Short distributed feedback fiber laser with unidirectional output for sensing applications

Haifeng Qi (祁海峰)[1,2*], Zhiqiang Song (宋志强)[1], Gangding Peng (彭纲定)[1,2], Shujuan Li (李淑娟)[1], and Chang Wang (王 昌)[1]

[1]*Shandong Key Laboratory of Optical Fiber Sensing Technologies, Laser Institute of Shandong Academy of Sciences, Jinan 250014, China*

[2]*School of Electrical Engineering and Telecommunications, The University of New South Wales, NSW, 2052, Australia*

**Corresponding author: qihf@sdu.edu.cn*

Received October 15, 2012; accepted December 20, 2012; posted online March 28, 2013

A short distributed feedback fiber laser with a nearly unidirectional output is fabricated and tested. The short fiber laser is made of a polarization-dependent phase-shift grating fabricated with a vertically polarized 244-nm ultraviolet (UV) laser. A single π phase-shift is introduced to a 2-cm grating at a specified position by directly moving the phase mask during UV beam scanning. Test results show that the laser has a single polarization longitudinal mode with 2.6-mW pump threshold. The backward-to-forward output power ratio is approximately 30:1. The relative intensity noise is –88 dB/Hz, and the linewidth is approximately 10 kHz at 75-mW 980-nm pumping. The unidirectional output and short dimension of this short fiber laser make it very useful in sensing applications, especially in multiplexed sensing applications.

OCIS codes: 140.3510, 140.3490, 060.2370.
doi: 10.3788/COL201311.041407.

Distributed feedback fiber lasers (DFB-FLs) show great potential in acoustic and seismic sensing because of their excellent properties, including single-frequency operation, mode-hop free, low noise, narrow linewidth, and small dimension[1−6]. Many fabrications and applications of DFB-FLs have been reported[1−8]. Most DFB-FLs are longer than 3 cm. Few examples have been reported for short DFB-FLs (especially Er-doped DFB-FL) smaller than 2 cm in length.

Some papers on ultra-short distributed Bragg reflector fiber laser (DBR-FL) have been recently presented[9,10]. Compared with DBR-FLs, short DFB-FLs have more robust single-mode operation. Using short DFB-FLs for hydroacoustic and seismic sensing means smaller dimension of the packaged sensors, lower pump consumptions, higher spatial resolution, and higher responsive frequency. Furthermore, the unidirectional output of DFB-FLs improves the utilization efficiency of lasers and reduces interference from the other output port to the adjacent sensing elements when used in a multiplexed array.

In this letter, we present the experimental results including the fabrication and characteristics of a 2-cm-long single phase-shift DFB-FL with a unidirectional output suitable for extensive application in acoustic and seismic sensing multiplexed arrays.

A 2-cm-long phase-shift grating ($L_g = 2$ cm) was written in a 4-cm-long photosensitive Er-doped fiber (Nufern, peak absorption at 1 530 nm is 8 dB/m) that was spliced to the passive matching pigtail fiber (Nufern 980 Hp) at both ends. The grating was written by scanning a 244-nm frequency doubled harmonic continuous-wave (CW) Ar-ion laser across the phase mask and fiber. The induced index modulation could be obtained and controlled with an accurate scanning speed. A polarization-dependent grating was generated by a vertically polarized ultraviolet (UV) scanning laser[11]. In the fabrication process, the phase shift was introduced by a simple relative movement of the phase mask to the fiber during beam scanning[12]. The movement of the phase mask to achieve an accurate π phase-shift is a quarter of the period of the phase mask mounted on a piezoelectric actuator (PI, P-752.11c) with nanometer resolution. Different from the procedure used to obtain phase-shifted grating in the shield method[5] and post-processing method[6], the generated phase shift in this technique is only dependent on the relative displacement of the phase mask without relation to the UV-induced index change. The schematic diagram for this phase shift grating is shown in Fig. 1.

Based on the three-level rate equation of Er ion and the transfer matrix analysis approach[7], we simulated the pump-output characteristics of the 2-cm-long DFB-FL. We obtained an optimized index modulation amplitude of approximately 2×10^{-4} and used a phase shift position of $0.4L_g$ to obtain the optimized high output and backward-to-forward laser power ratio (Fig. 2). The simulation results indicate an index modulation amplitude of $\Delta n_{ac} \sim 2 \times 10^{-4}$ to obtain the highest output power of the DFB-FL for symmetrical phase-shifted DFB-FL. The simulation of the influence of phase shift position indicates that a phase shift position at approximately

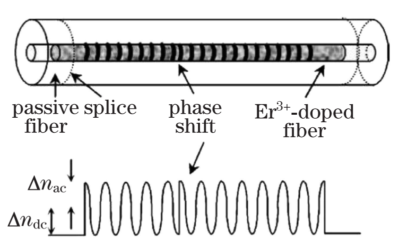

Fig. 1. DFB-FL grating structure with a single π phase shift located in $0.4L_g$.

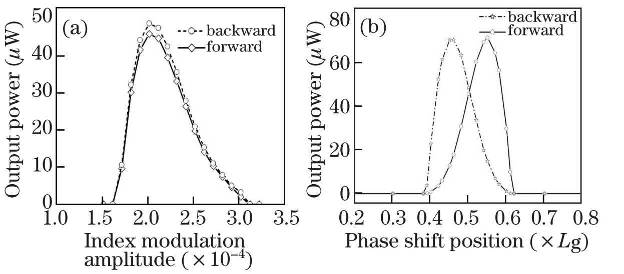

Fig. 2. Theoretical simulation of the output characteristics. (a) $0.5L_g$ phase shift position and 100-mW pump; (b) 2.0×10^{-4} index modulation and 100-mW pump.

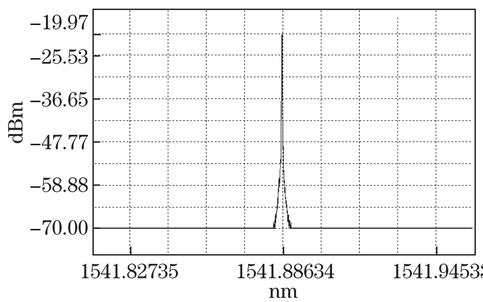

Fig. 3. Backward output spectrum of the DFB-FL.

$0.45L_g$ is needed to obtain the highest backward output. However, the unidirectional degree is not sufficient if the phase-shift is at $0.45L_g$, where the backward-to-forward output ratio is approximately 10:1. To achieve an even higher ratio, we fabricated a 2-cm DFB-FL with a single π phase-shift located at $0.4L_g$. To obtain the accurate index modulation amplitude, we first tested the photosensitivity of the used Er-doped fiber by writing several 1-cm-long uniform fiber Bragg gratings at different scanning speeds and fitting these measured data with a nonlinear equation. Based on the experimental data and the fitted curve, we correspondingly changed the beam scanning speed to obtain an accurate index modulation.

The output power, laser spectrum, relative intensity noise, and linewidth of the fabricated DFB-FL were systematically tested. For the 980-nm pump, the power pumped into the pigtail fiber of the DFB-FL is only increased from 0 to 75 mW. The backward laser spectrum as shown in Fig. 3, was measured with a high-resolution spectrometer (Apex2040a, wavelength resolution of 0.16 pm). The signal-to-noise ratio (SNR) is over 50 dB, running in a single polarization mode without orthogonal polarization modes and multiple longitudinal modes. The pump-output curve (Fig. 4(a)) shows that the threshold is approximately 2.6 mW and that the slope efficiency for backward output is approximately 0.04%, which is slightly higher than the simulation result. The backward-to-forward output ratio is approximately 30:1 at over 40-mW pumping.

The relative intensity noise (RIN) was measured at different pump powers (Fig. 4(b)). The RIN peak at relaxation oscillation frequency decreases with increasing pump power, whereas the relaxation oscillation frequency increases. Thus, RIN is lower than –90 dB/Hz when pumped at 100 mW.

The linewidth of the DFB-FL was measured using the self-homodyne method with a 25-km delay interferometer.

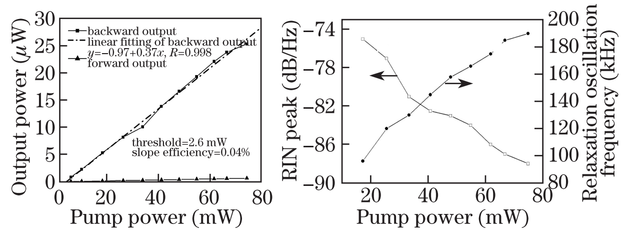

Fig. 4. (a) Output power and (b) relative intensity noise of the DFB-FL with pump power dependence.

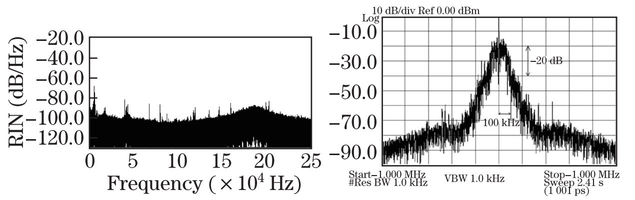

Fig. 5. (a) RIN and (b) linewidth of the DFB-FL at 75-mW pumping.

The frequency spectrum analysis (Fig. 5(b)) shows that the linewidth of the DFB-FL is approximately 10 kHz at 75-mW pumping, which can yield a coherence length of over 20 km.

In conclusion, the fabrication and characteristics of a 2-cm unidirectional DFB-FL on an Er-doped fiber were systematically reported. After simulating and optimizing the 0.04% slope efficiency and a nearly unidirectional output with a backward-to-forward output ratio of approximately 30:1 are experimentally obtained. A single polarized longitudinal mode operation is observed for the fabricated polarization-dependent phase-shift grating. The values of RIN and linewidth are –88 dB/Hz and approximately 10 kHz at 75-mW pumping, respectively. The short dimension, unidirectional output, and narrow linewidth of this DFB-FL make it very useful in multiplexed sensing arrays.

This work was supported by the Research Award Fund for Outstanding Middle-aged and Young Scientists of Shandong Province, China (No. BS2010DX030) and the International Science and Technology Cooperation Program of China (No. 2012DFA10730).

References

1. W. H. Loh and L. R. Iaming, Electron. Lett. **31,** 1440 (1995).
2. M. Sejka, P. Varming, J. Hubner, and M. Kristensen, Electron. Lett. **31,** 1445 (1995).
3. E. Ronnekleiv, S. W. Lovseth, and J. T. Kringlebotn, Proc. SPIE **4943,** 69 (2003).
4. S. Foster, A. Tikhomirov, M. Milnes, J. Velzen, and G. Hardy, Proc. SPIE **5855,** 627 (2005).
5. L. Wang, B. Chen, J. L. Chen, G. Y. Li, L. P. Chang, A. Sun, and Z. Q. Lin, Chin. Phys. Lett. **24,** 721 (2007).
6. J. Chen, L. Liang, B. Chen, W. Fan, Q. Qiao, S. Xue, and Z. Lin, Chinese J. Lasers (in Chinese) **30,** 581 (2003).
7. V. C. Lauridsen, J. H. Povlsen, and P. Varming, Electron. Lett. **34,** 2028 (1998).
8. G. A. Cranch, G. M. H. Flockhart, and C. K. Kirkendal, IEEE Sens. J. **8,** 1161 (2008).

9. Y. Zhang, B. Q. Guan, and H. Y. Tam, Opt. Express **17,** 10050 (2009).
10. A. C. Wong, D. Chen, H. J. Wang, W. H. Chung, H. Y. Tam, C. Lu, and B. Q. Guan, Meas. Sci. Technol. **22,** 045202 (2011).
11. M. Ibsen, E. Ronnekleiv, G. J. Cowle, M. O. Berendt, O. Hadeler, M. N. Zervas, and R. I. Lambing, in P*roceedings of Conference of Lasers and Electro-Optics* 245 (1999).
12. L. Poladian, B. Ashton, W. E. Padden, A. Michie, and C. Marra, Opt. Fiber Technol. **9,** 173 (2003).