Single-Longitudinal-Mode Fiber Ring Laser Employing an Equivalent Phase-Shifted Fiber Bragg Grating

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***Abstract*—A novel single-longitudinal-mode (SLM) fiber ring laser that incorporates an equivalent phase-shifted fiber Bragg grating acting as an ultra-narrow bandpass filter in the laser cavity is proposed. The equivalent phase-shifted fiber Bragg grating has an ultra-narrow transmission bandwidth which ensures an SLM lasing. Stable SLM operation without mode hopping is demonstrated.**

***Index Terms*—Equivalent phase shift (EPS), fiber Bragg grating (FBG), fiber ring laser, single longitudinal mode (SLM).**

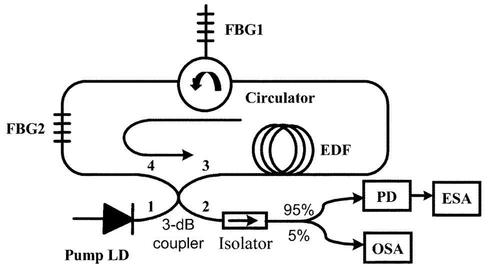

Fig. 1. Schematic diagram of the proposed fiber ring laser.

I. INTRODUCTION

STABLE continuous-wave single-longitudinal-mode (SLM) fiber lasers are of great interest for applications in fiber communications, fiber-optic sensors, optical spectroscopy, and microwave photonics systems. There are usually three types of fiber lasers: fiber ring lasers, distributed Bragg reflector (DBR) fiber lasers, and distributed feedback (DFB) fiber lasers. DBR and DFB fiber lasers can be high-quality laser sources for their SLM operation without mode hopping. However, the gain medium length of DBR and DFB fiber lasers is usually less than 10 cm. With low erbium concentration fiber, lasing is difficult to be established because of the low cavity gain. With high erbium concentration fiber (>30 dB/m at 1550 nm), self-pulsation will occur in the fiber laser due to the effect of erbium ion clustering [1]. A solution to this problem is to use erbium–ytterbium (Er–Yb) codoped fiber. However, specially designed Er–Yb codoped fibers with good photosensitivity are required in order to write fiber Bragg gratings (FBGs) in the fibers [2]. On the other hand, lasing is easy to be established for fiber lasers with a ring structure even by using a low erbium concentration fiber, in which the gain medium can be very long (typically longer than 10 m) to produce enough gain. However, the fiber ring lasers suffer from densely spaced multiple longitudinal modes, which severely limits their applications due to multimode oscillation, mode hopping, and relatively large linewidth. Although a number of methods have been proposed to solve the problem [3]–[7], these methods can hardly guarantee a long-term stability for lack of stable ultra-narrow bandwidth optical filter.

Recently, a technique to introduce equivalent phase shift (EPS) to FBGs has been proposed [8]. Precise phase shifts with different phase shift profiles can be realized by controlling the sampling period during the FBG fabrication. EPS FBGs can find many applications, such as optical code-division multiple-access (OCDMA) coding–decoding [8], and DFB fiber lasers [9]. Compared with the technique of true phase shift [10], the EPS can be controlled more precisely because it only requires a micrometer precision instead of nanometer precision during the FBG fabrication. Thus, an FBG with more precise phase shift leading to a much narrower transmission bandwidth is possible. In this letter, we propose a novel SLM fiber ring laser that incorporates an ultra-narrow bandwidth EPS FBG in the laser cavity. Stable SLM operation without mode hopping is realized. To the best of our knowledge, this is the first time that an SLM fiber ring laser is implemented using an EPS FBG with simple system configuration and excellent stability.

II. PRINCIPLE

There are multiple "ghost" gratings in a sampled FBG through Fourier analysis, which can be characterized by Fourier order m ($m = 0, \pm 1, \pm 2, \ldots$). If the sampling period is not constant, but chirped, an equivalent chirp can be introduced in the reflection peaks with $m \neq 0$ [11]. On the other hand, if only one sampling period is changed, while the other sampling periods are kept the same, an EPS will be introduced [8], [9]. FBGs with a π-EPS can have an ultra-narrow transmission bandwidth.

The configuration of the proposed fiber ring laser is shown in Fig. 1. A 980-nm pump laser diode is used to pump the 5-m Corning 1550 C Er-doped fiber (EDF) through a conventional 3-dB optical coupler. About 55% of the 980-nm pump power is

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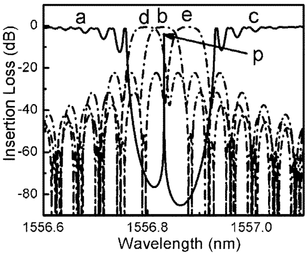

Fig. 2. Schematic diagram of the transmission spectrum of the EPS FBG (FBG2) (solid line) and the reflection spectrum of the uniform FBG (FBG1) (dotted–dashed line). The central wavelength of FBG1 can be tuned to different locations by applying strain.

sent to the ring cavity via Port 3 to pump the EDF, 16% of the pump power is directed to the isolator through Port 2, and 29% of the power is lost in the coupler. In the proposed configuration, the 16% pump power to the isolator can be used by adding a length of EDF to amplify the lasing output. In this situation, the residual pump power to the isolator is very weak which ensures a safe use of the isolator. Two FBGs (FBG1 and FBG2) combined with an optical circulator are used to determine the lasing wavelength. FBG1 is a regular uniform FBG; FBG2 is an EPS FBG with ultra-narrow transmission bandwidth. At Port 2 of the 3-dB coupler, an isolator is connected to block the residual 980-nm light and the reflection light. To monitor the output of the laser, a 5 : 95 coupler is used. Five percent of the output power is sent to an optical spectrum analyzer, and the other 95% is sent to a photodetector (PD) followed by an electrical spectrum analyzer (ESA). The key component that ensures an SLM operation is the EPS FBG (FBG2) in the laser cavity. Fig. 2 is a schematic diagram illustrating the operation of the SLM fiber ring laser using an EPS FBG combined with a tunable uniform FBG. It can be seen from Fig. 2 that FBG2 has an ultra-narrow transmission passband at the center of the $m = -1$ refection band. FBG1 is a regular uniform FBG, which has a reflection bandwidth (dotted–dashed line) much greater than the transmission passband of FBG2. The central wavelength of FBG1 can be tuned by applying strain. In our experiment, the central wavelength of FBG1 is tuned to five different locations at a, b, c, d, e, as shown in Fig. 2.

Although the 3-dB reflection bandwidth of FBG1 is about 0.11 nm in our setup, it is still much larger than the cavity mode spacing. Thus, there will exist multiple longitudinal modes at the output of the laser if the central wavelength of FBG1 is tuned to the locations at a and c in Fig. 2. To guarantee a SLM operation, a bandpass filter with a narrower passband than the cavity mode spacing should be used. This is achieved by using an EPS FBG (FBG2), which has π EPS in the reflection peak with a Fourier order of $m = -1$, implemented by increasing the sampling period by 50% in the center of the grating and keeping other sampling periods unchanged [8] during the fabrication. As can be seen from Fig. 2, an ultra-narrow transmission bandwidth is generated. If the central wavelength of FBG1 is tuned to the location at b, the same location of the transmission band of FBG2; the overall transmission band is solely determined by FBG2. Considering that the FBG2 has an ultra-narrow transmission bandwidth which can be less than the mode spacing of the fiber laser, SLM operation would be expected.

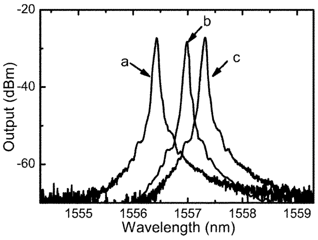

Fig. 3. Output spectra of the fiber ring laser when FBG2a is used. The spectra at a, b, and c corresponding to the central wavelength of FBG1 is tuned to the locations at a, b, and c in Fig. 2.

Note that at the two sides of the ultra-narrow transmission band, there are two wide stopbands. If the central wavelength of FBG1 is tuned at one of the two stopbands, that is, the locations at d or e, the ring cavity loss is very high and the lasing cannot be established.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

To verify the SLM operation, two EPS FBGs with different transmission bandwidths are fabricated. The sampling is implemented by switching ON and OFF the ultraviolet (UV) scanning beam using an electrically controlled optical shutter. The lengths of FBG2a and FBG2b are, respectively, 60 and 39 mm. The UV laser is a frequency-doubled Argon–Ion laser emitting at 244 nm. Both FBG2a and FBG2b have an equivalent π phase shift in the $m = -1$ reflection peaks with a sampling period of 0.5 mm and duty cycle of about 50%. The index modulation is about 3.6×10^{-4} for FBG2a and 4.3×10^{-4} for FBG2b. During the fabrication, we introduced a linear equivalent chirp to the $m = -1$ reflection peak of FBG2a to increase the reflection bandwidth by linearly chirping the sampling period [11]. In this situation, the transmission bandwidth of FBG2a is also slightly increased and estimated to be about 0.1 pm (12.5 MHz, 3 dB). FBG2b has a narrower transmission bandwidth estimated to be 0.02 pm (2.5 MHz). Since the bandwidth is much smaller than the mode spacing, the inclusion of FBG2b would ensure an SLM operation. To select the ultra-narrow transmission band, a third FBG (FBG1) is fabricated. FBG1 is a regular uniform FBG with a 3-dB bandwidth of 0.11 nm. The central wavelength of FBG1 can be tuned by applying strain.

We first use FBG2a in the fiber ring cavity. When the central wavelength of FBG1 is tuned to the location at a shown in Fig. 2, the overall bandwidth is determined by FBG1. Since FBG1 has a 3-dB bandwidth of 0.11 nm, multilongitudinal-mode lasing is expected. The optical spectrum is shown in Fig. 3. To verify that the laser is operating in the multilongitudinal mode, the optical output is applied to a PD and the electrical signal at the output of the PD is monitored by an ESA. As can be seen from Fig. 4(a), beating signals between different longitudinal modes are observed. The frequency spacing between neighboring beating signals is 16 MHz, which is exactly the mode spacing of the fiber ring laser. Similar results are obtained when the central wavelength of FBG1 is tuned to the location at c in Fig. 2. When the central wavelength of FBG1 is tuned to the location at b, the laser bandwidth is only determined by FBG2a. The optical spectrum of the laser is shown in Fig. 3. The electrical spectrum of the beating signal is shown in Fig. 4(b).

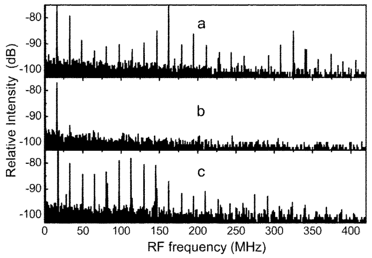

Fig. 4. Electrical spectra of the beating signals corresponding to the laser outputs when the central wavelength of FBG1 is tuned to the locations at a, b, and c in Fig. 2.

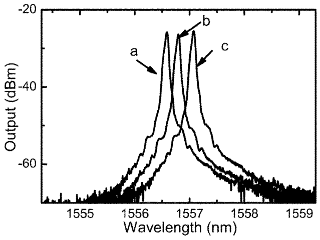

Fig. 5. Output spectra of the fiber ring laser when FBG2b is used. The spectra at a, b, and c corresponding to the central wavelength of FBG1 is tuned to the locations at a, b, and c in Fig. 2.

As can be seen, a beating signal resulted from the beating of two longitudinal modes is generated. The 3-dB bandwidth of FBG2a is estimated to be about 0.1 pm (12.5 MHz) which is close to the mode spacing. Two competing longitudinal modes are generated, which leads to an unstable beating signal.

Then, FBG2a is replaced by FBG2b in the laser ring cavity. FBG2b is fabricated using the EPS technique, but no equivalent chirp is introduced. Based on our design, the transmission bandwidth of FBG2b is estimated to be 0.02 pm (2.5 MHz). The optical spectra of the laser when FBG1 is tuned to the three different locations at a, b, and c shown in Fig. 5. When the central wavelength of FBG1 is tuned to the locations at a or c, the overall bandwidth is only determined by FBG1, multilongitudinal-mode operation is expected. This is verified by observing the beating signals at the output of the PD, shown in Fig. 6(a) and (c). However, when the central wavelength of FBG1 is tuned to the location at b, the same location of the transmission band of FBG2b, the overall bandwidth is completely determined by FBG2b which is smaller than the mode spacing; no beating signals would be expected. This is verified by the electrical spectrum shown in Fig. 6(b), no beating signals are observed on the ESA.

The stability of the fiber ring laser is also studied. Once the SLM lasing is established, the lasing wavelength are very stable. Even when FBG1 is slightly tuned, the lasing wavelength is kept unchanged. In addition, since the passband of FBG2b is extremely narrow, the SLM operation is always maintained, no mode hopping is observed. This is different from the SLM fiber ring laser proposed in [10], in which a true phase-shifted FBG was incorporated in the laser cavity. Since the transmission bandwidth of the true phase-shifted FBG was 0.075 nm, greater than the cavity mode spacing, multiple longitudinal modes would appear within the bandwidth, leading to mode hopping and poor stability [10]. We should also emphasize here that the proposed approach is different from the approaches using a saturable absorber to achieve SLM operation [5], [7]. The saturable absorbers in [5] and [7] are acting as autotracking ultra-narrow-band filters, which select always the dominant mode. Because of the mode competition, the dominant mode may change, which leads to a poor stability.

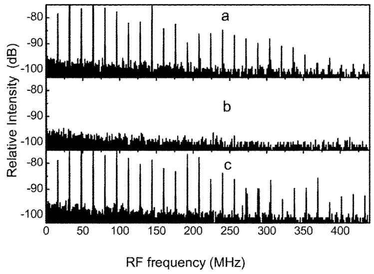

Fig. 6. Electrical spectra of the beating signals corresponding to the laser outputs when the central wavelength of FBG1 is tuned the locations at a, b, and c in Fig. 2.

Since the wavelength stability of the proposed fiber ring laser depends only on the stability of the EPS FBG. With proper packaging and temperature compensation, a stable SLM fiber ring laser with high output power is possible.

IV. Conclusion

A novel SLM fiber ring laser has been demonstrated. The SLM operation was ensured by incorporating an EPS FBG into the ring cavity. The EPS FBG had a transmission bandwidth smaller than the mode spacing of the fiber ring, ensuring a stable SLM operation without mode hopping. Compared with the SLM fiber ring lasers using a true phased-shifted FBG or a saturable absorber-based autotracking filter, the proposed laser has a better stability.

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