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Actively mode-locked dual-wavelength fiber laser with close wavelength spacing using a fiber Bragg grating

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Abstract. A simple actively mode-locked fiber ring laser is proposed and successfully demonstrated to generate dual-wavelength picosecond pulses with close wavelength spacing using one Bragg grating in standard single-mode fiber. The proposed laser can be made to operate in stable dual-wavelength at room temperature, due to the birefringence characteristic of the FBG induced by transverse strain. Transverse strain loading on the FBG allows the wavelength spacing to be controlled. Generation of stable dual-wavelength pulses with a pulsewidth of 212–234 ps and a tunable wavelength separation from 0.2 to 0.44 nm at a pulse rate of 1.05 GHz was demonstrated.

Key words: dual-wavelength lasing, erbium-doped fiber, fiber Bragg grating, fiber laser, short-pulse generation

1. Introduction

Multiwavelength actively mode-locked erbium-doped fiber (EDF) ring lasers are attractive optical sources in wavelength-division-multiplexed (WDM) fiber communication systems, fiber sensing, and time-resolved spectroscopy. Dual-wavelength short pulses also find applications in the field of optical pump-probe measurement. Various techniques have been proposed to generate dual or multiple wavelength pulses from a harmonically mode-locked fiber laser in the last few years (Bakhshi *et al.* 1999; Li and Chan 1999; Chen *et al.* 2000; Lee and Shu 2000; Town *et al.* 2000; Deparis *et al.* 2001; Zhao *et al.* 2001; Chan and Shu 2002; Lou *et al.* 2002; Pudo *et al.* 2002; Yang *et al.* 2002; Pudo and Chen 2003). Fiber Bragg gratings (FBGs), on the other hand, are ideal wavelength selection components for fiber lasers due to the unique advantages of fiber compatibility, ease of use and low cost. Different FBGs have been incorporated in the laser cavities to perform simple or more elaborated filtering functions including cascaded FBGs (Bakhshi *et al.* 1999; Li and Chan 1999; Chen *et al.* 2000), linear chirped fiber gratings (Town *et al.*

2000; Chan and Shu 2002; Yang *et al.* 2002), a superstructured sampled FBG (Zhao *et al.* 2001), a polarization-maintaining FBG (Deparis *et al.* 2001). However, it is difficult to obtain a small wavelength separation at room temperature because of the large homogeneous broadening of the EDF. To avoid this problem, a technique based on temporal-spectral multiplexing of the pulses was proposed (Town *et al.* 2000; Yang *et al.* 2002). Recently, by using multiple EDF cavities, multi-wavelength lasers with a wavelength spacing as narrow as 0.3–0.4 nm were demonstrated (Pudo *et al.* 2002; Pudo and Chen 2003). However, the need to use multiple EDF cavities with carefully adjusted lengths makes the scheme complicated and expensive to implement.

In this letter, we present a simple dual-wavelength actively mode-locked fiber laser with close wavelength spacing using one FBG in standard single-mode fiber (SMF). This is done by splitting the transmission dip of the FBG into two closely separated ones, which specify the lasing wavelengths of the laser. The proposed laser can be made to operate in stable dual-wavelength at room temperature, due to the birefringence characteristic of the FBG induced by transverse strain. Transverse strain loading on the FBG allows the wavelength spacing to be controlled and the wavelength separation can be changed continuously without changing the pulse repetition rate by simply tuning the FBG. Furthermore, the intensities of the pulses at the two wavelengths can be equalized easily by adjustment of a polarization controller (PC). The laser has the advantage over alternative techniques in that it is spectrally stable and has a simple configuration, increased control of tuneability and low cost.

2. Experimental setup and principle

The configuration of the proposed laser is shown schematically in Fig. 1. The ring laser mainly consists of a 15-m-long EDF whose concentration is about

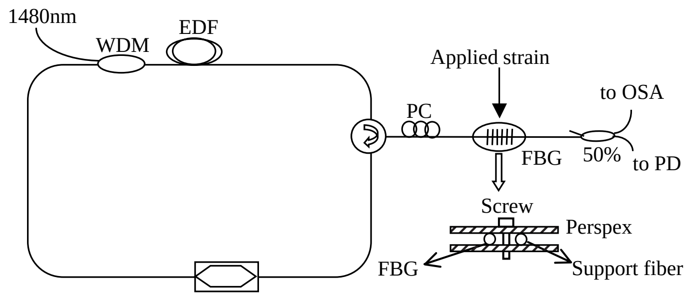

Fig. 1. Schematic diagram of the proposed laser.

500 ppm, a $LiNbO_3$ modulator, a optical circulator (OC), a PC, and a FBG with a section of strain modulation. The EDF was pumped by a 1480 nm laser diode at 80 mW through a WDM coupler. The PC is used to rotate the polarization state and allowed continuous adjustment of the birefringence within the cavity. The FBG was placed between two pieces of Perspex. Transverse strain was applied through a screw on the FBG along with another fiber of the same type with coating removed, to ensure the load is applied from an orthogonal direction. The laser output was taken via a 50% fused fiber coupler, placed just after the FBG. The spectral and temporal characteristics of the mode-locked pulses were monitored simultaneously using an optical spectrum analyzer (OSA)(ADVANTEST Q8383) with 0.1 nm resolution and fast photodiode (PD) connected to a digital oscilloscope (HP8348A), respectively.

When there is no transverse strain applied, the Bragg reflection wavelength of a FBG is given by $\lambda = 2\Lambda n_{\mathrm{eff}}$, where n_{eff} is the initial effective refractive index, λ is Bragg wavelength, and Λ is the period of the grating. As consequence of an applied transverse load, the refractive index of the FBG will change and become birefringence and two plane-polarized waves will propagate, with the principle axes of polarization parallel and perpendicular to the direction of the applied load (see Fig. 2). If Δn_{eff} represents the effective refractive index difference between the two orthogonal states of polarization, two different resonance wavelengths will result with spacing $\Delta\lambda = 2\Lambda\Delta n_{\mathrm{eff}}$ (Gafsi and EI-Sherif 2000). That is, the transmission dip of the FBG will split into two closely separated ones, as shown in Fig. 3. Changes in the transverse strain can modify the index difference and the wavelength spacing will change accordingly.

The operation principle of the laser is as follows. The birefringence induced by the FBG is beneficial to diversify the polarization states of different wavelength in the EDF and enhance the polarization hole burning (PHB). This PHB greatly increases the inhomogeneous gain broadening of EDF and accordingly reduces the wavelength competition (Hernandez-Cordero *et al.* 1998). Then, it is possible to achieve stable dual-wavelength oscillations with

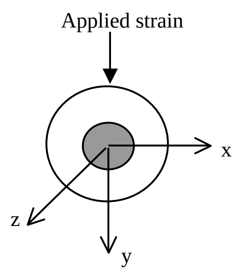

Fig. 2. Indicatrix of the disturbed FBG.

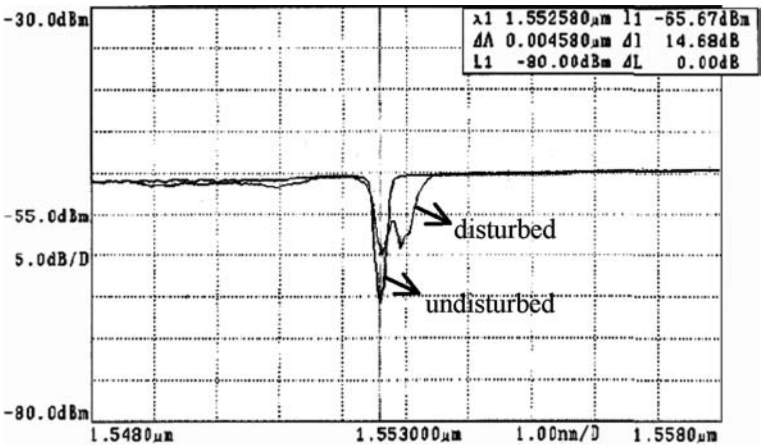

Fig. 3. Transmission spectrum of the FBG undisturbed and disturbed.

close wavelength spacing at room temperature. In this scheme, the cavity length, and hence, the cavity resonance frequency are almost the same for both wavelengths and the wavelength separation can be changed continuously without changing the pulse repetition rate by simply tuning the FBG. Furthermore, the intensities of the pulses at the two wavelengths can be equalized easily by adjustment of the PC because the two longitudinal modes are separated in polarization.

3. Results and discussions

The SMF used for fabrication of the FBG was hydrogen loaded for seven days in a pressure vessel at 120 bar. The FBG was subsequently fabricated by the phase mask method. Fig. 3 shows the measured transmission spectra of the FBG undisturbed and disturbed. As can be seen from the figure that when the transmission dip split into two closely separated ones, the corresponding transmission rates decrease. That's also why we use the FBG as the output coupler. Fig. 4 shows the dual-wavelength operation of the proposed laser when the screwed angle was 0.4 rad. The corresponding wavelength spacing was 0.2 nm. The mode-locked pulses corresponding to the spectra shown in Fig. 4 is given in Fig. 5 when the repetition rate is 1055.2 MHz. This frequency corresponds to the 105th harmonic of the fundamental frequency of 10.05 MHz. Fig. 5(a) shows the dual-wavelength output pulses train directly from the laser. The corresponding pulse width is 212 ps and the average output power was about 1.18 mW. The dual-wavelength output pulses from the laser were then launched into a 50-km single-mode fiber, which had a dispersion parameter of about 10.0 ps/(nm km) at 1550 nm.

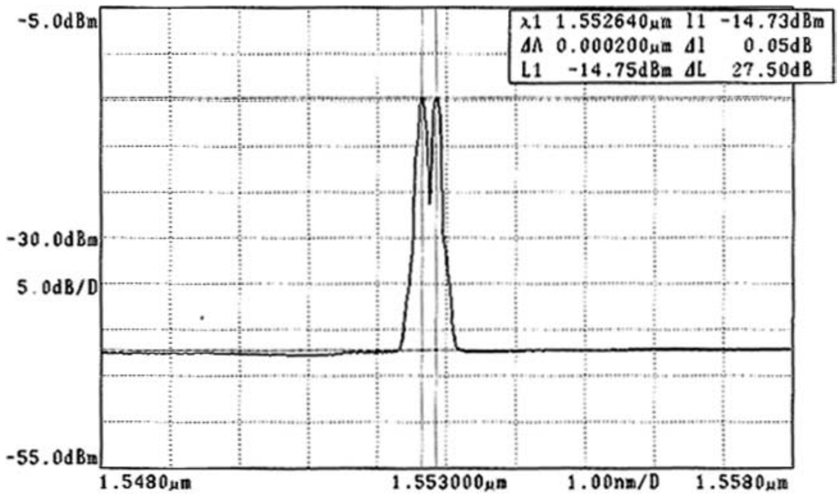

Fig. 4. Dual-wavelength operation of the laser for a wavelength separation of 0.2 nm.

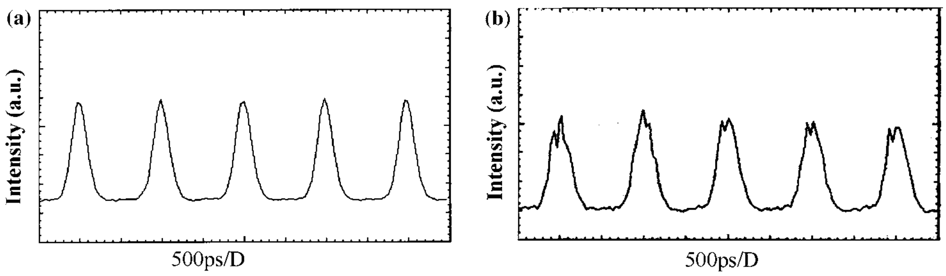

Fig. 5. Optical waveforms of the laser output for a wavelength separation of 0.2 nm when the modulation frequency was 1055.2 MHz. (a) output pulses from the laser, (b) dual-wavelength output pulses traveling through a 50-km single-mode fiber.

The output pulses from the fiber is shown in Fig. 5(b). As can be seen from the figure that the time difference between the pulses at the two wavelengths was about 100 ps, which agrees well with the result of 100 ps calculated from the value of the dispersion parameter of the fiber.

Fig. 6 shows the spectra obtained when the wavelength spacing of the output pulses of the laser was tuned to 0.44 nm. The laser output was stable at room temperature, as shown in the figure by 16 times repeated scan of the output spectrum. Amplitude variation of the two laser lines was less than 0.2 dB. The corresponding waveforms of the output pulses are shown in Fig. 7 when the repetition rate is 1055.2 MHz. Fig. 7(a) shows the dual-wavelength output pulses train directly from the laser. The pulsewidth was measured to be 234 ps and the average output power was about 1.35 mW. The waveform of the output pulses after 50-km single-mode fiber

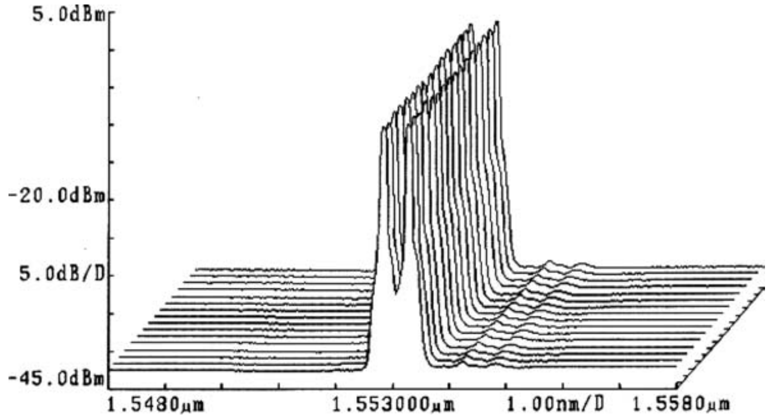

Fig. 6. Repeated scans of the output spectrum under dual-wavelength operation for a wavelength separation of 0.44 nm.

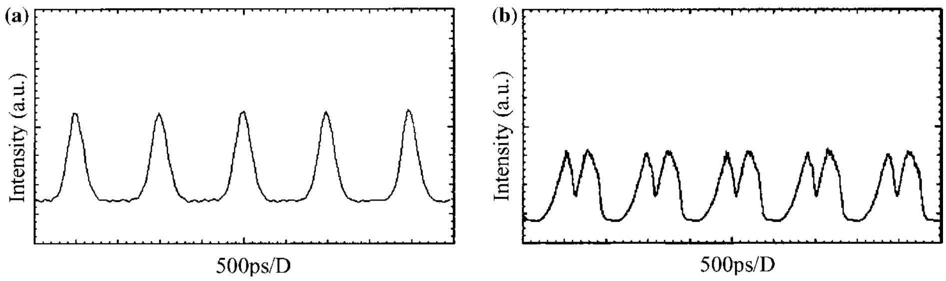

Fig. 7. Optical waveforms of the laser output for a wavelength separation of 0.44 nm when the modulation frequency was 1055.2 MHz. (a) output pulses from the laser, (b) output pulses after 50-km single-mode fiber propagation.

propagation are shown in Fig. 7(b). As shown in the figure, the time difference between the pulses at the two wavelengths was about 210 ps, which agrees well with the result of 215.6 ps calculated from the value of the dispersion parameter of the fiber.

In the experiment, the dual-wavelength operation was very stable at room temperature and no significant drift in wavelength was detected. This is because the PHB greatly increased the inhomogeneous gain broadening of EDF and accordingly reduced the wavelength competition at room temperature. Bending and twisting the fiber led to the change in the output characteristic. When there is no perturbation, the output state is very stable. That also verified the principle of this method. There was small variation in the output power when the wavelength spacing was tuned, mainly due to the reflectivity changes mentioned above, but the wavelength separation can be changed continuously without changing the pulse repetition rate by simply tuning the FBG. Another point we have to note is that with decreased pump power at a given polarization controller setting, the total output power is decreased but the dual-wavelength operation is sustained without significant degradation in the spectrum.

The pulsewidth is somewhat large, we think that it arises from two sources in the experiments: firstly, when we obtained dual-wavelength operation through adjustment the PC, the corresponding polarization states in the cavity was not always the best mode-locked status, due to the polarization sensitivity of the $LiNbO_3$ modulator. So, the pulse-widths were somewhat large mainly due to the light polarization status inputting the modulator. We think this condition can be partly improved by replacing the polarization-sensitive $LiNbO_3$ modulator by a polarization- insensitive modulator. Secondly the narrow bandwidth of the output spectrum. As is predicted by active-mode-locking theory, even in the absence of nonlinear effects, a narrower filter bandwidth leads to a longer pulse duration. In our experiment, the bandwidth of the fiber grating is only 0.1–0.21 nm, thus leading to a large pulsewidth. The time-bandwidth products of all wavelengths are 2.6–2.9 indicating that the pulses are very chirped and not transform-limited. The reason is somewhat similar to that mentioned above. The chirp arises also from cavity dispersion and dispersion obtained during propagation through the 50-km SMF.

4. Conclusion

In conclusion, we have proposed and successfully demonstrated a simple scheme for generating dual-wavelength mode-locked pulses with close wavelength spacing using one Bragg grating in SMF. The proposed laser can be made to operate in stable dual-wavelength at room temperature, due to the birefringence characteristic of the FBG induced by transverse strain. Transverse strain loading on the FBG allows the wavelength spacing to be controlled. Generation of stable dual-wavelength pulses with a pulsewidth of 212–234 ps and a tunable wavelength separation from 0.2 to 0.44 nm at a pulse rate of 1.05 GHz was demonstrated. The laser has the advantage over alternative techniques in that it is spectrally stable and has a simple configuration, increased control of tuneability and low cost.

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References

Bakhshi, B.and P.A. andrekson. *IEEE Photon. Technol. Lett.* **11** 1387, 1999.
Chan, S.W. and C. Shu. *IEEE Photon. Technol. Lett.* **14** 771, 2002.
Chen, L.R. G.E. Town, P.Y. Cortes, S. LaRochelle and P.W.E. Smith. *Electron. Lett.* **36** 1921, 2000.
Deparis, O., R. Kiyan, S.A. Vasiliev, O.I. Medvedkov, E.M. Dianov, O. Pottiez, P. Megret, and M. Blondel. *IEEE Photon. Technol. Lett.* **13,** 284, 2001.
Gafsi, R. and M. A. EI-Sherif. *Optical Fiber Technol.* **6** 299, 2000.
Hernandez-Cordero, J., V.A. Kozlov, A.L.G. Carter and T.F. Morse. *IEEE Photon. Technol. Lett.* **10** 941, 1998.
Lee, K.L. and C. Shu. *IEEE Photon. Technol. Lett.* **12** 624, 2000.
Li, S. and K.T. Chan. *IEEE Photon. Technol. Lett.* **11** 179, 1999.
Lou, J.W. T.E. Carruthers and M. Currie. *IEEE Photon. Technol. Lett.* **14** 281, 2002.
Pudo, D. and L.R. Chen. *Electron. Lett.* **39,** 272, 2003.
Pudo, D., L.R. Chen, D. Giannone, L. Zhang and I. Bennion. *IEEE Photon. Technol. Lett.* **14** 143, 2002.
Town, G.W., L. Chen and P.W.E. Smith. *IEEE Photon. Technol. Lett.* **12** 1459, 2000.
Yang, S., Z. Li, S. Yuan, X. Dong.and Q. Zhao. *IEEE Photon. Technol. Lett.* **14** 1494, 2002.
Zhao, D. K.T. Chan, Y. Liu, L. Zhang and I. Bennion. *IEEE Photon. Technol. Lett.* **13** 191, 2001.