Stable Triple-Wavelength Fiber Ring Laser With Ultranarrow Wavelength Spacing Using a Triple-Transmission-Band Fiber Bragg Grating Filter

Li Xia, P. Shum, *Senior Member, IEEE*, YiXin Wang, and Tee Hiang Cheng, *Senior Member, IEEE*

***Abstract*—A stable 50-pm-spaced triple-wavelength fiber ring laser with nearly equal output power at each lasing line is achieved experimentally by incorporating a triple-transmission-band fiber Bragg grating filter in the fiber ring cavity. Such a laser will be very useful in applications requiring closely spaced multiwavelength components.**

***Index Terms*—Fiber Bragg grating (FBG), fiber ring laser, phase shift, transmission band.**

ALL-FIBER multiwavelength lasers have attracted much interest recently because of their applications in wavelength-division-multiplexing transmission systems and optical networks [1]. Furthermore, these lasers, especially those with ultranarrow wavelength spacing, have many potential applications in microwave generation [2], high resolution spectroscopy, and fiber-optic sensing, etc. Traditionally, one can achieve multiwavelength lasing by cascading several uniform fiber Bragg gratings (FBGs) together, which is based on the spatial hole-burning effect [3], or superimposing two chirped FBGs, which actually consists of a series of Fabry–Pérot (F-P) resonators [4]. However, these methods cannot realize the multiwavelength lasing with ultranarrow wavelength spacing (<100 pm).

Although in [5], the possibility of introducing multiple phase shifts was proposed to open up narrowband transmission bands inside the stopband of FBG, the relation between the wavelength spacing and the positions of multiple phase shifts was not provided in detail. Furthermore, the specific and promising applications using this kind of transmission-band filters have not been fully demonstrated yet. In this letter, three π-phase shifts are successfully introduced in one FBG structure and the triple-transmission-band with ultranarrow wavelength spacing (about 50 pm) are demonstrated. When the triple-transmission-band filter is applied in the fiber ring laser configuration, a stable 50-pm-spaced triple-wavelength lasing with an output power flatness less than 0.7 dBm is obtained.

To the best of our knowledge, it is the first time that multiwavelength lasing with 50-pm (or below) wavelength spacing using the FBG passive devices is achieved.

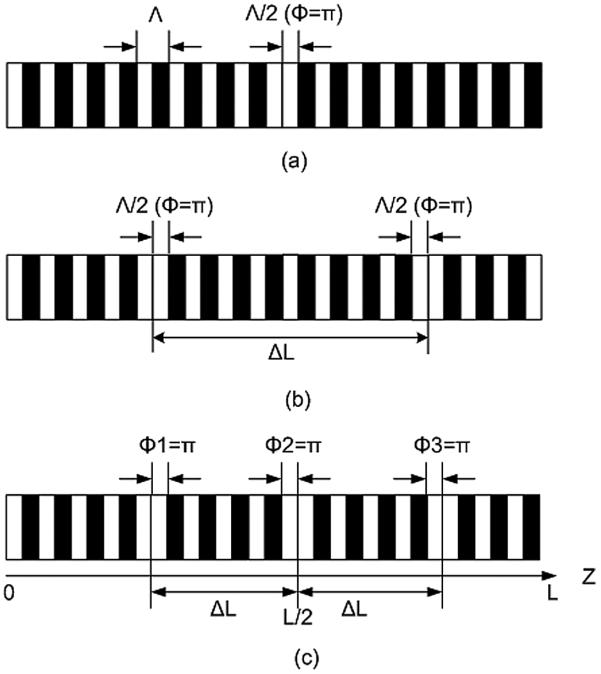

Fig. 1. Schematic diagram of the proposed optical transmission-band FBG filter with (a) single π-phase shift; (b) two π-phase shifts; (c) three π-phase shifts.

The transmission characteristic of an FBG with multiple phase-shifted sections is the key element in our fiber laser design. A traditional phase shift structure used in single wavelength distributed feedback Bragg laser [6] is that single π-phase shift is introduced in the middle of a uniform FBG. This structure is demonstrated in Fig. 1(a) with a grating period Λ. Therefore, one ultranarrow transmission band is opened at the center of the stopband of the FBG. Following this idea, in order to achieve two narrow transmission bands in the stopband of the FBG, we propose the use of two π-phase shifts in the FBG structure with a separation distance of ΔL. Considering an F-P cavity lies in the distance ΔL, the resonant condition can be expressed as

$$(2\Delta\beta) * (2\Delta L) = \pi \tag{1}$$

where $\Delta\beta$ is the detuned wavelength propagation constant. This condition is different from that of usual F-P cavity. In the left side of (1), $2\Delta\beta$ is applied because of the FBG structure here. In the right side, π is used instead of 2π, as a π-phase shift difference exists at the two ends of the cavity. As a result, the wavelength spacing is determined by

$$\Delta\lambda = \frac{\lambda^2}{8n\Delta L} \tag{2}$$

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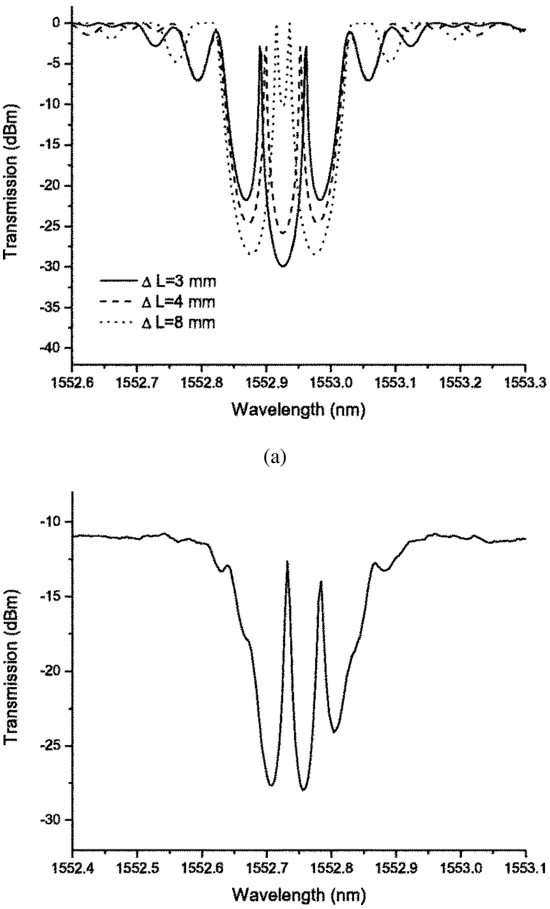

(a)

(b)

Fig. 2. (a) Simulated FBG spectra of two π-phase shifts with $\Delta L = 3, 4$, and 8 mm. (b) Fabricated FBG spectrum of two π-phase shifts with $\Delta L = 4$ mm.

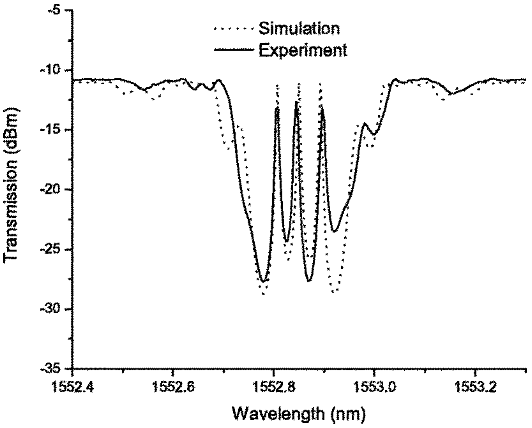

Fig. 3. Simulated (dotted line) and experimental (solid line) FBG spectra of three phase shifts with $\Delta L = 4$ mm.

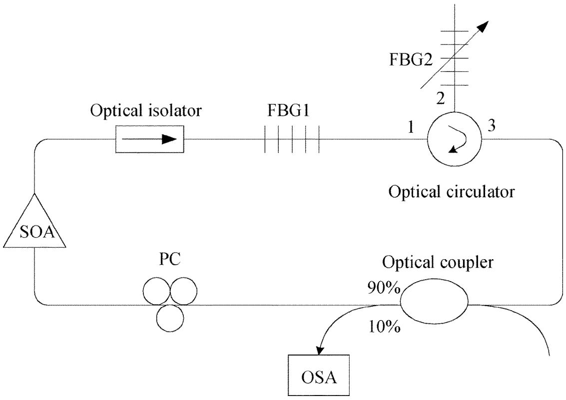

Fig. 4. Configuration of the proposed triple-wavelength fiber ring laser.

where n is the effective refractive index of the fiber. Compared to the usual F-P cavity mode spacing, the wavelength spacing of two resonant modes is four times smaller in our design. Therefore, it is possible to get a very narrow and adjustable wavelength spacing $\Delta\lambda$ in the stopband of FBG when the distance ΔL is carefully controlled. The schematic diagram of this kind of optical transmission-band FBG filter is shown in Fig. 1(b).

Here, a transfer matrix approach is adopted to calculate the corresponding transmission spectra [7]. All phase shifts are chosen to be π in the following simulations. The simulation curves are plotted in Fig. 2(a) with $\Lambda = 535.49$ nm, grating length $L = 24$ mm, coupling coefficient $\kappa = 230\ \text{m}^{-1}$, $\Delta L = 3$, 4, and 8 mm, respectively. It is seen that two ultranarrow transmission bands located symmetrically with respect to the center of the FBG's stopband. The wavelength spacing is about 0.069, 0.052, and 0.026 nm, respectively, which are in good agreement with the results from the expression (2).

To verify our design, this kind of FBG is fabricated on UV-photosensitive fiber through a phase mask scanning method. The resolution of translation stage is 1 μm. The phase shift π is realized by detuning the relative position $\Lambda/2$ between phase mask and the photosensitive fiber at the proper grating position using piezoelectric transducer (PZT). The precision of the PZT (PI E-501.00) is about several nanometers. The length of the FBG is 2.4 cm. In Fig. 2(b), the transmission spectrum of two π-phase shifts with a separation distance $\Delta L = 4$ mm is shown. It is seen that the wavelength spacing $\Delta\lambda$ equals 0.052 nm, which well matches the simulation result in Fig. 2(a).

Finally, in order to achieve three narrow transmission bands with equal wavelength spacing in the stopband of the FBG, three π-phase shifts are introduced in the uniform FBG structure with an equally separate distance ΔL. The schematic diagram of this filter is sketched in Fig. 1(c). The simulated and experimental results are compared in Fig. 3 with grating parameters of $\Lambda = 535.47$ nm, $L = 24$ mm, $\kappa = 200\ \text{m}^{-1}$. The positions of π-phase shift $\Phi1$, $\Phi2$, and $\Phi3$ are located at 8, 12, and 16 mm, respectively, along the FBG structure. It is seen that the triple-transmission-band was successfully obtained. The wavelength spacing among these three transmission bands is about 0.050 nm.

Our laser setup is shown in Fig. 4. To avoid strong homogeneous line broadening of the EDF at room temperature, we use a semiconductor optical amplifier (SOA) as the gain medium with a polarization-dependent gain of <0.5 dB. A polarization controller (PC) is used before the SOA to align the polarization direction of the light entering the SOA. In addition, an optical isolator is used to block the reflection light from FBG1 into the SOA. The lasing output is obtained from the 10% end of optical coupler and sent to an optical spectrum analyzer (OSA). The whole cavity length is about 5 m, which leads to a frequency spacing of 41.2 MHz between the neighboring longitudinal modes.

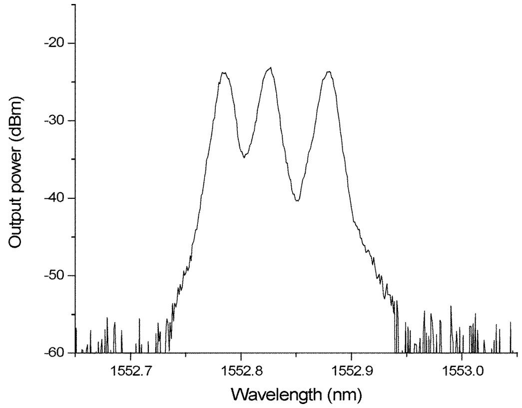

Fig. 5. Lasing spectrum of the triple-wavelength.

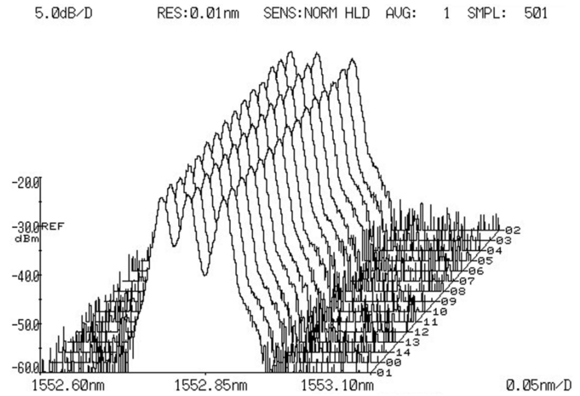

Fig. 6. Lasing spectra taken at a 2-min interval.

The fabricated triple-transmission-band FBG above is then served as FBG1 in the laser ring cavity, to achieve the triple narrow bandwidth filtering. FBG2 is another important device to get the stable multiwavelength lasing in our configuration. The central wavelength of FBG2 should match that of FBG1, and the bandwidth of FBG2 needs to be less than the bandwidth of FBG1's stopband, as well as covers the whole lasing transmission bands in FBG1. A feasible way to obtain this FBG2 is to use the chirped FBG. Through controlling the chirp coefficient and grating length, it is easy to satisfy the required bandwidth. However, in our experiment, the FBG filter shown above in Fig. 2(b) with dual-transmission-band was utilized. When this filter is used in the reflection mode, it can provide three reflection bands with a wavelength spacing of nearly 0.050 nm. We adjust its central wavelength to match that of the FBG1 through strain detuning. Therefore, by incorporating this dual-transmission-band FBG as FBG2 to reflect the light with three corresponding wavelengths, triple-wavelength lasing at 1552.78, 1552.83, and 1552.88 nm with ultranarrow wavelength spacing of about 50 pm was observed, as shown in Fig. 5. All lasing bandwidths are less than 10 pm for the ultranarrow transmission-band filtering by FBG1. The output powers of these three wavelengths are -23.76, -23.13, and -23.63 dBm, respectively, with the SOA driving current at 115 mA. The peak at the longest wavelength seems to be further away than expected. This is due to the limitation in the OSA resolution (0.01 nm), which prevents the minor difference in picometer-order being recorded accurately.

To study the stability of the laser, 15 measurements were taken at a time interval of 2 min and the lasing spectra are shown in Fig. 6. The worst output power fluctuation among these lasing lines is within 0.8 dBm. The worst wavelength shift is assumed to be less than 0.01 nm for the limitation of OSA resolution. During the experiment, the PC is not adjusted to compensate for the polarization change of the cavity. Since these wavelengths are generated from the same grating and laser cavity, the stability of this kind of multiwavelength ring laser can be guaranteed.

The ultimate limit in the ultranarrow wavelength spacing is the sidemode suppression ratio (SMSR) of FBG1. When the two transmission bands are close enough, these two bands will emerge into one band and the corresponding SMSR will be low. This effect is demonstrated with dotted line in Fig. 2(a). The maximum number of transmission bands from this approach is mainly determined by the grating bandwidth, which is related to the whole grating length and strength. If more transmission bands are included with certain wavelength spacing, lower SMSR and larger bandwidth of each transmission band will exist, which will eventually degrade the quality of lasing line.

The bandwidth of the generated lasing lines can be further decreased through writing longer FBG structure and getting more narrow transmission bands. Thus, the single longitudinal mode lasing in each wavelength is expected in our laser configuration.

In summary, the proposed technique presents a simple and cost-effective solution to produce a triple-wavelength lasing with ultranarrow wavelength spacing of 50 pm. This kind of multiwavelength laser can find applications in generating various high-quality high-frequency microwave signals, high resolution spectroscopy, and fiber-optic sensing, etc.

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