Stable single frequency Er-doped all-fiber ring laser with fiber Bragg grating Fabry-Perot filter

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Received August 30, 2004

Using a fiber Bragg grating (FBG) and a Fabry-Perot cavity composed of two fiber Bragg gratings (FBGFP) as its frequency-selective components, a type of single frequency all-fiber ring laser permits oscillation only on one longitudinal mode of the main cavity without modehopping while the cavity length can be up to tens of meters. The salient feature is due to the single narrowband resonance of the FBGFP filter. Such a fiber ring laser is achieved experimentally, and the laser mode is limited inside the single resonance of the FBGFP.

OCIS codes: 140.3510, 140.3560, 060.2340.

Continuous-wave (CW) fiber lasers employing rare-earth-doped fibers have been studied as a potential source in the telecommunications and high-resolution spectroscopy communities due to their narrow line-width, low intensity noise, high output power, and direct fiber compatibility. In these applications, the oscillating frequency must be well defined. This can only be achieved when the longitudinal mode hops are inhibited. One approach is to use a short cavity with narrowband reflectors such as fiber gratings, so that there are a few longitudinal modes with frequencies within the active ion gain profile[1,2]. However, the output power is limited by the short cavity length. Another method is to use a long cavity and additional elements to reduce the number of longitudinal modes. In these fiber lasers, a tunable band-pass (TBP) filters with full-width at half-maximum (FWHM) of about 1 nm and a fiber Fabry-Perot etalon with a narrow bandwidth (NBFFP)[3] or compound ring structure as an effective NBFFP[4,5] are often used to restrict possible laser modes. Because the NBFFP has a relatively small free spectral range (FSR), there is more than one NBFFP resonance inside the bandwidth of the TBP filter. Therefore mode hops between the adjacent resonances of NBFFP easily occur. This letter presents a type of all-fiber ring laser using a fiber Bragg grating (FBG) and a Fabry-Perot cavity composed of two fiber Bragg gratings (FBGFP) as its frequency-selective components. The structure permits single longitudinal mode operation even in a long cavity.

The structure of the fiber ring laser is shown in Fig. 1. C1 and C2 are optical fiber couplers, EDF is Er-doped fiber, OI is optical isolator. FBG1, FBG2, and FBG3 are fiber Bragg gratings with the same Bragg wavelength. FBG3 reflects the light back to the ring cavity and forms a positive feedback. A shot Fabry-Perot cavity is composed of FBG1 and FBG2. When the FBGFP cavity length satisfies[6,7]

$$L = \left(m - \frac{1}{2}\right)\left(1 + \frac{\overline{\delta n_{\mathrm{eff}}}}{n_{\mathrm{eff}}}\right)\Lambda, \tag{1}$$

where m is a round figure and $m \leq \frac{n_{\mathrm{eff}}}{\nu \overline{\delta n_{\mathrm{eff}}}}$, ν is the fringe visibility of the index change, Λ is the period of the FBG, n_{eff} is the effective refractive index, and $\overline{\delta n_{\mathrm{eff}}}$ is the 'dc' index change spatially averaged over a grating period, this etalon has a single resonance at the Bragg wavelength inside the bandwidth of the FBG. Then the resonance can be selected out by FBG3. The spectrum is shown in Fig. 2. By using the phase mask method, the FBGs were fabricated with a photosensitive fiber (PS-RMS-50 from StockerYale). The CW UV source with output wavelength at 244 nm was a frequency-doubled argon ion laser (Innova 300C FreD by Coherent). The FWHM of the resonance was about 2.5 pm, measured by a lightwave measurement system (Aglient8614A) with resolution of 1 pm.

The salient feature of the FBGFP filter is that it can have only one frequency resonance inside the bandwidth of its FBGs. Utilizing this kind of filter as an intra-cavity frequency-selective component in a fiber ring laser, only one particular longitudinal mode can be selected out without modehopping. Figure 3 illustrates the mode selection mechanism. In a normally fiber ring laser, a TBP

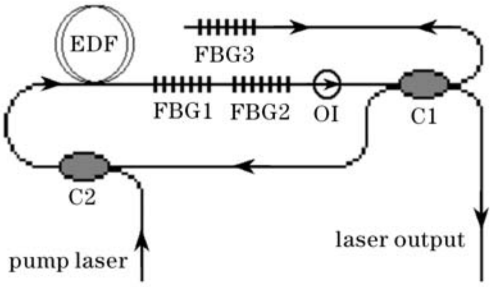

Fig. 1. Configuration of a single frequency EDF ring laser with FBGFP.

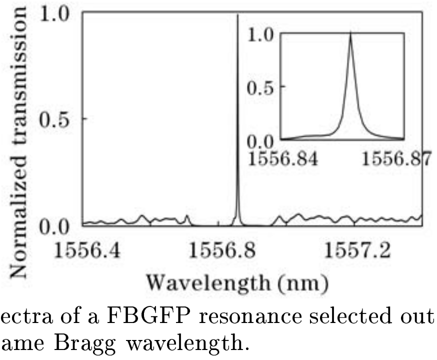

Fig. 2. Spectra of a FBGFP resonance selected out by a FBG with the same Bragg wavelength.

1671-7694/2005/040212-03 http://www.col.org.cn

filter with FWHM of about 100 GHz was used to provide a first restriction on the possible main cavity laser modes (see Fig. 3(a)). Then, with the addition of an intra-cavity NBFFP, which characterized a relatively small FWHM (about 100 MHz) and FSR (about 2 GHz) compared with the FWHM of the TBP, the possible lasing modes were limited inside the NBFFP resonances (see Fig. 3(b)). The vernier-type mismatch of the main cavity modes with the NBFFP resonator enhanced the effective TBP discrimination and made it possible for one mode to oscillate. However, the modehopping between the NBFFP resonances easily occurred due to the small FSR. In our case (see Fig. 3(c)), a FBG with FWHM of about 25 GHz provided a preliminary restriction on the main cavity modes. A FBGFP filter then made a further restriction and limited the possible cavity modes inside its single resonance. The FWHM of the FBGFP resonance in our experiment was about 310 MHz. When the spacing of the main cavity modes was larger than the FWHM of the FBGFP resonance, i.e., when the overall cavity length was less than 6 m in our case, there definitely would be only one cavity mode which could oscillate.

The FBGFP filter was completely compatible with the fiber ring laser. The insert of the filter did not add parasitic loss to the ring cavity. An optical isolator (OI) was introduced to form a unidirectional ring cavity because the FBGFP reflects light outside its resonance, which led to an unstable operation through generation of spurious modes. The unidirectional ring cavity was a traveling wave cavity, which was more suitable for a single longitudinal mode operation because of the lack of a spatial hole-burning effect.

In our experiment, overall cavity length of the fiber ring laser was about 20 m, which corresponded to the longitudinal mode spacing of 10 MHz. The estimated erbium concentration was 8.55×10^{24} m^{-3}. Its numerical aperture was 0.223. The pump light wavelength was 980 nm. The output spectrum of the fiber ring laser using FBGFP is shown in Fig. 4, measured by an optical spectrum analyzer (Aglient86142B) with best resolution of 0.06 nm. The pump power was 100 mW, and the output power was 3.16 mW. The signal to noise ratio was around 50 dB. The slope efficiency was 3.16%, which could be improved when the output coupler C1 was replaced by a circulator.

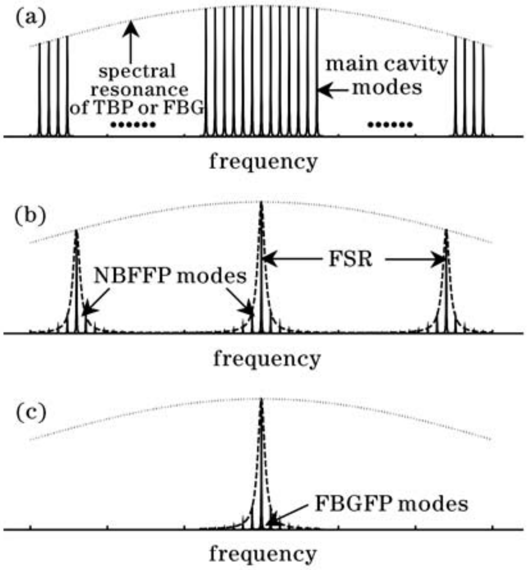

Fig. 3. Illustration of mode selection in a fiber ring laser. (a) Preliminary restriction on main cavity modes by a tunable bandpass filter or a FBG, (b) possible lasing modes by using NBFFP, (c) single longitudinal mode lasing by using FBGFP.

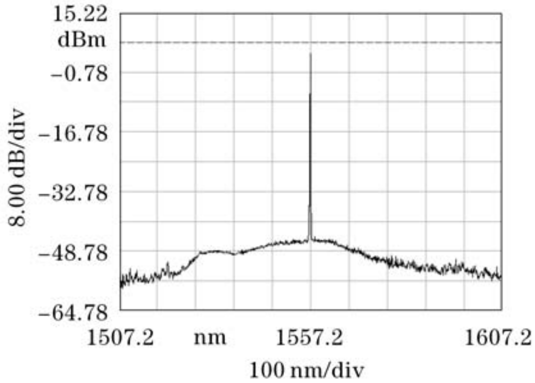

Fig. 4. The laser output spectrum measured by an optical spectrum analyzer.

In order to measure the laser output line-width with better resolution, another FBGFP filter with FWHM of 310 MHz and another OI were used. The OI was placed between the laser output and the measuring filter. By tuning the measuring filter, the output line-width could be measured. Normally, the coupling wavelength of a FBG has linear relations with respect to both strain and temperature. When strain exists along the whole FBGFP, it induces the same spectral shift for both the FBG and the FBGFP. That is acceptable when the FBGFP cavity is very short. In our experiment, a FBG and a FBGFP were both fixed with each of their ends on a motor stage of PI 405-DG. The precision of the motor stage was 7 nm per count. The spacing of the two fixed ends of the FBG or FBGFP was about 175 mm. The tunability of a FBGFP and a FBG with respect to strain is shown in Fig. 5(a). The motor stage moved 1000 counts every step, which equaled to 40 μstrain. The measured strain coefficients of the FBG3 and FBGFP were 1.03 pm/μstrain and 1.05 pm/μstrain, respectively. The difference was mostly caused by the slightly different fixing spacing. Therefore, using this kind filter as frequency-selective element, the fiber ring laser can also have a continuously tunable output wavelength with the range determined by the FBGs.

Figure 5(b) shows the measured FWHM of the laser output, which was about 2.7 pm (335 MHz). The motor stage moved 10 counts every step, which equaled to 0.4 μstrain. No modehopping was observed at this measuring resolution. As can be estimated reasonably, modehopping should be suppressed in sub-nanometers (tens of megahertz), which means the cavity modes was completely limited inside the FBGFP resonance. Thus in the application where the laser output linewidth is needed to be no more than tens of megahertz, the laser cavity length can be discretionarily decided. When the laser cavity length was no more than 6 m, the laser would definitely oscillate in one specifically longitudinal mode without modehopping. When the FWHM of the FBGFG resonance was improved to tens of megahertz, for example, by increasing the reflectivity of the FBGs, the maximum cavity length for single longitudinal mode operation would reach tens of meters. Compared with the linewidth of 0.04 nm reported in Ref. [8], where a single FBG was used in the fiber ring laser, the structure with FBGFP could narrow the output linewidth of the laser.

The Bragg wavelength of FBG is sensitive to the environment, such as temperature and strain[9]. The shift of Bragg wavelength is usually compensated by strain. Many compensation structures are reported. By using the frequency or the power of the laser output as a feedback to control the compensation, the FBGs can be stabilized at the wavelength we needed. Furthermore, the temperature effect is a kind of a slow effect, which will not cause modehopping as the FBG is stabilized.

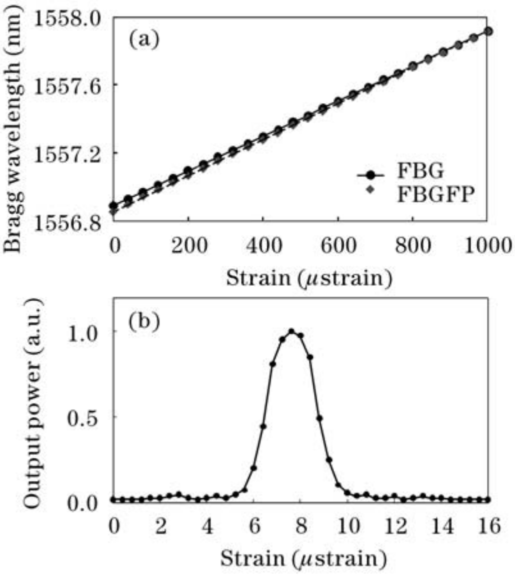

Fig. 5. (a) Tunabilities of a FBGFP and a FBG with respect to strain. (b) The output line-width of the fiber ring laser measured by another FBGFP filter.

This letter provides a type of single frequency all-fiber ring laser using a FBG and a FBGFP as its frequency-selective components. The FBGFP has only one resonance with a very small bandwidth. Thus this kind of fiber ring laser permits oscillation on only one longitudinal mode without modehopping while the cavity length can be up to tens of meters, which means great gain potential for single mode operation. Therefore, a continuously tunable laser with narrow line-width, stable single frequency, and high power can be achieved by this structure.

This work was supported by National Science Fund for Distinguished Young Scholars of China (Project 60125513) and the Jiangsu Province Natural Science Foundation of China (No. BK2004207). Y. Cui is the author to whom the correspondence should be addressed, his e-mail address is cyp@seu.edu.cn.

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