Tunable and Switchable Fiber Ring Laser Among Four Wavelengths With Ultranarrow Wavelength Spacing Using a Quadruple-Transmission-Band Fiber Bragg Grating Filter

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***Abstract*—Four π-phase shifts are introduced in a uniform fiber Bragg grating (FBG) structure to realize a quadruple-transmission-band filter with ultranarrow 40-pm wavelength spacing. Four separate single-wavelength lasings at 1552.60, 1552.63, 1552.67, and 1552.71 nm, and three pairs of dual-wavelength lasings among above four wavelengths, are achieved stably by incorporating the quadruple-transmission-band FBG filter in a fiber ring cavity with a tunable uniform FBG acting as coarse frequency selection. This new kind of laser will be very useful in applications requiring closely spaced and tunable single- or dual-wavelength components.**

***Index Terms*—Fiber Bragg grating (FBG), fiber ring laser, quadruple-transmission-band filter, ultranarrow wavelength spacing.**

DYNAMIC fiber-optic components, including not only tunable filters but also diverse wavelength management and control devices such as switchable add–drop filters and lasers, are in increasing demand in emerging wavelength-division-multiplexing (WDM) network architectures. A wide variety of tunable and switchable technologies have been developed to meet various needs with fiber Bragg grating (FBG) devices, such as highly birefringent operation [1], acoustooptic superlattice modulator [2], stretched grating, and thermal induced phase-shift [3]. Liu *et al.* used multiple discrete FBGs to achieve a swithable and tunable multiwavelength erbium-doped fiber laser by adjusting variable optical attenuators [4]. However, all these approaches bear some disadvantages, such as polarization sensitivity, large swichable wavelength spacing (several nanometers). Smaller switchable wavelength spacing, and hence, stronger multiplexing capability is desirable in the WDM network or sensor configuration. Therefore, it is meaningful to achieve tunable and switchable function with a narrow wavelength spacing, e.g., 40 pm.

Although in [5] the possibility of introducing multiple phase shifts into a normal FBG was proposed to open up narrowband transmission bands inside the stopband of FBG, the detailed fabrication as well as specific applications with this kind of transmission-band filter, have not been fully demonstrated yet. In this letter, first, a quadruple-transmission-band filter is fabricated by introducing four π-phase shifts along a uniform FBG structure with controllable separation distance. This filter is then applied in a fiber ring laser configuration with another uniform FBG introduced to form the cavity. Tunable and switchable single-wavelength and dual-wavelength lasings with about 40 pm spacing are achieved successfully. The laser offers an optical signal-to-noise ratio of $>$30 dB, an output-power uniformity for dual-wavelength operating at $<$0.8 dBm, and an output-power stability of $<$0.6 dBm.

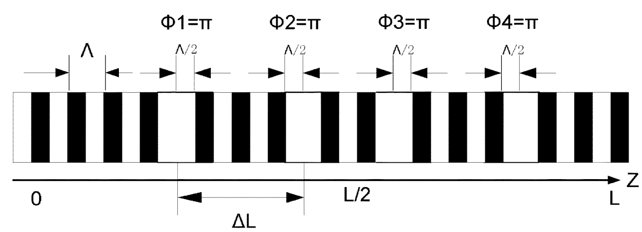

Fig. 1. Schematic diagram of the proposed quadruple-transmission-band FBG filter with four π-phase shifts.

As we know, a traditional phase-shift structure used in single wavelength distributed feedback Bragg laser [6] has single π-phase shift in the middle of grating. Due to this π-phase shift, one ultranarrow transmission band is opened at the center of the FBG's stopband. Following this strategy, in order to achieve four narrow transmission bands with equal wavelength spacings in the stopband of the FBG, four π-phase shifts can be introduced in the uniform FBG structure with an equal separation in distance ΔL. The wavelength spacing among the four transmission bands is determined by $\Delta\lambda = (\lambda * \lambda)/(8n\Delta L)$ (n is the efficient refractive index of the fiber). Compared to the usual Fabry–Pérot cavity mode spacing, the wavelength spacing of two resonant modes is four times smaller in our design. This is because a π-phase shift difference exists in both sides of each FBG cavity ΔL. The schematic diagram of this filter is sketched in Fig. 1.

To verify our design, the FBG filter was fabricated on UV-photosensitive fiber through the phase mask scanning method. The resolution of translation stage is 1 μm. The π-phase shift is realized by detuning the relative position to half of the grating period ($\Lambda/2$) between phase mask and the photosensitive fiber at the proper grating position using a piezoelectric ceramic translation (PZT) stage. The precision of

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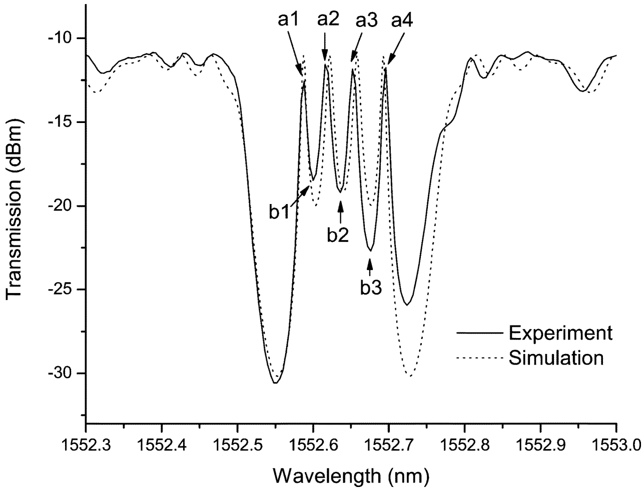

Fig. 2. Simulated (dotted line) and fabricated (solid) spectra of quadruple-transmission-band FBG filter.

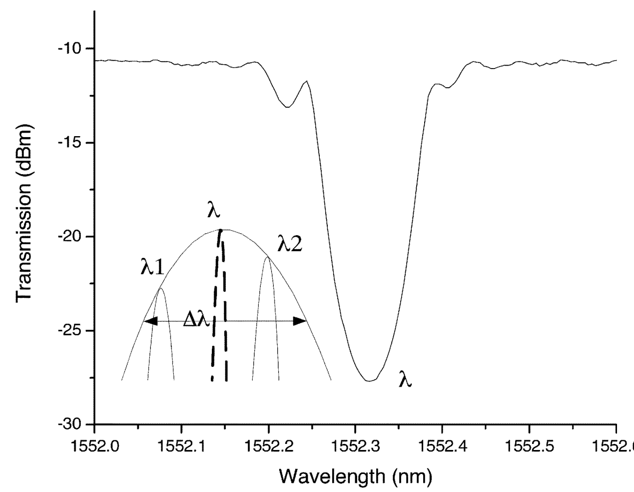

Fig. 4. Fabricated uniform FBG spectrum. The inset shows the detail of single-wavelength (dotted line) and dual-wavelength (solid line) filterings.

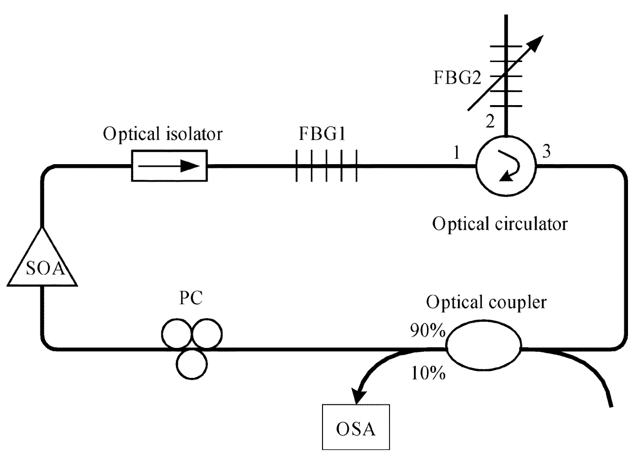

Fig. 3. Configuration of the proposed fiber ring laser.

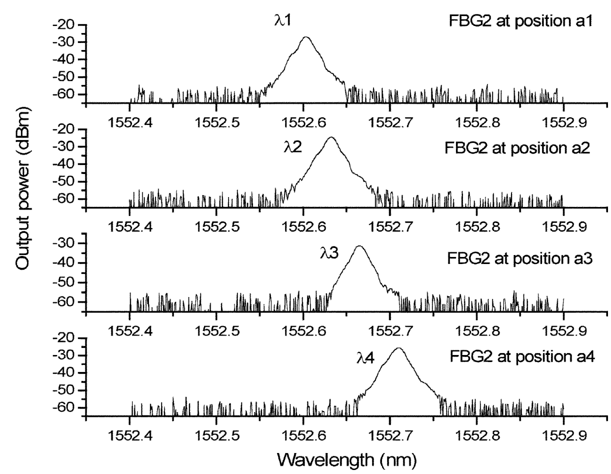

Fig. 5. Lasing spectra of single-wavelength at positions of $a1$, $a2$, $a3$, and $a4$, respectively.

the PZT is about several nanometers. The length of this FBG is 2.4 cm. Four π phase shift $\Phi1$, $\Phi2$, $\Phi3$, and $\Phi4$ are introduced at the positions of 6, 10, 14, and 18 mm, respectively, along the FBG structure. The measured transmission spectrum is shown in Fig. 2 (solid line). It is seen that four narrow transmission bands are located symmetrically with respect to the center of the FBG's stopband. Here, a transfer matrix approach is also adopted to calculate the corresponding transmission spectra [7]. The positions of simulated π-phase shifts are the same as those in the fabrication. Other parameters are chosen as the grating period $\Lambda = 535.39$ nm, grating length $L = 24$ mm, and coupling coefficient $\kappa = 200$ m^{-1}. The simulation result is plotted as the dotted line in Fig. 2. The average wavelength spacing here is 0.046 nm, which is in a reasonable agreement with the result from the experiment. The small discrepancy in the asymmetric shape of the filter may be due to the positions, and the amount of phase shifts in the fabrication did not agree exactly with those in the simulation. Another possible cause is the uniformity of UV exposure along the whole grating structure. Fortunately, the filter is used in the transmission mode and the four transmission bands are barely affected.

The laser setup is shown in Fig. 3. To avoid strong homogeneous line broadening of the erbium-doped fiber at room temperature, we use a semiconductor optical amplifier (SOA) as the gain medium. The laser cavity has 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 fabricated quadruple-transmission-band FBG above is then served as FBG1 in the laser ring cavity, to achieve the four-narrow-bandwidth filtering. FBG2 is also a critical device to ensure the stable lasing in our configuration. In the experiment, considering the fabricated FBG2 shown in Fig. 4 with a reflectivity of about 16 dB and bandwidth of 0.88 nm, we adjust its central wavelength to match the different positions in the FBG1's spectrum through strain detuning. When it is detuned to the positions of $a1$, $a2$, $a3$, and $a4$ (see Fig. 2), respectively, the central wavelength of FBG2 well matches one of the transmission-band windows in FBG1. This is demonstrated with dotted line in the inset of Fig. 4. Thus, single-wavelength lasing easily happens. Four separate single-wavelength lasings at 1552.60 ($\lambda1$), 1552.63 ($\lambda2$), 1552.67 ($\lambda3$), 1552.71 nm ($\lambda4$), with corresponding output power of -26.80, -24.47, -31.12, and -25.55 dBm, respectively, are illustrated in Fig. 5. These

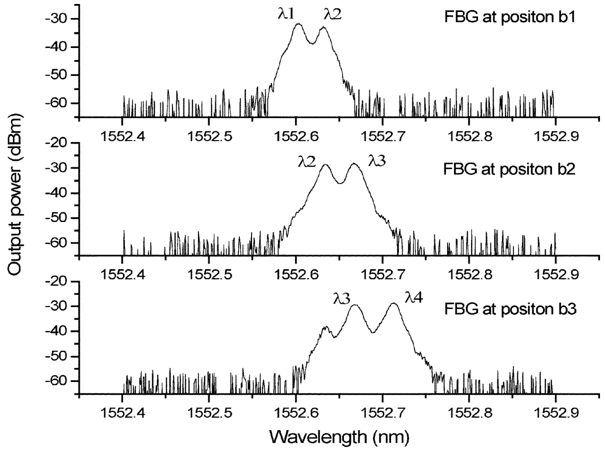

Fig. 6. Lasing spectra of dual-wavelength at positions of $b1$, $b2$, and $b3$, respectively.

lasing wavelengths are corresponding to the transmission bands $a1$, $a2$, $a3$, and $a4$, of FBG1. In all situations, the SOA driving current works at 92 mA. Because of the narrow transmission-band filtering, all lasing bandwidths are less than 10 pm.

When the center wavelength of FBG2 is detuned to the positions of $b1$, $b2$, and $b3$, it is seen that the bandwidth of FBG2 can cover two of the quadruple-transmission-bands in FBG1. Thus, dual-wavelength lasing can happen. Three pairs of dual-wavelength lasing are illustrated in Fig. 6 according to different lasing positions of $b1$, $b2$, and $b3$. The first pair works at 1552.60 and 1552.63 nm with corresponding output powers of −31.94 and −32.75 dBm. The second pair works at 1552.63 and 1552.67 nm with corresponding output powers of −28.51 and −28.04 dBm. The third pair works at 1552.67 and 1552.71 nm with corresponding output powers of −29.33 and −28.63 dBm. It is seen that the advantage of this kind of dual-wavelength filtering, shown in the inset of Fig. 4 (solid line), can counterpoise the reflectivity discrepancy between two transmission bands and easily equalize the output powers between the two lasing wavelengths. The uniformity of output powers from each pair of lasings can be controlled within 0.8 dBm.

To study the stability of the laser, we monitored all single-wavelength and dual-wavelength operations in half an hour and found that all operations worked stably. Here, one single-wavelength lasing at 1552.60 nm was recorded in Fig. 7(a) and the other dual-wavelength lasing at 1552.67 and 1552.71 nm was shown in Fig. 7(b). In these two figures, 15 measurements are taken at a time interval of 2 min. The output-power stability at each lasing line is within 0.6 dBm. The worst wavelength shift should be less than 0.01 nm for the limitation of OSA resolution. During the measurement, 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 fiber ring laser can be guaranteed.

The whole cavity length is about 5 m, which corresponds to a frequency spacing of 41.2 MHz between the neighboring longitudinal modes. The bandwidth of the generated lasing lines can be further decreased through writing longer FBG structure and getting even narrower transmission bands. In this way, the single longitudinal mode lasing in each wavelength is expected in our laser configuration.

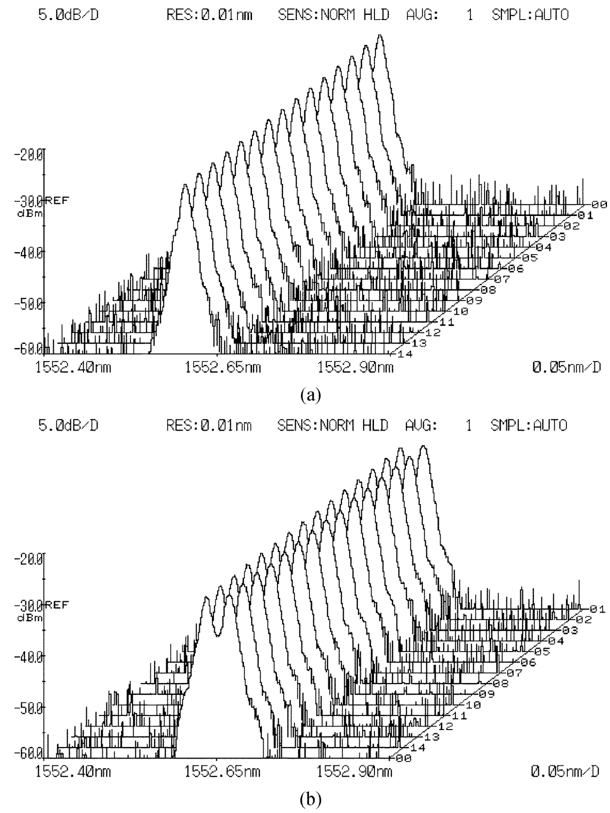

Fig. 7. Lasing spectra taken at a 2-min interval with (a) single-wavelength at 1552.60 nm; (b) dual-wavelength at 1552.67 and 1552.71 nm.

In summary, we have proposed a simple and cost-effective solution to produce a tunable and switchable single- or dual-wavelength laser with ultranarrow wavelength spacing. This kind of fiber ring laser can find applications in optical wavelength switching networks, high resolution spectroscopy, and fiber-optic sensing, etc.

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