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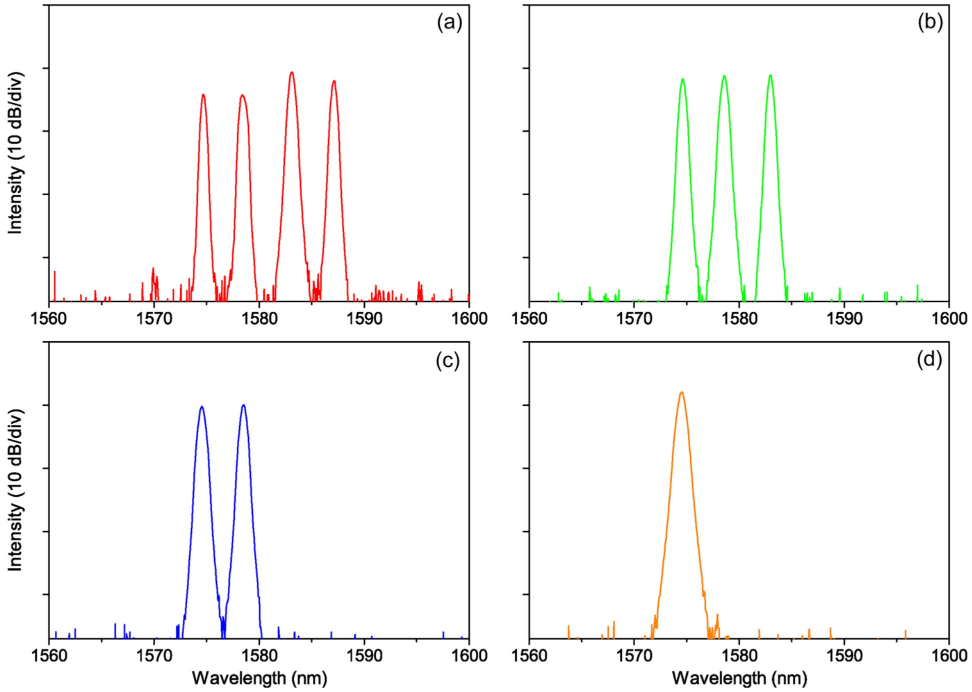

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Tunable Multiwavelength Passively Mode-Locked Fiber Ring Laser Using Intracavity Birefringence-Induced Comb Filter

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Abstract: A simple configuration for the generation of tunable multiwavelength picosecond-pulse fiber ring lasers by exploiting the intracavity birefringence-induced comb filter is demonstrated. The fiber laser is passively mode locked by using nonlinear polarization rotation (NPR) technique. The polarization-dependent isolator combined with the intracavity birefringence acts as two functions: the tunable comb filter and the mode locker. Up to four-wavelength picosecond pulses were simultaneously obtained in the experiment. The mode competition of the multiwavelength lasing is suppressed by the use of NPR-induced intensity-dependent loss. In addition, the number of the lasing wavelengths, the lasing location, and the spacing between the lasing wavelengths could be flexibly tuned by properly rotating the polarization controllers.

Index Terms: Multiwavelength lasers, passively mode-locked, fiber lasers, birefringence filter.

1. Introduction

Multiwavelength pulses fiber lasers have attracted much attention due to their wide applications in wavelength-division-multiplexed (WDM) optical fiber communication, optical fiber sensing, optical signal processing, and optical instrumentation. To date, many approaches have been proposed to realize the multiwavelength pulses operation. The self-seeded Fabry–Perot laser diode (FP-LD) with fiber Bragg gratings (FBGs) was used to generate the multiwavelength pulses [1], [2]. Nevertheless, the reflected wavelengths of the FBGs must be finely adjusted to the selected modes of the FP-LD, and the modulation frequency or the external cavity length should be tuned to make the feedback pulses arrive at the FP-LD during the pulse-buildup time. The actively mode-locked technique is also an effective way to generate multiwavelength optical pulses [3]–[6]. The multiwavelength actively mode-locked pulses have such advantages as high repetition and narrow wavelength spacing. However, it cannot be neglected that a modulator has to be incorporated into the laser cavity, which increases the cost and the insertion loss. In addition, the pulses should pass through the modulator synchronously to generate stable multiwavelength pulses, which means that other techniques need to be employed to ensure the multiwavelength actively mode-locked operation which makes the laser system more complex.

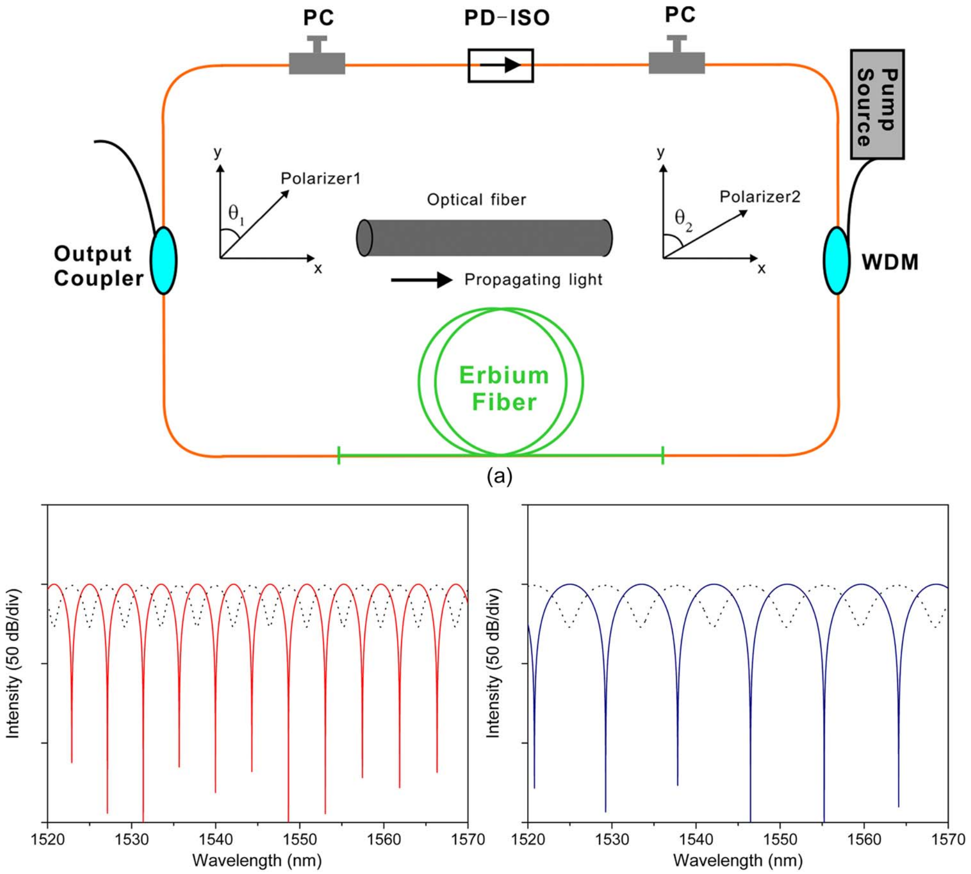
In passively mode-locked fiber lasers, the output pulses have the benefits of the high peak power and good stability. Moreover, the laser system is much simpler since no modulator is required in passively mode-locked fiber lasers. Therefore, the multiwavelength passively mode-locked fiber lasers are also worthy to be investigated. The main challenge of stable multiwavelength erbium-doped fiber (EDF) lasers at room temperature is the strong homogeneous line broadening. However, by taking the intrinsic advantage of the intensity-dependent loss induced by the nonlinear polarization rotation (NPR) technique, one can efficiently suppress the mode competition [7]–[10] and obtain the stable multiwavelength passively mode-locked operation at room temperature. The stable dual- or triple-wavelength passively mode-locked fiber laser by using the polarization maintain fiber (PMF) [11] or all normal dispersion cavity [12] have been demonstrated. However, the PMF incorporated in the laser cavity fixes the channel spacing which is unfavorable for obtaining tunable operation, and the pulses generated from an all normal dispersion cavity have larger pulse duration with lower peak power. The multiwavelength passively mode-locked operation can also be achieved by slicing the broadband pulse spectrum with a comb filter [13]. Nevertheless, the fiber laser also lacks flexible operation. In some practical applications, the tunability of multiwavelength mode-locked fiber laser, such as the number of the lasing wavelengths and the spacing between the lasing wavelengths, should be investigated. The most popular approaches used to realize the tunable operation of the multiwavelength fiber lasers are to incorporate an additional tunable comb filters such as the Lyot filter [14], the Sagnac loop with FBG [15], and the modified Mach–Zehnder interferometer [16]. Actually, a polarizer inserted into the cavity of the fiber ring laser can also act as a tunable comb filter whose channel spacing varies with the cavity birefringence. In this paper, we report a simple tunable multiwavelength picosecond pulses fiber ring laser based on the intracavity birefringence-induced comb filter and the NPR technique. The polarizer provided by the polarization-dependent isolator (PD-ISO) combining with the intracavity birefringence serves as both the tunable comb filter and the mode locker. Up to four-wavelength picosecond pulses were simultaneously obtained. Furthermore, the number of the lasing wavelengths, the lasing location and the lasing wavelength spacing could be flexibly tuned by properly rotating the polarization controllers (PCs).

2. Experimental Setup and Principle

The schematic of the proposed fiber ring laser is shown in Fig. 1(a). A 5-m-long EDF with a dispersion parameter of $D \approx -15$ ps/(nm $\cdot$ km) and a 13.3-m-long single-mode fiber (SMF) with a dispersion parameter of $D = 17$ ps/(nm $\cdot$ km) comprise the ring cavity. Therefore, the fundamental repetition is 11.02 MHz. The PD-ISO provides the functions of the tunable comb filter and the mode locker by combing with the intracavity birefringence. Two PCs are employed to adjust the polarization states of the pulses and the cavity birefringence by squeezing the fiber inside them. The output is taken by a 10% fiber coupler. An optical spectrum analyzer (OSA) and an oscillograph are used to study the pulse spectrum and the output pulse-train, respectively. The pulse duration was also measured by using a commercial autocorrelator. Since the fiber laser has a ring structure, it is equivalent to a length of birefringent fiber with two polarizers at both ends, which can be treated as a Lyot birefringence filter, as shown in the inset of Fig. 1(a). The transmission function of intracavity birefringence-induced comb filter can be described as [17]–[19]:

$$T = \cos^2\theta_1 \cos^2\theta_2 + \sin^2\theta_1 \sin^2\theta_2 + \frac{1}{2}\sin(2\theta_1)\sin(2\theta_2)\cos(\Delta\varphi_L + \Delta\varphi_{NL}). \qquad (1)$$

Here, θ_1 and θ_2 are the angles between the polarization directions of the polarizers and the fast axes of the fiber, and $\Delta\varphi_L = 2\pi L(n_y - n_x)/\lambda$ and $\Delta\varphi_{NL} = 2\pi n_2 PL\cos(2\theta_1)/(\lambda A_{eff})$ are the linear and the nonlinear cavity phase delay, respectively. L is equal to the laser cavity length, λ is the



(a)

(b)

Fig. 1. (a) Schematic of the proposed tunable multiwavelength fiber ring laser. (b) Calculated tunable transmission spectra of the intracavity birefringence-induced comb filter by rotating the PCs.

operating wavelength, n_2 is the nonlinear coefficient, P is the instantaneous power of input signal, and A_{eff} is the effective fiber core area. From (1), one knows that the transmission coefficient varies periodically with respect to the wavelength. Consequently, it can be treated as a spectral comb filter whose channel spacing is dependent on the intracavity birefringence. Although the laser cavity is constructed with SMF, there is strong birefringence caused by the fiber squeezing of the PCs and the fiber winding. Note that the rotation of the PCs changes the cavity birefringence and the angles of θ_1 and θ_2. Therefore, the spectral spacing and the transmission peak position of the intracavity birefringence-induced comb filter can be tuned by rotating the PCs, as shown in Fig. 1(b).

3. Results and Discussions

The NPR technique was used to achieve the self-started mode-locking operation of the fiber laser. The mode-locking threshold was about 20 mW in our fiber laser. In the experiment, when we increased the 980 nm pump power above the mode-locking threshold, the fiber laser achieved the mode-locking state by properly adjusting the PCs. Depending on the settings of the cavity parameters, such as the 980-nm pump power and the orientations of the PCs, up to four-wavelength picosecond pulses could be always obtained. Then, we fixed the pump power in the following experiment, which was about 75 mW. First, we concentrated on the lasing wavelength number tunability of the multiwavelength mode-locked operation in the fiber ring laser. Fig. 2 presents the lasing wavelength number tunable operation in our fiber laser via properly rotating the PCs. Due to the adjustment of the PCs, which results in the variations of the comb spectrum of the intracavity

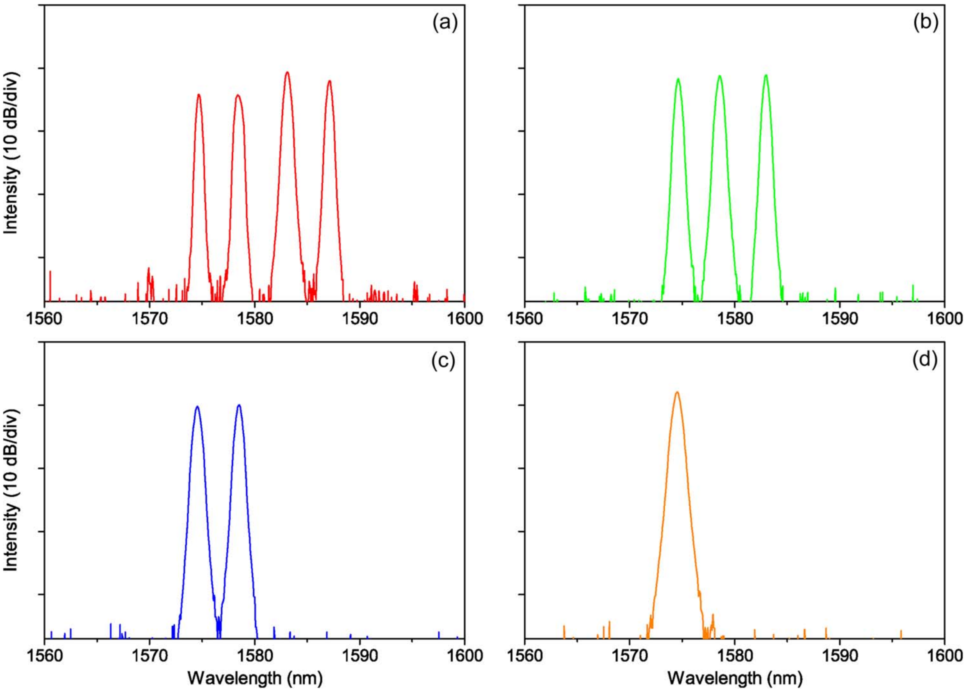


Fig. 2. Tunable operation of the lasing wavelength number by properly adjusting the orientations of the PCs.

birefringence-induced comb filter, the number of the lasing wavelengths could be continuously tuned from 4 to 1, as shown in Fig. 2. Specifically, in Fig. 2(a), the central wavelengths of the four pulses locate at 1574.68 nm, 1578.49 nm, 1583.05 nm, and 1587.12 nm, respectively. Consequently, the channel spacing of the four lasing wavelengths is $\sim$4 nm, which corresponds to an average cavity refractive index difference 3.2×10^{-5}. Correspondingly, the 3-dB spectral bandwidths of the four pulses are 0.60 nm, 0.80 nm, 0.72 nm, 0.64 nm, respectively.

Since the four lasing wavelengths were simultaneously mode-locked by using NPR technique, the intensity-dependent loss induced by the NPR effect can be used to efficiently suppress the mode competition. Therefore, the output multiwavelength pulses were stable at room temperature in the experimental observation. Note that the intensities and transmission peak positions of multiwavelength mode-locked pulses are mainly determined by the transmission function of the intracavity birefringence-induced comb filter. Thus, the intensities of the multiwavelength pulses as well as the central wavelengths shown in Fig. 2 changed slightly during the process of the adjustment of the PCs. It is worthy to note that the tunable operation of the lasing wavelength number is a reversible process, which can be tuned back to four wavelengths by rotating the PCs in a contrary direction. In the experiment, the output pulses at other wavelength regions could also be obtained by rotating the PCs; however, we only concentrated on the lasing wavelength region from 1570 nm to 1590 nm here. Then we observed individual pulse at different wavelength in the time domain. Apart from the intensity differences, the four-wavelength pulses were similar to each other, including the same repetition shown on the oscillograph due to the limited response of the photodetector. Therefore, we illustrated the pulse-train and the autocorrelation trace corresponding to Fig. 2(d). In Fig. 2(d), the 3-dB spectral bandwidth is 0.88 nm. The pulse duration, assumed as the fit of hyperbolic secant pulse shape, is 3.48 ps, as shown in Fig. 3. Correspondingly, we have shown the mode-locking pulse-train in the inset of Fig. 3. The average output power of the pulse-train is 1.65 mW. The pulse repetition, which is determined by the cavity length, is 11.02 MHz.

As the PCs were rotated in proper positions, a larger spectral spacing of the comb filter could be obtained. Moreover, the transmission peak position could be continuously tuned with the adjustment of the PCs [20]. When the channel spacing of the intracavity birefringence-induced comb filter

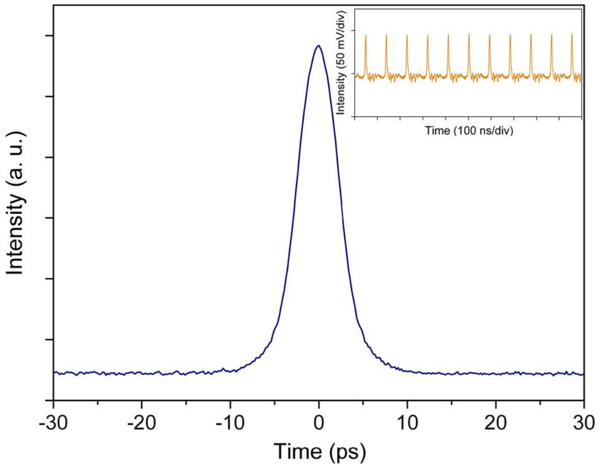


Fig. 3. Autocorrelation trace and pulse-train corresponding to Fig. 2(d).

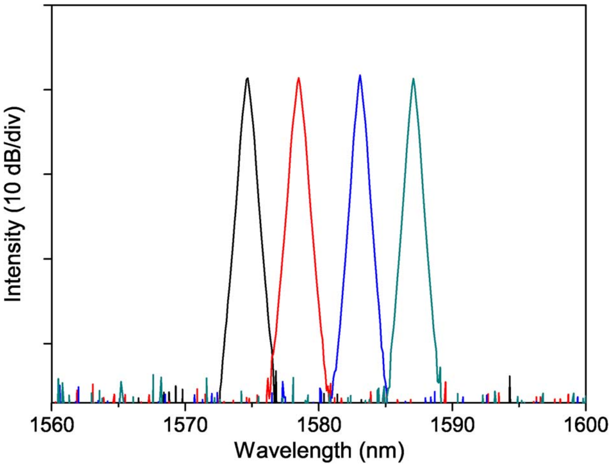


Fig. 4. Output spectra of the single wavelength tunable operation.

becomes comparable with that of the four lasing wavelength range shown in Fig. 2(a), the single-wavelength pulse operation could be flexibly tuned to anyone location of the four lasing wavelengths, as shown in Fig. 4. In the case of single-wavelength tunable operation, the 3-dB spectral bandwidth and the intensity of the lasing pulse are almost kept invariable.

With the further adjustment of the PCs, we were able to obtain the dual-wavelength switching operation with different channel spacing. Fig. 5 illustrates the output spectra of the dual-wavelength switching operation (red and blue dotted curves) with two different lasing channel spacings. The wavelength separations of the dual-wavelength pulses are $\sim$4 nm and $\sim$8 nm in Fig. 5(a) and (b), respectively. Here, we also can deduce that the average cavity refractive index difference is about 1.6×10^{-5} in Fig. 5(b). In Fig. 5(a), the intensities of the dual-wavelength pulses are almost equal. Nevertheless, the dual-wavelength pulses in Fig. 5(b) show a larger difference in the pulse's intensities.

In the experiment, the relative intensities of the lasing wavelengths varied with the PC settings. It is because that the transmission function of the laser system with respect to wavelength is related to the PC settings. By slightly adjusting the PCs, we could change the relative strength of the pulses and the wavelength separation between the lasing wavelengths. In addition, note that the lasing pulses should simultaneously satisfy both the mode-locking condition and the transmission function

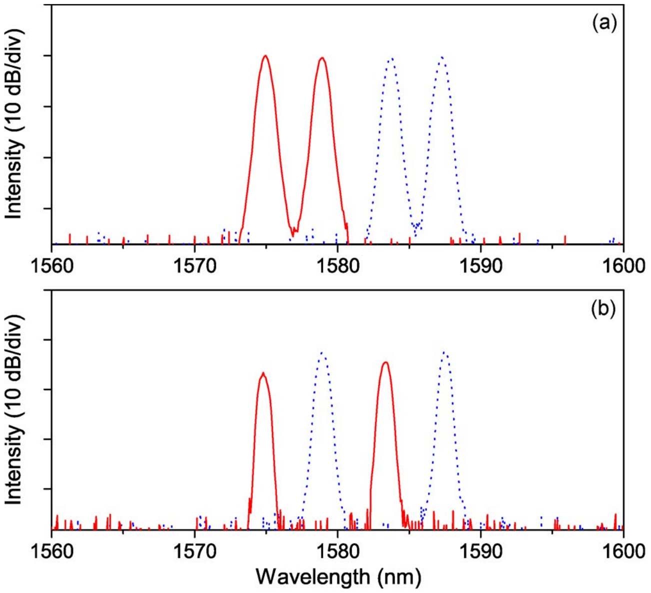


Fig. 5. Dual-wavelength switching operation. The wavelength separations are (a) ~4 nm and (b) ~8 nm.

of the comb filter. As a result, the experimentally obtained channel spacing and the relative intensities between the lasing wavelengths were not accurately identical, i.e., in Figs. 2 and 5. Nevertheless, the generally tunable behavior of the output spectra of multiwavelength pulses is still defined by the intracavity birefringence-induced comb filter. In addition, it is also to note that the 3-dB spectral bandwidths of the pulses were narrower than 1 nm, and no spectral sidebands were observed in the experiment because the obtained pulses in our fiber laser are regarded as linear pulses but not soliton pulses [18].

4. Conclusion

In conclusion, we have demonstrated a tunable multiwavelength passively mode-locked fiber ring laser in conjunction with the intracavity birefringence-induced comb filter. The tunability of the comb filter, which consists of a polarizer and intracavity birefringence, was realized by rotating the PCs. Up to four-wavelength picosecond pulses were obtained by using the NPR technique. By taking the intrinsic advantage of NPR-induced intensity-dependent loss mechanism, the stable multiwavelength pulses output was achieved. Furthermore, we could flexibly tune the lasing wavelength number, the lasing locations and the separation between the lasing wavelengths with proper adjustment of the PCs.

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References

[1] S. Li, K. T. Chan, Y. Liu, L. Zhang, and I. Bennion, “Multiwavelength picosecond pulses generated from a self-seeded Fabry–Perot laser diode with a fiber external cavity using fiber Bragg gratings,” *IEEE Photon. Technol. Lett.*, vol. 10, no. 12, pp. 1712–1714, Dec. 1998.

[2] Y. Liu, K. S. Chiang, and P. L. Chu, “Generation of dual-wavelength picosecond pulses from a self-seeded Fabry–Perot laser diode and a polarization-maintaining fiber Bragg grating,” *IEEE Photon. Technol. Lett.*, vol. 16, no. 7, pp. 1742–1744, Jul. 2004.

[3] G. E. Town, L. Chen, and P. W. E. Smith, “Dual wavelength modelocked fiber laser,” *IEEE Photon. Technol. Lett.*, vol. 12, no. 11, pp. 1459–1461, Nov. 2000.

[4] S. Pan and C. Lou, "Multiwavelength pulse generation using an actively mode-locked erbium-doped fiber ring laser based on distributed dispersion cavity," *IEEE Photon. Technol. Lett.*, vol. 18, no. 4, pp. 604–606, Feb. 2006.

[5] J. Yao, J. P. Yao, and Z. Deng, "Multiwavelength actively mode-locked fiber ring laser with suppressed homogeneous line broadening and reduced supermode noise," *Opt. Express*, vol. 12, no. 19, pp. 4529–4534, Sep. 2004.

[6] Z. Chen, H. Sun, S. Ma, and N. K. Dutta, "Dual-wavelength mode-locked erbium-doped fiber ring laser using highly nonlinear fiber," *IEEE Photon. Technol. Lett.*, vol. 20, no. 24, pp. 2066–2068, Dec. 2008.

[7] S. L. Pan and C. Y. Lou, "Stable multiwavelength dispersion-tuned actively mode-locked erbium-doped fiber laser using nonlinear polarization rotation," *IEEE Photon. Technol. Lett.*, vol. 18, no. 13, pp. 1451–1453, Jul. 2006.

[8] X. Feng, H. Tam, and P. K. A. Wai, "Stable and uniform multiwavelength erbium-doped fiber laser using nonlinear polarization rotation," *Opt. Express*, vol. 14, no. 18, pp. 8205–8210, Sep. 2006.

[9] C. H. Tu, W. G. Guo, Y. N. Li, S. G. Zhang, and F. Y. Lu, "Stable multiwavelength and passively mode-locked Yb-doped fiber laser based on nonlinear polarization rotation," *Opt. Commun.*, vol. 280, no. 2, pp. 448–452, Dec. 2007.

[10] Z. Zhang, L. Zhan, K. Xu, J. Wu, Y. Xia, and J. Lin, "Multiwavelength fiber laser with fine adjustment, based on nonlinear polarization rotation and birefringence fiber filter," *Opt. Lett.*, vol. 33, no. 4, pp. 324–326, Feb. 2008.

[11] Y. D. Gong, X. L. Tian, M. Tang, P. Shum, M. Y. W. Chia, V. Paulose, J. Wu, and K. Xu, "Generation of dual wavelength ultrashort pulse outputs from a passive mode locked fiber ring laser," *Opt. Commun.*, vol. 265, no. 2, pp. 628–631, Sep. 2006.

[12] H. Zhang, D. Y. Tang, X. Wu, and L. M. Zhao, "Multi-wavelength dissipative soliton operation of an erbium-doped fiber laser," *Opt. Express*, vol. 17, no. 15, pp. 12 692–12 697, Jul. 2009.

[13] Z. X. Zhang, K. Xu, J. Wu, X. B. Hong, and J. T. Lin, "Two different operation regimes of fiber laser based on nonlinear polarization rotation: Passive mode-locking and multiwavelength emission," *IEEE Photon. Technol. Lett.*, vol. 20, no. 12, pp. 979–981, Jun. 2008.

[14] M. P. Fok, C. Shu, and W. W. Tang, "A cascadable approach to produce widely selectable spectral spacing in birefringent comb filters," *IEEE Photon. Technol. Lett.*, vol. 18, no. 18, pp. 1937–1939, Sep. 2006.

[15] X. Shu, S. Jiang, and D. Huang, "Fiber grating Sagnac loop and its multiwavelength-laser application," *IEEE Photon. Technol. Lett.*, vol. 12, no. 8, pp. 980–982, Aug. 2000.

[16] Z. C. Luo, A. P. Luo, and W. C. Xu, "Polarization-controlled tunable all-fiber comb filter based on a modified dual-pass Mach–Zehnder interferometer," *IEEE Photon. Technol. Lett.*, vol. 21, no. 15, pp. 1066–1068, Aug. 2009.

[17] C. J. Chen, P. K. A. Wai, and C. R. Menyuk, "Soliton fiber ring laser," *Opt. Lett.*, vol. 17, no. 6, pp. 417–419, Mar. 1992.

[18] D. Y. Tang, L. M. Zhao, B. Zhao, and A. Q. Liu, "Mechanism of multisoliton formation and soliton energy quantization in passively mode-locked fiber lasers," *Phys. Rev. A, Gen. Phys.*, vol. 72, no. 4, p. 043816, Oct. 2005.

[19] Z. C. Luo, W. C. Xu, C. X. Song, A. P. Luo, and W. C. Chen, "Pulse-train nonuniformity in an all-fiber ring laser passively mode-locked by nonlinear polarization rotation," *Chin. Phys. B*, vol. 18, no. 6, pp. 2328–2333, Jun. 2009.

[20] H. Zhang, D. Y. Tang, R. J. Knize, L. Zhao, Q. Bao, and K. P. Loh, "Graphene mode locked, wavelength-tunable, dissipative soliton fiber laser," *Appl. Phys. Lett.*, vol. 96, no. 11, p. 111 112, Mar. 2010.