Ultra-short distributed Bragg reflector fiber laser for sensing applications

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Abstract: We present an ultra-short distributed Bragg reflector fiber laser written in Er/Yb co-doped fiber. The entire laser is only 8.4 mm in length. The lasing threshold is less than 1 mW. The optical signal-to-noise ratio of the laser output is better than 70 dB. The laser emits two orthogonal polarization modes and generates a beat signal with signal-to-noise ratio of ~70 dB and 3-dB linewidth of ~3 kHz. The laser has longitude mode spacing comparable to the grating bandwidth. This obviates the possibility of mode hopping when the laser is subjected to any external perturbations.

OCIS codes: (060.2370) Fiber optics sensors; (060.3510) Lasers, fiber; (060.3735) Fiber Bragg gratings; (140.3570) Lasers, single-mode

References and links

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1. Introduction

Fiber laser sensors have been attracting interest over the past few years because of their high signal-to-noise ratio and narrow linewidth that permit high resolution sensing. According to the working principle, fiber laser sensors can be classified into two types: wavelength encoding sensor and polarimetric sensor. The former converts measurands into operation wavelength shift of the fiber laser [1–3], which is similar to that of fiber grating sensor. The latter converts measurands into change in beat frequency between the two orthogonal polarization modes from the laser [4–9]. To achieve high resolution, the fiber laser needs to

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operate in single longitude mode. Various single longitude mode laser configurations for sensing applications have been demonstrated, including those use intracavity saturable absorber [5] or fiber grating etalon [9] as mode filter, distributed feedback (DFB) structures [1–3], and distributed Bragg reflector (DBR) structures [7,8]. Configurations using intracavity absorber or fiber grating etalon are too complicated in structure, making them difficult to multiplex and unsuitable for applications requiring small size sensors. DFB fiber laser consists of a single fiber Bragg grating written in active fiber with a phase shift incorporated into the grating structure. DBR fiber laser consists of two wavelength-matched fiber Bragg gratings at both ends of a short section of active fiber. These two structures have been widely investigated as active fiber sensors. Advantages of DFB fiber laser are that it offers robust single mode operation and high resilience to environmental perturbations. However, DFB fiber laser is typical ~5 cm in length, which is too long for applications requiring point sensors. DBR fiber laser can be made shorter. To date, 2-3 cm long DBR fiber lasers have been achieved [7,10]. The length is still too long for applications requiring high spatial resolution sensors. Furthermore, the long cavity length results in longitude mode spacing much smaller than the grating reflection bandwidth, so the laser is susceptible to mode hopping if it is subjected to external perturbations such as temperature or strain gradients. This significantly limits the practical applications of DBR fiber laser.

In this paper, we demonstrate an ultra-short DBR fiber laser with total cavity length, including two fiber Bragg gratings, of only 8.4 mm. To the best of our knowledge, this is the shortest fiber laser ever reported. The laser has longitude mode spacing comparable to the grating bandwidth, so the cavity supports only one longitude mode within the grating bandwidth. This obviates the possibility of mode hopping when the laser is subjected to any external perturbations. The laser emits two orthogonal polarization modes and generates a beat signal with signal-to-noise ratio of ~70 dB and 3-dB linewidth of ~3 kHz. The laser is ideal for point sensing applications.

2. DBR fiber laser inscription

The active fiber used in the experiments was Er/Yb co-doped fiber. The fiber has a B-Ge-Si annulus with a diameter of 16 µm around the 4-µm diameter Er-Yb phosphosilicate core. Typical absorption of the fiber at 980 nm is 2-3 dB/cm. The DBR laser was fabricated by directly photowriting two wavelength-matched Bragg gratings into the active fiber. Compared to the scheme that splices two fiber Bragg gratings to a short length of active fiber [11], directly photowriting Bragg gratings in the active fiber can provide much lower threshold because it avoids intercavity splice loss. The experimental setup is shown in Fig. 1. The UV source is 193 nm excimer laser. We have written DBR lasers in the same fiber at 248 nm but hydrogen-loading is necessary and the hydrogen-induced loss requires longer fiber length of ~3 cm to provide sufficient optical gain for lasing to occur. Since the 193 nm laser induces index change by two-photon excitation process, it dose not require hydrogen loading to photosensitize the fiber. This not only simplifies the laser fabrication but also avoids the laser efficiency degradation resulting from hydrogen-induced loss at pump wavelength and excited-state lifetime reduction of Er^{3+} ions. The beam scanning technique was used, in which the phase mask and the fiber were fixed, while the laser beam was scanned along the fiber. The two gratings were written with the same beam scanning speed so that they have the same ac and dc index change, and therefore the same center wavelength.

We first wrote the high reflectivity (HR) grating. The grating transmission spectrum was monitored with a broadband source (BBS) and an optical spectrum analyzer (OSA). Figure 2 shows the growth of the grating during UV inscription. The energy and repetition rate of the 193 nm excimer laser were set to 2.5 mJ and 100 Hz, respectively. A 4.6-mm long HR grating with reflectivity around 40 dB was easily fabricated with our inscription system.

We then wrote the low reflectivity (LR) grating using the same beam scanning speed and the same laser settings. During the inscription of the LR grating, the BBS was turned off and a

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980 nm pump laser was turned on, so that the laser output could be monitored. Figure 3 shows the output power of the laser as a function of the length of the LR grating. When the grating length reaches to ~2.0 mm, the gain can compensate the cavity loss, and the laser starts to oscillate. From the grating growth shown in Fig. 2, the threshold reflectivity for lasing oscillation is estimated to be ~17 dB. We stopped the grating inscription after the laser output power slightly exceeded the maximal value. The length of the LR grating was 2.8 mm. The reflectivity of the LR grating is estimated to be ~25 dB.

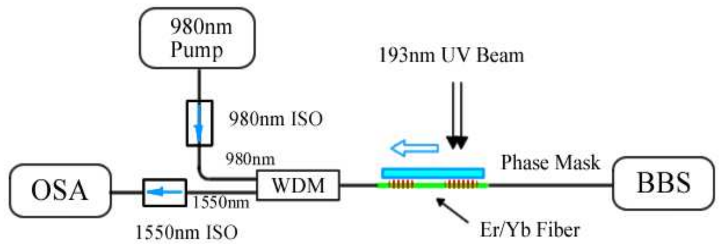

Fig. 1. Experimental setup for DBR fiber laser inscription.

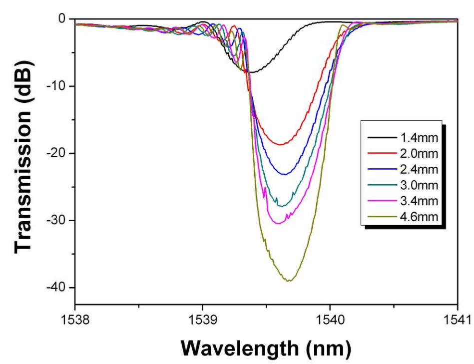

Fig. 2. Transmission spectra of the grating at different lengths.

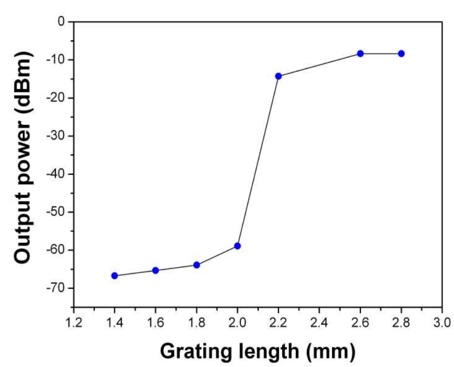

Fig. 3. Peak power of the laser versus length of the LR grating.

3. Results and discussion

Figure 4 shows the photograph of the DBR fiber laser. The green section is the Er/Yb co-doped fiber, which emits green upconversion fluorescence. Two gratings with length of 4.6 mm and 2.8 mm are written inside the doped fiber. The grating spacing is 1 mm. The entire laser is therefore only 8.4 mm in length.

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Figure 5 shows a typical output spectrum of the ultra-short fiber laser measured with an OSA. The laser output centered around 1539.6 nm with signal-to-noise ratio of better than 70dB. The laser emits two orthogonal polarization modes. When the laser output is monitored with a high speed photodetector, a beat signal will be generated by the two polarization modes from the laser. Figure 6 shows a typical beat signal spectrum measured with a radio frequency (RF) spectrum analyzer. The beat signal centered around 1.707 GHz with signal-to-noise ratio of ~70 dB. The inset in Fig. 6 shows the enlarged view of the beat spectrum. The 3-dB bandwidth of the beat signal is ~3 kHz.

Figure 7 shows the laser output power as a function of pump power. The laser output power was measured with an optical power meter. As can be seen in Fig. 7, the lasing threshold is less than 1 mW. The slope efficiency is ~0.86%. For sensing applications, laser output power is not a key factor. Tens of μw output power is sufficient to achieve high performance measurement due to the high signal-to-noise ratio. The low threshold will greatly benefit sensor multiplexing since a few mW of remaining power at the final sensor is sufficient to pump the laser. This means that a 980 nm laser with moderate output power can pump an array of fiber lasers.

Fig. 4. The photograph of the DBR fiber laser.

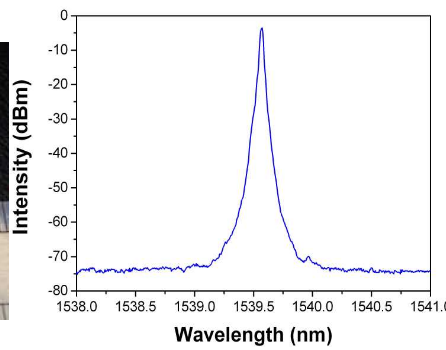

Fig. 5. Output spectrum of the DBR fiber laser.

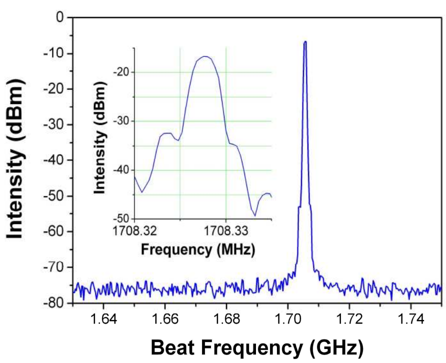

Fig. 6. Beat signal spectrum of the fiber laser.

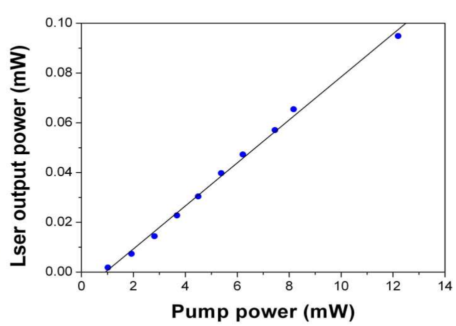

Fig. 7. Laser output power versus pump power.

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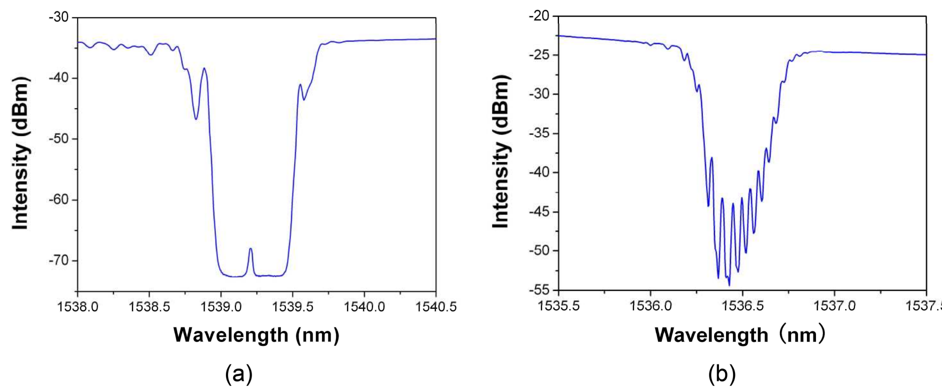

Fig. 8. Transmission spectra of two Fabry-Perot cavities with the grating end-to-end spacing of (a) L_0 = 1mm, and (b) L_0 = 9 mm.

Mode hopping is a key problem that limits practical applications of DBR fiber lasers. Typical DBR fiber lasers are a few cm long, leading to longitude mode spacing much smaller than the grating bandwidth. As a result, there are multiple modes that satisfy conditions for lasing oscillation. The dominant mode oscillates and other modes are suppressed, so the lasers can operate in single longitude mode. However, the lasers are susceptible to mode hopping if they are subjected to external perturbations.

The grating bandwidth is typically 0.2–0.5 nm, depending on reflectivity and length of the grating. The numbers of mode supported by the cavity is mainly determined by the mode spacing. The mode spacing is given by

$$\Delta\lambda = \frac{\lambda^2}{2n_{eff}L_{eff}} \tag{1}$$

where λ is the lasing wavelength, n_{eff} is the effective index of fiber core, L_{eff} is effective length of the laser cavity which is given by [12]

$$L_{eff} = L_0 + l_{eff1} + l_{eff2} \tag{2}$$

where L_0 is end-to-end spacing between the two gratings, $l_{eff1,2}$ are the effective lengths of the two gratings which are given by

$$l_{eff} = l_g \frac{\sqrt{R}}{2\text{atanh}\left(\sqrt{R}\right)} \tag{3}$$

where l_g and R are the length and reflectivity of the grating, respectively. For the above ultra-short DBR fiber laser, the mode spacing is calculated to be $\Delta\lambda$ = ~0.4 nm, which is comparable to the grating bandwidth shown in Fig. 2. This means that the cavity supports only one longitude mode.

This is confirmed by Fig. 8, which shows the measured transmission spectrum of the ultra-short fiber laser (L_0 = 1.0 mm). For comparison, the transmission spectrum of another DBR fiber laser with L_0 = 9.0 mm is also shown in Fig. 8. The spectra were measured using the OSA with resolution setting to 0.02 nm. The grating bandwidth for the ultra-shout cavity is larger than that of the 9.0 mm cavity because the grating length in the ultra-short cavity is much shorter than that in the 9.0 mm cavity. It is clear from Fig. 8 that, the ultra-short cavity supports only one mode, whereas the 9.0 mm cavity supports at least 6 modes. The Fabry-Perot fringe pattern and Bragg wavelength of the grating exhibit almost the same sensitivity to temperature or strain, therefore a DBR fiber laser with cavity length supporting multiple

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modes may be free of mode hopping under strong uniform perturbations. However, small uneven perturbation or localized perturbation to the subsection of laser cavity can result in mode hopping due to the grating spectrum distortion. This has been previously demonstrated in [10], where a DBR fiber laser with two grating lengths of 11 mm and 9 mm, and grating spacing of $L_0 = 5.0$ mm, was free of mode hopping at a large temperature variation from room temperature to 500 °C, however, it mode-hopped to the adjacent lower wavelength mode due to the localized UV heating during the grating inscription.

For the ultra-short DBR fiber laser, there is only one mode within the grating reflection bandwidth. This ensures a robust single mode operation and obviates the possibility of mode hopping when the laser is subjected to any external perturbations.

4. Conclusion

An ultra-short DBR fiber laser was fabricated by directly inscribing two wavelength-matched gratings in an Er/Yb co-doped fiber. The total length of the fiber laser, including two Bragg gratings, is only 8.4 mm. The lasing threshold is less than 1 mW. The optical signal-to-noise ratio of the laser output is better than 70 dB. The laser emits two orthogonal polarization modes and generates a beat signal with signal-to-noise ratio of ~70 dB and 3-dB linewidth of ~3 kHz. The laser has longitude mode spacing of ~0.4 nm, which is comparable to the grating bandwidth. This obviates the possibility of mode hopping when the laser is subjected to any external perturbations. The laser is desirable for applications requiring high resolution and small size sensors.

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