, measured by the RF ESA with the cavity L2 of 15 cm.

4. Conclusion

We experimentally demonstrated the SLM operation from a linear-cavity fiber laser which contains four FBGs to form an asymmetric three-cavity structure. Since four FBGs are directly written into a section of photosensitive EDF, there is no fusion splice point in the three cavities, which has the advantages of compactness and ease of fabrication. The stable SLM operation at a wavelength of 1545.112 nm with an OSNR of about 60 dB is verified experimentally without mode competition and hopping. Finally, the excellent mode-selecting ability of the asymmetric three-cavity structure is also verified by measuring the properties of the fiber laser with an L2 length of about 15 cm. We find that the gain fiber length is no longer limited to only several centimeters based on the asymmetric three-cavity structure for SLM operation of short cavity linear fiber lasers. The proposed scheme provides a simple and cost-effective approach to realizing a stable single-longitudinal-mode fiber laser.

Acknowledgment

The authors would like to thank the optical fiber group of the Institute of Lightwave Technology in Beijing Jiaotong University for supplying high-quality photosensitive EDF.

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