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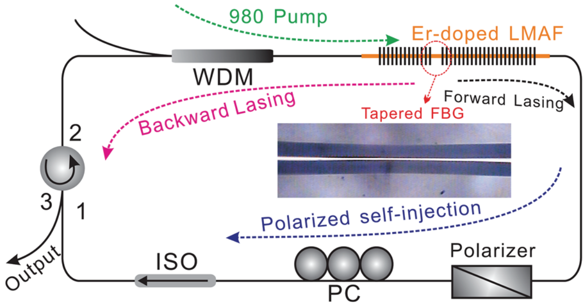

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Single-Frequency and Single-Polarization DFB Fiber Laser Based on Tapered FBG and Self-Injection Locking

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Abstract: A stable single-polarization narrow linewidth single-frequency distributed feedback (DFB) fiber laser is proposed and demonstrated. For the first time, to our knowledge, the tapered FBG written in the photosensitive large-mode-area (LMA) high-concentration erbium-doped fiber (EDF) is applied in the DFB fiber laser. Self-injection locking is used to make the proposed DFB fiber laser operate in the stable single-polarization state and reduce the linewidth of the DFB fiber laser. The LMA high-concentration EDF is fabricated by the modified chemical vapor deposition technique. The tapered FBG can be seen as the equivalent phase shift FBG, and the equivalent π phase shift is produced by tapering the uniform FBG directly. The threshold of the DFB fiber laser is about 145 mW, and the maximum output power is 43.55 mW at 450-mW pump power. The measured and modified slope efficiencies of the DFB fiber laser are approximately 14.27% and 15.82%, and the optical signal-to-noise ratio (OSNR) of the laser is over 55 dB. The stable single-polarization and single-frequency operation of the fiber laser is realized, and the measured 20-dB linewidth of DFB fiber laser with self-injection locking and without self-injection locking are approximately 10.3 and 52.3 kHz, respectively.

Index Terms: Fiber Bragg gratings, fiber laser, self-injection locking, single-frequency.

1. Introduction

Distributed-feedback (DFB) fiber laser is an attractive device for wavelength-division-multiplexing (WDM) systems, optical microwave signal generation, and sensing applications due to its robust single-mode operation, narrow linewidth, fiber compatibility, and ease of fabrication [1]–[3]. Moreover, the single-polarization single-frequency narrow linewidth fiber lasers can be coherently beam-combined [4] to increase the output power. Thus, stable high power single-polarization single-frequency narrow linewidth DFB fiber sources are highly desirable for the fiber laser sources [5], [6].

Cusano *et al.* presented a novel FBG configuration involving micro-structured FBG and employing localized defects along the grating region realized by post processing local structuration of the host fiber [7], [8]. The perturbation acts as a distributed phase shift with the consequent formation of a defect state inside the stop-band spectrum similarly to the effect observed in phase shift fiber Bragg grating (PS-FBG) [9]. Then, they proposed the use of the electric arc discharge (EAD) to achieve localized defects along the FBG structure [10]. This method can realize a new ultra-narrow band-pass filter (BPF) which is same to the PS-FBG. Recently, we utilized this method to realize the stable single-frequency narrow linewidth ring fiber laser [11] and the measurement of the multiple parameters [12].

To realize a stable single-frequency operation of the fiber laser, different styles have been implemented. The ring fiber laser [13], [14] is rather complex and expensive systems with hardly achievable wavelength stability. At the same time, it needs ultra-narrow BPF and has low output power and slope efficiency. Short linear cavity distributed Bragg reflector (DBR) fiber laser [15] or the DFB fiber laser can overcome these problems above [16]. They have simple, robust, and compact structure providing operation without longitudinal mode hopping. However, they need high concentration and gain of active optical fiber. Spiegelberg *et al.* have reported DBR laser emission around 1550 nm in Er/Yb co-doped phosphate glass fiber [15]. However, the Er/Yb co-doped phosphate glass fiber with photosensitivity is very expensive and the spliced joints between the two different fibers may cause high loss and mechanical fragility, because phosphate and silica glasses have different optical, mechanical, and thermal properties. Since the ordinary EDF has low doped concentration and gain, in this paper, the methods of enlarging the mode area and multi-compound doped are proposed to increase the erbium-doped concentration and gain of the active fiber core. Li *et al.* proposed a PS-FBG written in the high concentration EDF to realize the DFB fiber laser, but the stable single-polarization state was not verified and the laser linewidth was not narrow enough, which restricted its practical application [17]. In our previous work, the tapered FBG which was written in the passive single-mode fiber (SMF) had the characteristics of the narrowband filter to realize the selection of the laser longitudinal mode, but the structure was rather complex and had low output power and slope efficiency. In the meantime, the laser linewidth was not narrow enough, which also restricted its practical application [18].

Many applications demand stable single-polarization single-frequency laser sources. However, the DFB fiber laser without any internal polarization selection elements operates in both orthogonally polarized modes simultaneously [19]. In order to obtain a stable single-polarization lasing, various techniques such as to twist the DFB laser [20] or to introduce a polarization dependent phase shift in the fiber resonator [21] have been proposed. However, the stable or controllable single-polarization operation is difficult to realize. Babin *et al.* proposed a DFB fiber laser which achieved the single-polarization operation at certain pump power without any polarization components [22], but the stable single-polarization state could only be realized at high pump power not at any arbitrary pump power. Yamashita and Cowle proposed the method of the self-injection locking utilizing a polarization-selective optical feedback composed of a mirror and a polarizer [23], and the method of the self-injection locking was a good way to realize the stable single-polarization operation.

In this letter, we propose a stable single-polarization single-frequency narrow linewidth DFB fiber laser based on the tapered FBG incorporating a large mode area (LMA) high concentration EDF by self-injection locking. For the first time as we know, the tapered FBG written in the LMA high concentration EDF is applied in the DFB fiber laser. The tapered FBG same as PS-FBG which produces equivalent π phased shift is created by tapering directly on the uniform FBG. The self-injection locking is employed to make the proposed DFB fiber laser operate in single-polarization state and reduce the linewidth of the DFB fiber laser. The threshold of the DFB fiber laser is about 145 mW, and the measured maximum output power is 43.55 mW at 450 mW pump power. The measured and modified slope efficiencies of the DFB fiber laser are approximately 14.27% and 15.82%, and the optical signal-to-noise ratio (OSNR) of the fiber laser at 160 mW pump power is more than 55 dB. The stable single-frequency laser operation is achieved, and the measured 20 dB linewidth of the DFB laser with self-injection locking and without self-injection locking are approximately 10.3 kHz and 52.3 kHz, respectively.

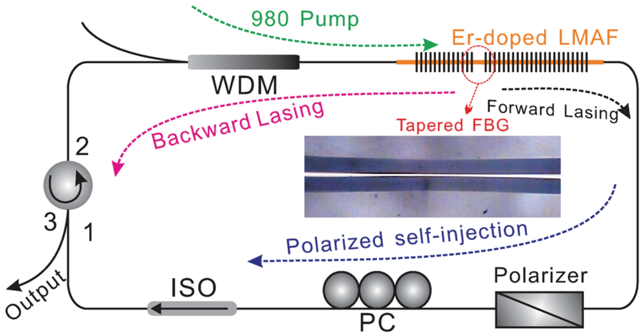


Fig. 1. Experimental configuration of the DFB fiber laser with self-injection locking and the tapered region of the tapered FBG under the microscope.

2. Experimental Principle and Structure

Fig. 1 shows the experimental setup of the proposed DFB fiber laser with self-injection locking. The proposed laser consists of a 980/1550 nm wavelength division multiplex (WDM), a 14 cm tapered FBG written directly in a section of 15 cm homemade EDF as the laser structure and the gain medium, a 980 nm pump source (maximum output power 450 mW), a polarizer and polarization controller (PC) which select either of the two polarizations to be feedback, and an isolator (ISO) assuring the unidirectional operation and the optical circulator (OC) which is employed to help the implementation of the laser output and sustain the unidirectional oscillation in the laser cavity. The 980 nm pump laser is coupled into the LMA high concentration EDF from the pumping port of the WDM. The tapered FBG same as equivalent π PS-FBG forms the DFB laser cavity and produces the laser output (forward laser output and backward laser output). The self-injection locking scheme which includes an OC, an ISO, a polarizer, and a PC can select either of the two polarizations to be feedback into the cavity of DFB laser. Thus, it can change the equilibrium between two polarizations and realize the single-polarization operation [23]. The structure of the self-injection locking is spliced with the two outputs of DFB fiber laser. The polarizer is connected to the forward output of the DFB fiber laser. The outgoing light from the forward output of DFB fiber laser will go to the port 1 of the OC, via the polarizer, PC which select either of the two polarizations to be feedback to the cavity of the DFB fiber laser and the ISO which is used to avoid back reflection. Through port 2 of the OC, the light can be feedback into the DFB fiber laser again. Then the output laser is monitored at port 3 of the OC so that the polarization state of the fiber laser is investigated. The laser output is monitored by an optical spectrum analyzer (OSA; ANDO AQ6317C) with a wavelength resolution of 0.01 nm and an electrical spectrum analyzer (ESA; Agilent N9010A, 9 kHz $\sim$ 26.5 GHz) connected to a photo detector (PD; Tektronix CSA803A SD-48PD subunit, 33 GHz). In order to protect the OSA and PD from high-power damage, the output laser is properly attenuated before being injected into the OSA. The linewidth of the proposed laser is measured with the delayed self-heterodyne method. The polarization state of the fiber laser is investigated by the lightwave polarization analyzer (PA, HP 8509B).

The LMA high concentration EDF we used was made by our laboratory and was fabricated by the modified chemical-vapor deposition (MCVD) technique. In order to improve the gain characteristic, flatness, and erbium-doped concentration, the erbium-doped concentration core of the fiber was multi-compound doped of Bi^{3+}, Ga^{3+}, Er^{3+}, and Al^{3+}. Meanwhile, we adopted fluorine-doped technique to reduce the relative index difference (Δn), which realized single-mode transmission of the EDF in 1.5 μm band. The measured parameters of the LMA high concentration EDF is shown in Table 1.

The tapered FBG same as PS-FBG which produces equivalent π phased shift is created by tapering directly on the uniform FBG. We fabricated a 14 cm length of uniform FBG using the phase-mask scanning technique. The uniform FBG was written in a 14 day hydrogen-loaded

TABLE 1

Measured Parameters of the LMA High Concentration EDF

cutoff wavelength nm	mode field diameter μm @1550nm	absorption coefficients dB/m@1530nm	erbium-doped concentration $ions / m^3$
1350.91	12.2801	84.253	4.19×10^{25}

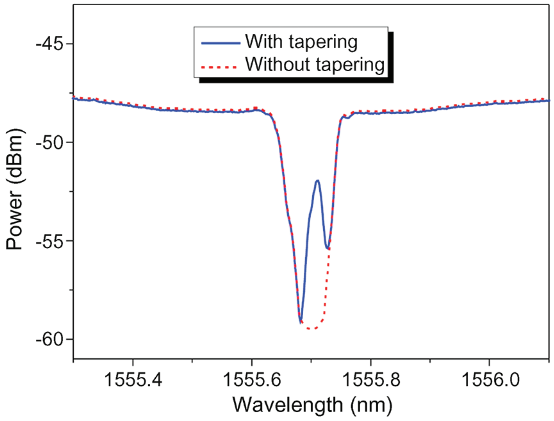


Fig. 2. Experimental transmission spectrum of the tapered FBG (red dot line) without tapering; (black line) with tapering.

(10 Mpa; at room temperature) germanium-doped LMA high concentration EDF with a 14 cm uniform phase mask which had a period of 1075 nm scanned by 248 nm KrF excimer laser ultraviolet light. The red dot line in Fig. 2 shows the measured transmission spectrum of the fabricated uniform FBG. The 3 dB bandwidth and the transmission depth of this FBG are 0.046 nm and 11 dB, respectively. Then, through a fusing-and-pulling treatment with a fiber fusion splicer (FSU975), the transmission spectrum of the tapered FBG (the black line) has one transmission peak generated by tapering directly on uniform FBG (the tapered region approximately 0.46 mm long, and waist diameter 105 ± 2 μm), as shown in Fig. 2. Due to the limit of the OSA resolution, we can only find a shallow peak. The tapered region which is equal to the phase shift point locates at 3 cm location of the tapered FBG from the pump source input port in order to achieve higher output laser power [24]. This method introduces a step-apodized profile which results in increasing the effective cavity length without changing the reflectivity from their optimum values and without increasing the total grating length. In the meanwhile, this design also increases the actual pump power delivered to the effective cavity since the phase shift position is moved closer to the pump source. Fig. 1 shows the tapered region of the tapered FBG under the microscope. We adopt the method of the anneal treatment to eliminate the influence of the hydrogen molecule ion on the radiation of the erbium ion.

On the basis of phase shift theory, the tapered FBG similar to the PS-FBG is analyzed in detail at the [18]. The phase delay $\Delta\Phi$ is dependent on the parameters of the tapered region such as length, waist radius and surrounding refractive index (SRI), according to

$$\Delta\Phi = \frac{4 \cdot \pi}{\lambda_B(z_{th})} \cdot \Delta n_{eff}(SRI, D_{th}) \cdot L_{th} \tag{1}$$

where λ_B is the optical wavelength corresponding to the tapered region position z_{th}. Δn_{eff} is the effective refractive index variation caused by tapering, which depends on SRI and the waist diameter D_{th}. L_{th} expresses the length of the tapered region [18]. Through adjusting the parameters of FBG (length, refractive index modulation depth) and taper (position, cavity length,

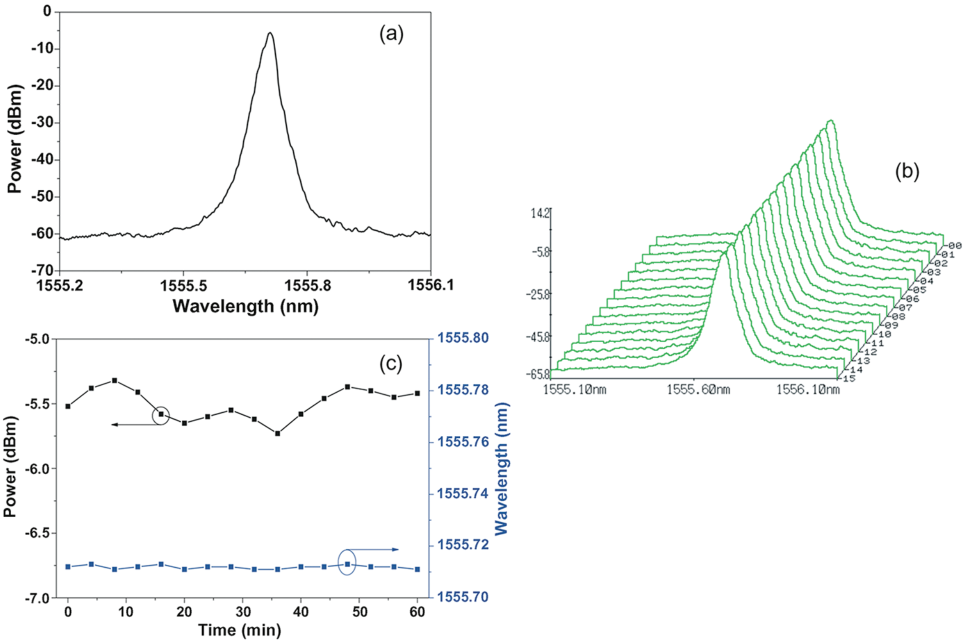


Fig. 3. (a) Measured optical spectrum of the DFB fiber laser at the pump power 160 mW. (b) Optical spectra of the DFB fiber laser with scans 16 times repeated at 4 min intervals in one hour. (c) Fluctuations of the laser peak power and center wavelength in one hour.

and waist radius), we can design the parameters of the phase shift. Therefore, the tapered FBG which produces equivalent π phased shift forms the DFB laser cavity, and it can be used in the DFB fiber laser.

3. Experimental Results and Discussion

The threshold of the DFB fiber laser with self-injection locking was approximately 145 mW. At the pump power of 160 mW (980 nm), the measured output spectrum at center wavelength of 1555.711 nm is shown in Fig. 3(a). The OSNR of the DFB fiber laser is more than 55 dB and the 3 dB bandwidth is 0.015 nm. In order to investigate the laser output stability, we measured the optical spectra of the fiber laser with scans repeated 16 times at 4 min intervals in one hour, as shown in Fig. 3(b). The fluctuations of wavelength and output power of the proposed fiber laser are less than 0.01 nm and 0.5 dB respectively, which represent stable lasing operation in the situation of the room temperature, as shown in Fig. 3(c).

The maximum measured output power of the DFB fiber laser with self-injection locking was measured about 43.55 mW at a pump power of 450 mW, corresponding to the slope efficiency of approximately 14.27% as shown in Fig. 4 (blue line). Because the mismatching mode area of the SMF-28 (about 10.5 μm) of the WDM and the homemade LMA high concentration EDF (about 12.2801 μm), the fusion splice between SMF-28 and homemade EDF can produce the loss of approximately 10.61% by $\alpha = -10\ \mathrm{lg}[4/(d_1/d_2 + d_2/d_1)^2]$, where d_1 and d_2 are the mode area diameter of the homemade EDF and SMF [17]. Thus, we should modify the real output power value excited from the EDF. Through calculating the results above, the modified slope efficiency is approximately 15.82%, as shown in Fig. 4 (orange line). We also measured the output of the DFB fiber laser without self-injection locking. The measured slope efficiencies of forward (red line) and backward (black line) output power of the DFB fiber laser are approximately 5.29% and 12.1%. With increasing the pump power, the backward output power increases linearly while the forward output increases slowly and reaches a maximum measured output power finally. The DFB fiber laser can realize unidirectional output, which is explained

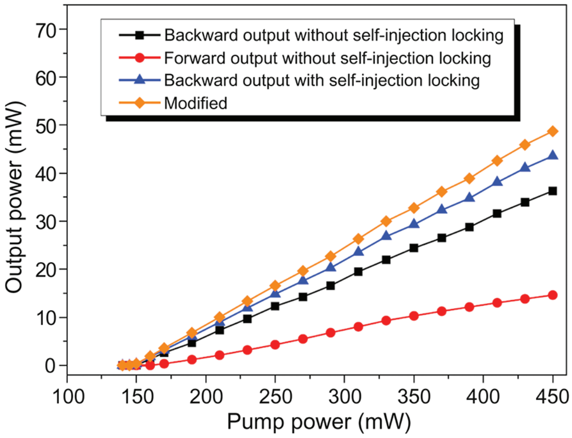


Fig. 4. Measured (blue line) and modified (orange line) output power variations of the DFB fiber laser with self-injection locking under the different input pump power. Measured forward (red line) and backward (black line) output power variations of the DFB fiber laser without self-injection locking under the different input pump power.

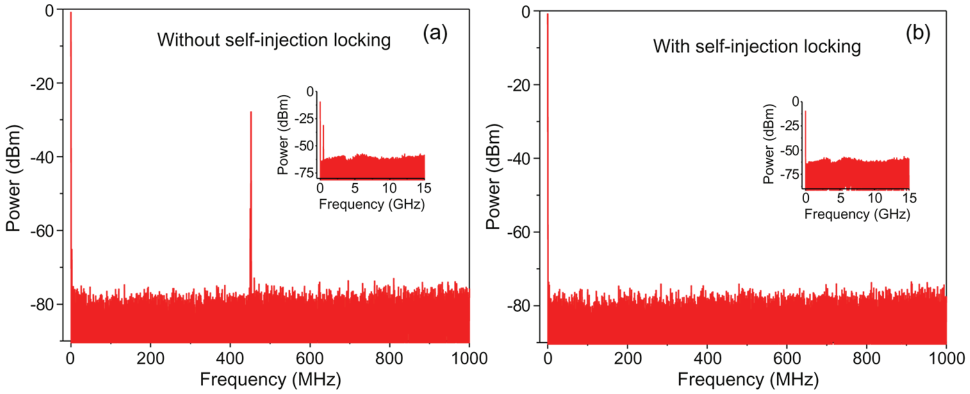


Fig. 5. Self-homodyne RF beat spectra of the DFB fiber laser. (a) Scanning frequency range 1 GHz and 15 GHz without self-injection locking. (b) Scanning frequency range 1 GHz and 15 GHz with self-injection locking.

by the Yelen *et al.* theory [24]. Thus, the output powers of the DFB fiber laser increase linearly and more quickly with the self-injection locking, than the output without self-injection locking, because the method of the self-injection locking can effectively restrain polarization mode competition to improve the output of the DFB fiber laser.

The RF beating spectrum of the DFB fiber laser in our experiment is measured through the self-homodyne method by the Agilent 9010 ESA. Fig. 5(a) shows the RF spectrum of the DFB fiber laser without self-injection locking at the scanning frequency range 15 GHz and 1 GHz. Owing to the DFB fiber laser which has two stable and coexisting polarization states, the ESA detected the two RF beating signals at 0 Hz and 452 MHz, respectively. The DFB fiber laser without the self-injection locking works in the multiple longitudinal mode operation correspond to the two beating signals in the ESA. The polarization mode spacing $\Delta\lambda$ can be calculated as

$$\Delta\lambda = \frac{c}{\lambda^2}\Delta f \tag{2}$$

where Δf is the beat frequency 452 MHz measured by ESA. λ is average wavelength, and c expresses the speed of the light. We can get $\Delta\lambda \approx 3.7 \times 10^{-3}$ nm [25]. Thus, we can estimate that the birefringence coefficient of the LMA high concentration EDF is about 3.5×10^{-6}. Mean

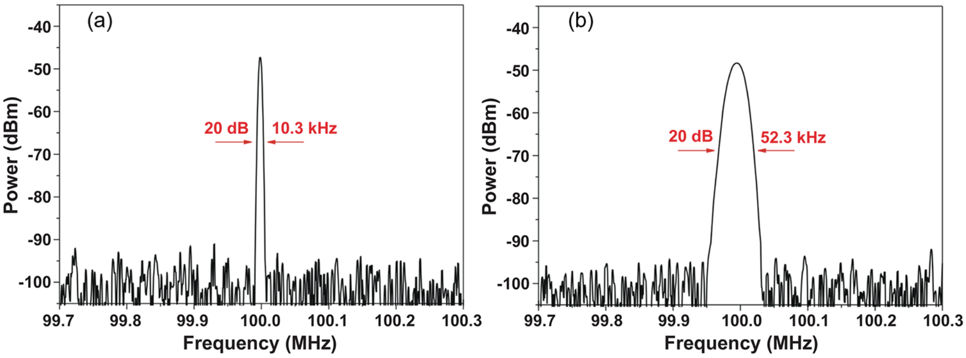


Fig. 6. Measured frequency spectra of the proposed laser using delayed self-heterodyne method (a) with self-injection locking and (b) without self-injection locking.

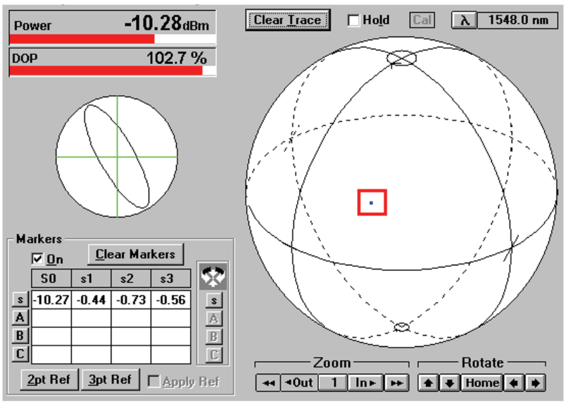
that, the polarization spacing of the DFB transmission optical spectrum which is induced by the birefringence of the LMA high concentration EDF is small; thus, we cannot distinguish them from the optical spectrum.

The method of the self-injection locking is used in the configuration of the proposed DFB fiber laser to obtain the single-polarization operation, as shown in Fig. 1. Fig. 5(b) shows the RF spectrum of the DFB fiber laser with self-injection locking at the scanning frequency range 15 GHz and 1 GHz. There is only one RF beating signals at 0 Hz, which indicate that the single-polarization light is realized through utilizing the method of the self-injection locking with PC, ISO, and polarizer. Through adjusting the PC, the method of the self-injection locking can ensure the DFB fiber laser operating at the X-polarization state or Y-polarization state.

The effective cavity length of the DFB fiber laser is estimated approximately 3.24 cm by [24], [26], which correspond to the free spectrum range (FSR) of about 3.17 GHz. The scanning frequency range of the ESA is 15 GHz, which is larger than the longitudinal mode spacing of the fiber laser (3.17 GHz) as show in Fig. 5(b). We find that there is only one beat frequency signal at 0 Hz, which indicates that the stable single-frequency operation of the DFB fiber laser is realized.

We use the delayed self-heterodyne method to measure the linewidth of the DFB fiber laser in this experiment with the self-injection locking and without the self-injection locking [27], as shown in Fig. 6(a) and (b). The delayed line of the delay self-heterodyne method is about 50 km in this experiment, corresponding to a nominal resolution of 4 kHz. The measured 20 dB linewidth of the DFB fiber laser with the self-injection locking and without the self-injection locking are approximately 10.3 kHz and 52.3 kHz, as shown in Fig. 6. Because the method of the self-injection locking can remove the influence of the self-pulsation to reduce the phase noise and wavelength shift, we can find that the method of the self-injection locking can effectively reduce the linewidth of the DFB fiber laser.

We also measure the polarization state of the DFB fiber laser with self-injection locking by the lightwave polarization analyzer (PA, HP 8509B). Through a segment of 0.5 m commercial SMF, we connect the output port of the DFB fiber laser with PA. In order to reduce the change of the polarization states, we ensure that the SMF which connects the output of the laser to PA is straight but not curved and twisty. The measured results of the DFB fiber laser polarization parameters accumulated in 2 min without external disturbance are shown in Fig. 7. There is almost one point at the Poincare sphere, which further indicates that the output of the DFB fiber laser with self-injection locking is at a stable single-polarization state. Owing to the measurement analysis of the equipment inducing the deviation, the apparent degree of polarization (DOP) in percentage term is as high as 102.7% (note that the DOP should be less than 100%). The results of the ESA and PA show that a stable single-polarization operation of DFB fiber laser could be successfully achieved by the method of the self-injection locking.



Power -10.28dBm

DOP 102.7 %

1548.0 nm

Markers

☑ On

	S0	s1	s2	s3
s	-10.27	-0.44	-0.73	-0.56
A				
B				
C				

Current point stocks parameters

Average optical power	S0	-10.27
Normalized stocks parameters	s1	-0.44
	s2	-0.73
	s3	-0.56

Fig. 7. Measured polarization parameters of the DFB fiber laser with self-injection locking. Table listing the data of the polarization parameters.

4. Conclusion

In conclusion, we have proposed a single-polarization single-frequency narrow linewidth DFB fiber laser based on the tapered FBG written in a LMA high concentration EDF by self-injection locking. The homemade LMA high concentration EDF was fabricated by the MCVD technique. The tapered FBG same as the equivalent PS-FBG is written in the homemade EDF and forms the DFB laser cavity. The self-injection locking is employed to make the proposed DFB fiber laser operate in single-polarization state and reduce the linewidth of the DFB fiber laser. The threshold of the DFB laser is about 145 mW, and the measured maximum output power is 43.55 mW at 450 mW pump power corresponding to the slope efficiency of 14.27%. The modified slope efficiency is 15.82% after including the insertion loss of the mode field mismatch, and the OSNR of the operating laser at 160 mW input pump power is more than 55 dB. The stable single-polarization single-frequency laser operation is achieved, and the measured 20 dB linewidth of the DFB laser with the self-injection locking and without the self-injection locking are approximately 10.3 kHz and 52.3 kHz.

References

[1] J. T. Kringlebotn, J. L. Archambault, L. Reekie, and D. N. Payne, “Er3+:Yb3+-codoped fiber distributed-feedback laser,” *Opt. Lett.*, vol. 19, no. 24, pp. 2101–2103, Dec. 1994.
[2] Y. Zhang, B.-O. Guan, and H.-Y. Tam, “Ultra-short distributed Bragg reflector fiber laser for sensing applications,” *Opt. Exp.*, vol. 17, no. 12, pp. 10 050–10 055, Jun. 2009.
[3] H. Qi *et al.*, “Apodized distributed feedback fiber laser with asymmetrical outputs for multiplexed sensing applications,” *Opt. Exp.*, vol. 21, no. 9, pp. 11 309–11 314, May 2013.
[4] P. Zhou *et al.*, “Coherent beam combining of two fiber amplifiers using stochastic parallel gradient descent algorithm,” *Opt. Laser Technol.*, vol. 41, no. 7, pp. 853–856, Oct. 2009.
[5] S. K. Turitsyn *et al.*, “Random distributed feedback fibre lasers,” *Phys. Rep.*, vol. 542, no. 2, pp. 133–193, Sep. 2014.
[6] H. Qi *et al.*, “Single-polarization distributed feedback fiber laser with multiple phase shifts,” *Chin. Opt. Lett.*, vol. 12, no. s2, Sep. 2014, Art. ID. S21403.
[7] A. Iadicicco, A. Cusano, S. Campopiano, A. Cutolo, and M. Giordano, “Microstructured fiber Bragg gratings: Analysis and fabrication,” *Electron. Lett.*, vol. 41, pp. 466–468, May 2005.
[8] D. Paladino, A. Iadicicco, S. Campopiano, and A. Cusano, “Not-lithographic fabrication of micro-structured fiber Bragg gratings evanescent wave sensors,” *Opt. Exp.*, vol. 17, no. 2, pp. 1042–1054, Jan. 2009.

[9] A. Cusano *et al.*, “Micro-structured fiber Bragg gratings. Part I: Spectral characteristics,” *Opt. Fiber Technol.*, vol. 13, no. 4, pp. 281–290, Oct. 2007.

[10] A. Cusano, A. Iadicicco, D. Paladino, S. Campopiano, and A. Cutolo, “Photonic band-gap engineering in UV fiber gratings by the arc discharge technique,” *Opt. Exp.*, vol. 16, no. 20, pp. 15 332–15 342, Sep. 2008.

[11] Y. Bin *et al.*, “Switchable single-polarization dual-wavelength ring laser based on structured PM-CFBG,” *IEEE Photon. Technol. Lett.*, vol. 26, no. 12, pp. 1227–1230, Jun. 2014.

[12] Y. Bin *et al.*, “Temperature-independent and strain-independent twist sensor based on structured PM-CFBG,” *IEEE Photon. Technol. Lett.*, vol. 26, no. 15, pp. 1565–1568, Aug. 2014.

[13] B. Yin, S. Feng, Z. Liu, Y. Bai, and S. Jian, “Tunable and switchable dual-wavelength single polarization narrow linewidth SLM erbium-doped fiber laser based on a PM-CMFBG filter,” *Opt. Exp.*, vol. 22, no. 19, pp. 22 528–22 533, Sep. 2014.

[14] P. Shilong and Y. Jianping, “A wavelength-tunable single-longitudinal-mode fiber ring laser with a large sidemode suppression and improved stability,” *IEEE Photon. Technol. Lett.*, vol. 22, no. 6, pp. 413–415, Mar. 2010.

[15] C. Spiegelberg *et al.*, “Low-noise narrow-linewidth fiber laser at 1550 nm,” *J. Lightw. Technol.*, vol. 22, no. 1, pp. 57–62, Jan. 2004.

[16] Y. Zhao *et al.*, “Research on a novel composite structure Er3+-doped DBR fiber laser with a π-phase shifted FBG,” *Opt. Exp.*, vol. 21, no. 19, pp. 22 515–22 522, Sep. 2013.

[17] Q. Li *et al.*, “DFB laser based on single mode large effective area heavy concentration EDF,” *Opt. Exp.*, vol. 20, no. 21, pp. 23 684–23 689, Oct. 2012.

[18] B. Yin *et al.*, “Stable single-polarization single-longitudinal-mode linear cavity erbium-doped fiber laser based on structured chirped fiber Bragg grating,” *Appl. Opt.*, vol. 54, no. 1, pp. 6–11, Jan. 2015.

[19] B.-O. Guan, L. Jin, Y. Zhang, and H.-Y. Tam, “Polarimetric heterodyning fiber grating laser sensors,” *J. Lightw. Technol.*, vol. 30, no. 8, pp. 1097–1112, Apr. 2012.

[20] Z. E. Harutjunian, W. H. Loh, R. I. Laming, and D. N. Payne. “Single polarisation twisted distributed feedback fibre laser,” *Electron. Lett.*, vol. 32, no. 4, pp. 346–348, Feb. 1996.

[21] H. Storøy, B. Sahlgren, and R. Stubbe. “Single polarisation fibre DFB laser,” *Electron. Lett.* vol. 33, no. 1, pp. 56–58, Jan. 1997.

[22] S. Babin, D. Churkin, A. Ismagulov, S. Kablukov, and M. Nikulin, “Single frequency single polarization DFB fiber laser,” *Laser Phys. Lett.*, vol. 4, no. 6, pp. 428, Jun. 2007.

[23] S. Yamashita and G. J. Cowle, “Single-polarization operation of fiber distributed feedback (DFB) lasers by injection locking,” *J. Lightw. Technol.*, vol. 17, no. 3, pp. 509, Mar. 1999.

[24] K. Yelen, L. M. B. Hickey, and M. N. Zervas, “A new design approach for fiber DFB lasers with improved efficiency,” *IEEE J. Quantum Electron.*, vol. 40, no. 6, pp. 711–720, Jun. 2004.

[25] X. H. Li *et al.*, “A novel erbium/ytterbium co-doped distributed feedback fiber laser with single-polarization and unidirectional output,” *Laser Phys. Lett.*, vol. 7, no. 1, p. 55, Jan. 2010.

[26] Y. O. Barmenkov, D. Zalvidea, S. Torres-Peiró, J. L. Cruz, and M. V. Andrés, “Effective length of short Fabry–Perot cavity formed by uniform fiber Bragg gratings,” *Opt. Exp.*, vol. 14, no. 14, pp. 6394–6399, Jul. 2006.

[27] G. Yin, B. Saxena, and X. Bao, “Tunable Er-doped fiber ring laser with single longitudinal mode operation based on Rayleigh backscattering in single mode fiber,” *Opt. Exp.*, vol. 19, no. 27, pp. 25 981–25 989, Dec. 2011.