Appl. Phys. B 88, 185–188 (2007)
DOI: 10.1007/s00340-007-2696-5

Applied Physics B
Lasers and Optics

L. XIA✉
P. SHUM
J. ZHOU
T.H. CHENG

Eight-wavelength switchable fiber ring laser with ultranarrow wavelength spacing using a quadruple-transmission-band polarization maintaining fiber Bragg grating

School of Electrical & Electronic Engineering, Nanyang Technological University, Block S1, 50 Nanyang Avenue, Singapore

Received: 7 November 2006/Revised version: 10 May 2007
Published online: 20 June 2007 •

ABSTRACT We propose and demonstrate an eight-wavelength switchable laser with approximately 40 pm wavelength spacing using a polarization maintaining fiber Bragg grating (PMFBG). This PMFBG has a specially designed quadruple-transmission-band. When it is used in a fiber ring configuration, four wavelengths can be switched in one state of polarization, while the other four can oscillate in the corresponding orthogonal state.

PACS 42.55.Wd; 42.81.-i; 42.81.Gs

1 Introduction

Wavelength-switchable fiber lasers are required for flexible dense-wavelength-division-multiplexed (DWDM) networks, many fiber optic-sensing systems and for spectroscopic studies. Although researchers at several laboratories have used fiber Bragg gratings (FBGs) to achieve multiwavelength lasing [1, 2] or tune a laser from one line to another with a wide variety of tunable and switchable technologies, such as highly birefringent operation, acousto-optic superlattice modulators, stretched gratings and thermal induced phase-shifts, the spacing between the lines has been relatively large (i.e., several nanometers) [3–6]. A fast and accurate wavelength switching method using a Fabry–Pérot semiconductor filter and fiber gratings was previously introduced, however, in many cases, especially DWDM, tuning among closely spaced lines is highly desirable [7]. A specially designed FBG is the key to fulfilling the requirements for this kind of switchable laser's operation. Recently, we reported a fiber ring laser that is switchable among four different lines separated by only 40 pm using a quadruple-transmission-band FBG [8]. Here we introduce more switching lines, to our knowledge for the first time. In order to achieve this we fabricated an FBG structure on the polarization maintaining (PM) fiber. As a result, eight lasing lines can be achieved separately. Among these lasing lines, four can be switched in one state of polarization, while the other four can oscillate in the corresponding orthogonal state of polarization. This kind of laser will be very useful in applications requiring closely spaced and switchable single wavelength components, even in the orthogonal polarization multiplexing situation.

✉ Fax: +(65) 67926894, E-mail: xiali@ntu.edu.sg

2 Design principle

A conventional output-coupling FBG has a single π-phase shift at its center and transmits a single-narrow band in the middle of its reflectance spectrum. Extrapolating from this principle, we designed a FBG with four π-phase shifts with an equal spatial separation on the polarization maintaining fiber. The schematic diagram of the optical bandpass FBG filter is shown in Fig. 1.

In order to estimate the mode spacing in the Fabry–Pérot (F–P) cavity with two Bragg reflectors we have, for simplicity's sake, taken two identical Bragg mirror phases $\Phi(\omega)$. The phase condition is

$$-4\Phi(\omega)+2\beta*(4\Delta L)=2m\pi\,,\quad m=1,2,... \tag{1}$$

Similar to the analysis [9], the wavelength spacing changes to

$$\Delta\lambda=\frac{\lambda^2}{8n\left(\Delta L+\frac{\pi}{2\kappa}\right)}\,, \tag{2}$$

where n is the effective refractive index of the fiber. For PM fiber, $n=n_x$ or n_y and $\Delta n=n_x-n_y$ is the birefringence of the fiber. κ is the coupling coefficient of the grating. The contribution $\pi/2\kappa$ is due to the evanescent penetration of the oscillating light field into the Bragg mirrors.

In comparison to the usual F–P cavity mode spacing, the wavelength spacing of two resonant modes is 4 times smaller in our design. One reason is the structure between the two Bragg mirrors is not the free fiber space, but still a Bragg grating structure. Therefore, 2β is used in (1) instead of β. The

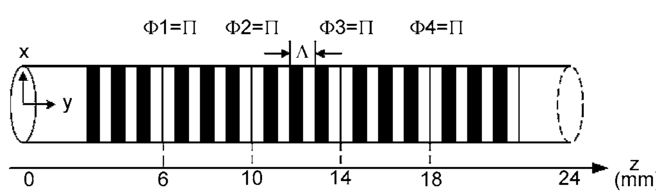

FIGURE 1 The schematic diagram of PMFBG with four π-phase shifts

other reason is the pre-introduced π-phase difference between two Bragg mirrors. The oscillating light needs two round trips to realize the $2m\pi$ phase condition. Therefore, it is possible to get a very narrow and adjustable wavelength spacing $\Delta\lambda$ in the stopband of the FBG when the distance ΔL is carefully controlled according to (2). The transfer matrix approach has been adopted to verify the corresponding transmission spectra [8].

3 Experimental results

We fabricated this FBG structure on the PM fiber through a phase mask scanning method. The length of this PMFBG is 2.4 cm. Four π-phase shifts $\Phi 1$, $\Phi 2$, $\Phi 3$ and $\Phi 4$ are introduced at the positions of 6, 10, 14 and 18 mm, respectively, along the FBG structure (see Fig. 1). Four transmission bands are observed at 1546.02, 1546.056, 1546.088, 1546.128 nm in one polarization state. When a PM fiber is exposed to UV light for grating inscription, the resulting index modulation gives rise to two spectrally shifted Bragg dips because of the fiber's birefringence [10]. In our experiment, the shifted distance is about 0.18 nm, which is determined by the fiber birefringence of $1.69e^{-4}$. Therefore, when the orthogonal polarization state is adjusted, the other four corresponding transmission bands appear at 1546.204, 1546.240, 1546.276, and 1546.316 nm. The measured transmission spectra are demonstrated in Fig. 2.

We constructed the laser in a ring configuration as shown in Fig. 3. A semiconductor optical amplifier (SOA) is used to avoid the broad homogeneous broadening of an erbium fiber amplifier. A polarization controller (PC) is applied in order to align the polarization direction of the light entering the FBG1 (PMFBG). 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 the optical coupler and sent to an optical spectrum analyzer (OSA).

The specially designed PMFBG, with four transmission bands, is part of the ring (FBG1), providing narrow bandwidth filtering and preserving the single polarization property of the laser. Another FBG (FBG2) fabricated in a normal single mode fiber with no phase shifts is coupled to the ring through an optical circulator. The reflective wavelength of FBG2 can be tuned by mechanical strain. Thus, when it was centered on one of the four transmission peaks of FBG1, the single wavelength oscillation with ultranarrow bandwidth occurs. The transmission spectrum of FBG2 is shown in Fig. 4. It can reflect above 99% of the light at the central wavelength for any polarization state. The inset consists of all eight lasing lines shown in one graph when FBG2 is tuned to the transmission band of FBG1.

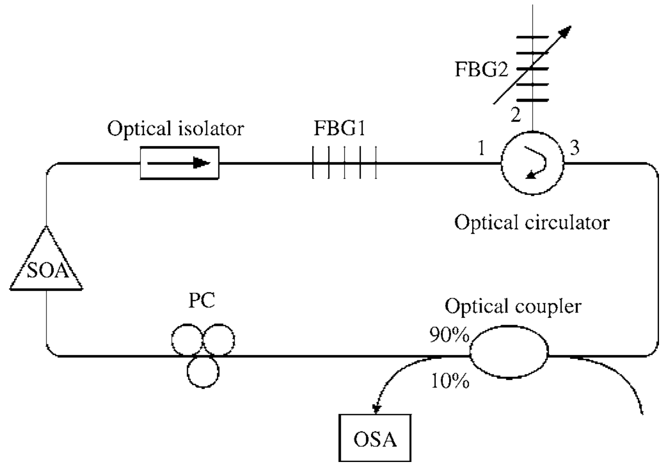

FIGURE 3 Configuration of the proposed fiber ring laser

When FBG2 is detuned to the positions of $a1$, $a2$, $a3$, and $a4$ (see Fig. 2), respectively, the central wavelength of FBG2 matches one of the transmission-band windows in FBG1. Thus, single-wavelength lasing effortlessly occurs. Four separate single-wavelength lasings at 1546.112 ($\lambda 1$), 1546.154 ($\lambda 2$), 1546.186 ($\lambda 3$), and 1546.226 nm ($\lambda 4$), with output powers of −3.33, −3.96, −2.61, and −2.40 dBm, respectively, are illustrated in Fig. 5. These lasing wavelengths correspond to the transmission bands, $a1$, $a2$, $a3$, and $a4$, of FBG1. About 0.1 nm shifts towards long wavelengths may be due to small strain differences applied in FBG1 between tests, after the

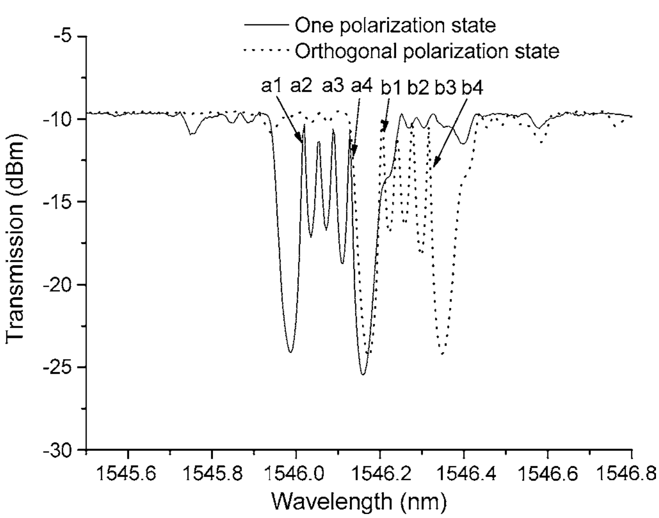

FIGURE 2 Transmission spectra of PMFBG in two orthogonal states of polarization

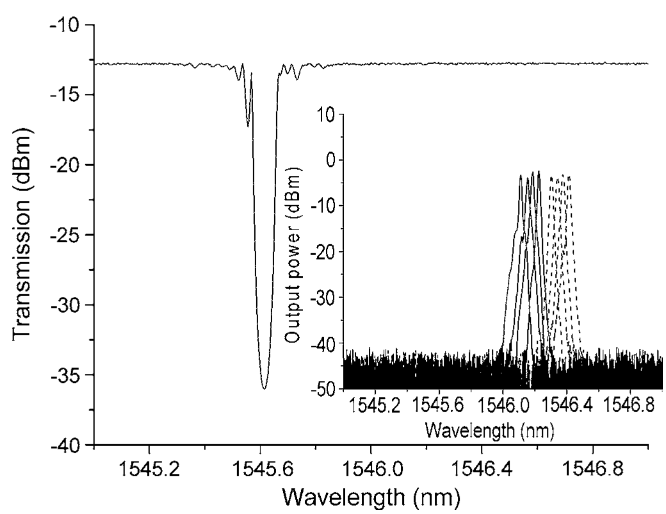

FIGURE 4 Transmission spectrum of FBG2 with all lasing lines in the *inset*

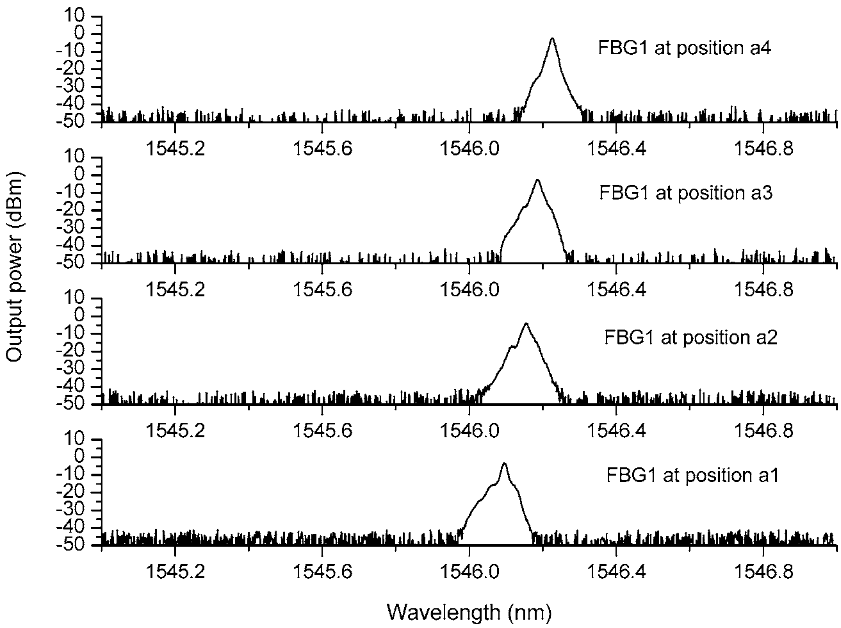

FIGURE 5 Four-wavelength switching spectrum in one state of polarization

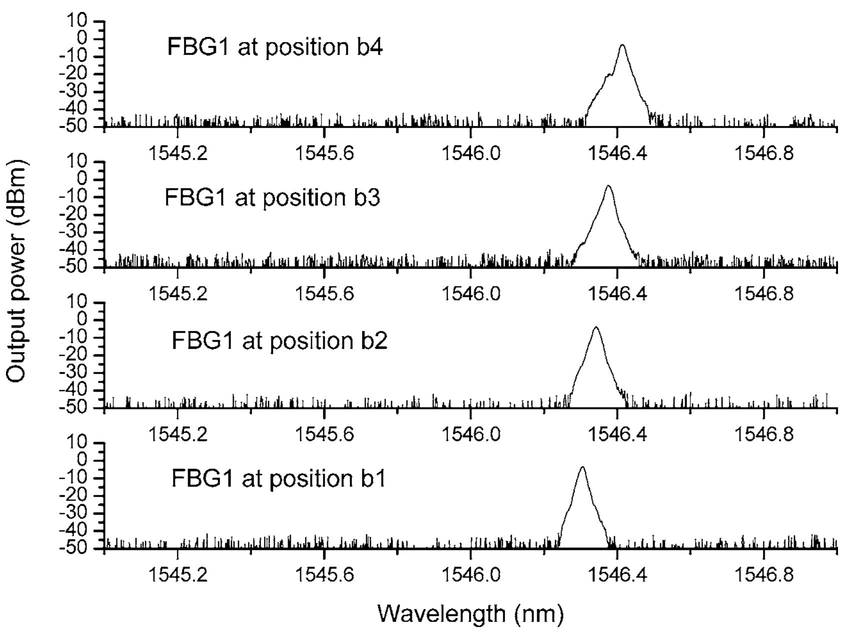

FIGURE 6 Four-wavelength switching spectrum in a corresponding orthogonal state of polarization

grating writing process and in the laser setup. In all situations, the SOA driving current works at 162 mA. The laser offers an optical signal-to-noise ratio (OSNR) of > 40 dB. 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 $b1$, $b2$, $b3$, and $b4$ and the PC is adjusted in order to obtain the orthogonal polarization state in the cavity, the other four wavelength switchings can occur. Four single-wavelength lasings at 1546.306 ($\lambda 5$), 1546.342 ($\lambda 6$), 1546.376 ($\lambda 7$), and 1546.414 nm ($\lambda 8$), with output powers of -3.28, -3.71, -3.20, and -3.07 dBm, respectively, are illustrated in Fig. 6 according to different lasing positions of $b1$, $b2$, $b3$, and $b4$.

In order to study the stability of the laser, we monitored all single-wavelength operations for half an hour and found that all operated stably over this interval. Figure 7 shows

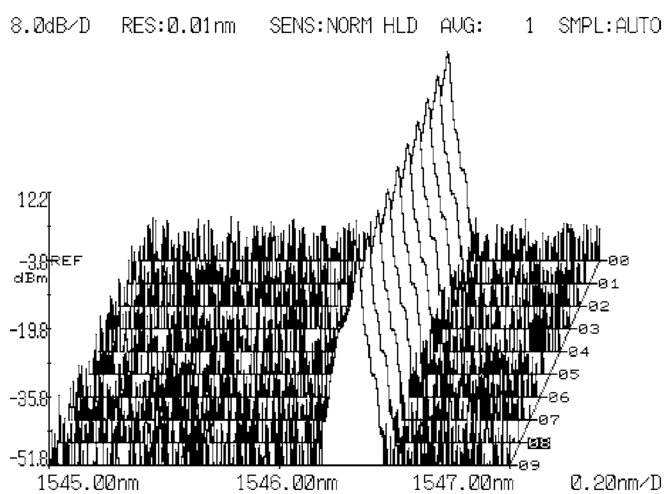

FIGURE 7 Lasing spectra recorded at 3 min intervals

the spectra of a single lasing line (λ6)taken at 3 minute intervals. The output-power stability at each lasing line is within 1 dBm. The worst wavelength shift should be less than 0.01 nm for the limitation of OSA resolution. Since these wavelengths are generated from the same grating and laser cavity, the stability of this kind of fiber ring laser can be guaranteed.

4 Conclusion

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

REFERENCES

1 X. Feng, H.-Y. Tam, W.-H. Chung, P.K.A. Wai, Opt. Commun. **263**, 295 (2006)
2 Z. Wang, Y. Cui, B. Yun, C. Lu, IEEE Photon. Technol. Lett. **17**, 2044 (2005)
3 S.P. Reilly, S.W. James, R.P. Tatam, Electron. Lett. **38**, 1033 (2002)
4 L. Wen-Fung, L. Po-Chiang, C. Wan-Ching, L. Dong, P.S.J. Russell, M. Ibsen, Laser. Elec.-Opt. CLEO **99**, 77 (1999)
5 S.Y. Li, N.Q. Ngo, S.C. Tjin, P. Shum, J. Zhang, J. Photon. Res. **1**, 205 (2003)
6 S. Yamashita, M. Yokooji, Opt. Commun. **263**, 42 (2006)
7 L. Shenping, K.S. Chiang, W.A. Gambing, Appl. Phys. Lett. **77**, 4268 (2000)
8 L. Xia, P. Shum, M. Yan, Y. Wang, T.H. Cheng, IEEE Photon. Technol. Lett. **18**, 2038 (2006)
9 A. Yariv, *Optical Electronics in Modern Communications*, 5th edition (Oxford University Press, New York, 1997), p. 634
10 I. Abe, R. Nogueira, B. Disesel, A. Ehlke, J. Tosin, P. Andre, J. Pinto, H. Kalinowski, Proc. SPIE **5036**, 224 (2003)