Dual Orthogonal Polarization States in an Active Mode-Locked Birefringent Fiber Ring Laser

Huy Quoc Lam, P. Shum, Le Nguyen Binh, Y. D. Gong, and Ming Tang

***Abstract*—We report the generation of dual amplitude pulses in an active mode-locked fiber laser within a birefringent cavity. Different to normal mode-locked pulses with identical amplitude and polarization state, and pulses polarized on both x- and y-axes simultaneously exist in the output pulse train. The two orthogonal pulse sequences have different amplitudes and lase at different wavelengths. Dual wavelengths are the result of red shift and blue shift of the x- and y-polarization states of the generated pulses, respectively, due to the detuning phenomena. Locking to individual x- or y-polarized pulse is also obtained by adjusting polarization controllers.**

***Index Terms*—Birefringence, duality, fiber laser, laser, mode-locked lasers, polarization.**

I. INTRODUCTION

ACTIVE mode-locked fiber lasers are very attractive for the generation of ultrashort optical pulses at multiple wavelengths with multiple gigabits-per-second repetition rate [1], [2]. Although tremendous investigations have been performed to explore mode-locking mechanisms and applications for various mode-locked fiber lasers [3], [4], dynamic behavior of the active mode-locked fiber laser is still not fully understood.

Recently, we reported a polarization-switching phenomenon of an active mode-locked fiber laser when tuning the modulation frequency [5]. In this letter, we further investigate the dynamic property of the active mode-locked fiber laser with a highly birefringent cavity. Dual-wavelength (dual-mode) pulses corresponding to orthogonal polarization states are generated simultaneously in the single cavity with different amplitude and pulse properties. By carefully adjusting the polarization state, we also achieve stable mode-locking of two modes separately. The demonstrated phenomenon is useful for understanding the polarization dynamic of the active mode-locked fiber laser and for developing highly stable light source for future optical networks or sensor applications.

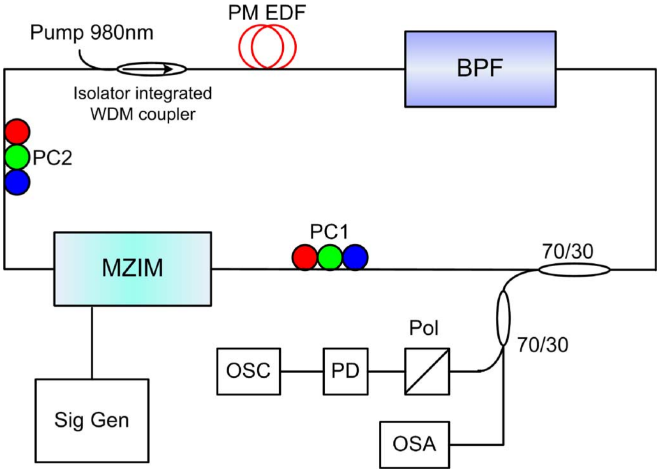

Fig. 1. Active mode-locked fiber laser with birefringent cavity. BPF: bandpass filter. MZIM: Mach–Zehnder intensity modulator. Pol: Polarizer. PD: photodiode. OSC: oscilloscope. OSA: optical spectrum analyzer. Sig Gen: signal generator.

II. EXPERIMENTAL SETUP

Fig. 1 shows the experimental setup of the active mode-locked fiber laser incorporating a birefringent cavity. The laser has a ring configuration with 15 m of polarization-maintaining erbium-doped fiber (PM-EDF) serving as a gain medium. This PM-EDF also causes the laser cavity to become birefringent. The PM-EDF is pumped by a 980-nm laser diode through a wavelength-division-multiplexing (WDM) coupler. An isolator integrated in the WDM ensures unidirectional lasing. A thin-film 1.2-nm tunable optical bandpass filter is used to tune the lasing wavelength. A $\mathrm{LiNbO_3}$ Mach–Zehnder intensity modulator is incorporated in the cavity to stimulate mode-locking through the amplitude modulation process. The modulator is driven by a microwave signal extracted from a signal generator. The polarization controller (PC) is used to adjust the polarization state of the lightwave signal traveling in the ring. The optical signal in the ring is coupled to the output port through a 70 : 30 coupler.

The output signal is monitored by a high-speed sampling oscilloscope (50-GHz 3-dB bandwidth) proceeded by a photodiode (45-GHz 3-dB bandwidth). A polarizer is also inserted in front of the photodiode when the polarization state of the output signal is analyzed. An optical spectrum analyzer with a resolution of 0.01 nm is used to record the pulse spectrum.

III. RESULTS AND DISCUSSION

The total length of the cavity is about 29.5 m which corresponds to a fundamental frequency f_R of 6.923 MHz. The

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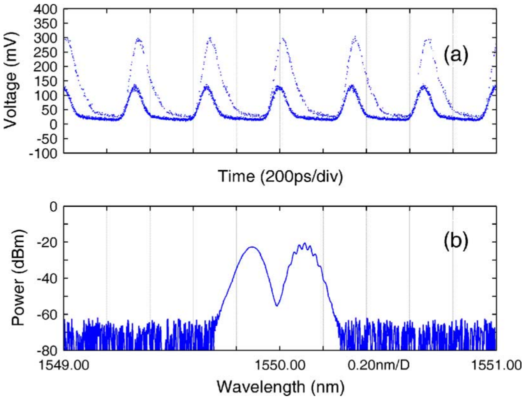

Fig. 2. (a) Oscilloscope trace of the output pulses shows dual-amplitude property of the pulse train; (b) the pulse spectrum also shows dual wavelengths.

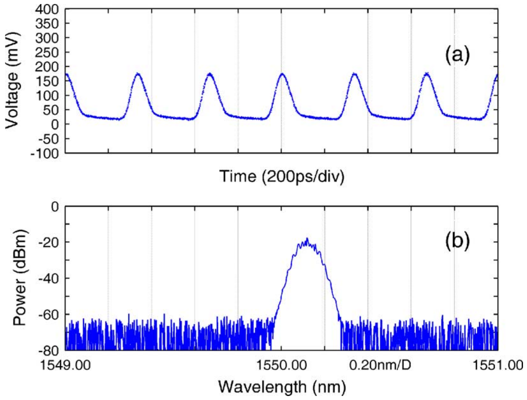

Fig. 3. (a) Pulse trace and (b) its spectrum when the PCs are adjusted so that only low amplitude pulses exist in the loop; clear underfoot shows no pulse dropping.

modulator is biased at the quadrature point. The central wavelength of the filter is 1550 nm. The modulation frequency is 2.997668 GHz, which corresponds to the resonance of the 433th harmonic. When the PC is adjusted at an appropriate position, we observed on the oscilloscope a well-defined mode-locked pulse train, as shown in Fig. 2(a). It is interesting to note that the pulse sequence has two amplitude levels. This indicates that the pulse train actually consists of low and high amplitude pulses which can be denoted as the x- and y- pulse sequences, respectively. It is noticed that the x-pulse sequence appears brighter than the y-pulse. This means that there are more x-pulses than that of the y-pulses in the pulse train. The sampling oscilloscope samples the pulse train for every sampling interval and each sample gives a dot on the screen. Therefore, more samples obtained for the high population of x-pulses result in a brighter trace of the x-pulse on the screen.

Fig. 2(b) shows the optical spectrum of the pulse train. The spectrum is totally different from a normal mode-locked pulse train spectrum. It does not follow a Gaussian shape with peak at the filter center wavelength; instead there exists two peaks located on two sides of the filter center wavelength. The separation is about 0.25 nm. The longer wavelength peaks at 1550.12 nm and has the mode-locked structure of several longitudinal modes of spacing about 0.02 nm that corresponds to the modulation frequency of 2.998 GHz. The shorter wavelength peaks at 1549.87 nm and has a smoother structure. It thus demonstrates that the mode-locked pulses are not only dual amplitudes in the time domain but also dual wavelengths in the frequency domain. It is questionable whether the two wavelengths are from the two types of pulses. One corresponds to x-pulses and the other corresponds to y-pulse.

To answer this question, we operated the laser in two different modes by adjusting the PCs. Fig. 3 shows the oscilloscope trace of the pulse train and its spectrum when the PC is adjusted to support only the x-pulse. There is now only the low amplitude component in the pulse trace. Clear underfoot pulse trace indicates that there is no pulse dropping. Every time slot in the pulse train is filled with the x-pulse. This results in the mode-locking as observed in its spectrum in Fig. 3(b). The spectrum shows that the x-pulse is corresponding to the long wavelength component of the dual-pulse spectrum.

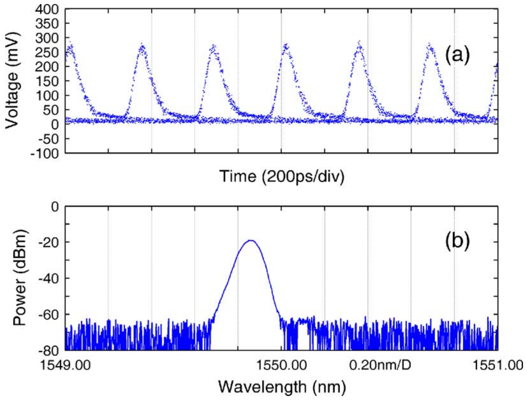

Fig. 4. (a) Pulse trace and (b) its spectrum when the PCs are adjusted so that only high amplitude pulses exist in the loop; underfoot shows that there are some pulses dropped in the loop.

Furthermore, the PCs are also adjusted to lock the laser to the high amplitude level pulse sequence. The low amplitude pulses no longer exist as shown in Fig. 4(a). In contrast to the x-pulse locking case, the pulse trace here has an underfoot. This means that not every time slot in the pulse train is filled. It is easily understood that the pulse dropping is caused by the energy limitation of the laser. High energy of the y-pulse requires high power from the pump to make all time slots filled. Failure to this requirement results in pulse dropping [4]. It is noted that the high amplitude pulse is brighter than that of the dual-pulses case. This means there are more y-pulses in the loop than before. The energy of the x-pulses transfers to the y-pulses and hence more y-pulses are formed but not all slots of the pulse train circulating in the loop are filled. Pulse dropping causes unequal spacing of the pulse. Therefore, the Fourier transformed pulse sequence no longer has a smooth mode-locking structure as the spectrum shown in Fig. 4(b). This spectrum corresponds to the short wavelength component of the dual-pulse spectrum.

Dual-pulses locking can be explained as follows. With proper setup of PC in the cavity, the laser can support two orthogonal modes which can be considered as the two eigen-modal solutions of the coupled nonlinear Schrödinger equations.

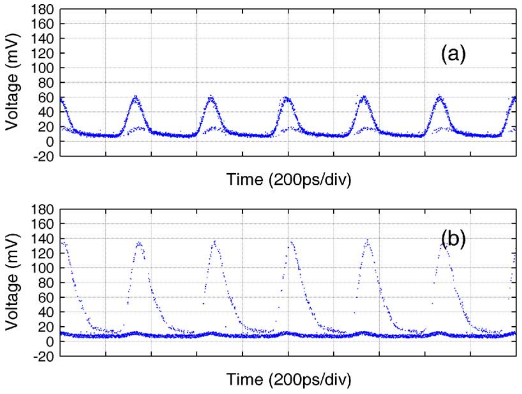

Fig. 5. (a) X-axis component and (b) y-axis component of the dual-pulse train; high amplitude pulses and low amplitude pulses are orthogonally polarized.

In the Nth order harmonic mode-locked fiber laser, there is not only one pulse but there are N pulses simultaneously traveling in the loop. A pulse of any solution can occupy one time slot in the pulse train. Therefore, there is a mixture of pulses from the two modes in the pulse train which appears as dual amplitude pulses overlapping on the oscilloscope screen.

Moreover, the slow and fast axis modes are under different detuning due to birefringence of the cavity. The slow axis mode is negatively detuned while the fast axis mode is positively detuned. It should be noted that the laser cavity has a normal dispersion with an average value of $-28.5\ \mathrm{ps/nm/km}$. In order to keep synchronizing, the wavelength of the slow axis mode is shifted to a longer wavelength so that it travels faster than the fast axis mode in the normal dispersion cavity. In contrast, the fast axis mode is shifted to a shorter wavelength and hence is slowed down by the normal dispersion of the fiber cavity [6], [7]. The wavelength shifting of the two modes is clearly observed in Figs. 2–4. The x-pulse spectrum is at longer wavelength while the y-pulse spectrum is at a shorter wavelength.

To verify that the pulse train consists of pulses on two orthogonal axes, we use a polarizer to analyze the output pulse train. The polarizer is rotated to two orthogonal positions. Fig. 5(a) is the pulse trace when the polarizer is at Position 1. The high amplitude pulses are attenuated and appear as the underfoot while the low amplitude pulses reach the maximum value. In contrast, as shown in Fig. 5(b), the low amplitude pulses are highly attenuated and the high amplitude pulses reach their maxima when the polarizer is set at Position 2.

It is noted that although no stabilization technique was applied, stable pulses were obtained for several hours when the laser was operated to generate either x-pulse or y-pulse alone; dual-pulse operation was stable for more than one hour. Besides, the phenomenon was also obtained when the modulation frequency increased to 10 GHz but the stability was an issue. Moreover, the adjustment needs to be carefully handled since the higher the frequency, the larger the bandwidth of the mode-locked laser; hence, the PMD effect will cause some polarization fading and coupling.

IV. CONCLUSION

By employing a birefringent ring cavity, we have generated a dual amplitude pulse train from an active mode-locked fiber laser. The pulse train consists of pulses polarized on both x- and y-axes. The x-polarized pulses have lower amplitude and lase at a longer wavelength than those of the y-axis ones. Therefore, we observed the dual amplitude pulse trace and dual wavelengths on the optical spectrum analyzer. Moreover, locking to only x-axis pulse or y-axis pulse has also been obtained by controlling the coupled polarization state of the generated lightwave.

REFERENCES

[1] M. Nakazawa, “Ultrafast optical pulses and solitons for advanced communications,” in *5th Pacific Rim Conf. Lasers and Electro-Optic (CLEO/Pacific Rim 2003)*, Taipei, Taiwan, 2003.

[2] K. K. Gupta, N. Onodera, K. S. Abedin, and M. Hyodo, “AM mode-locked fibre ring laser generating highly stable, higher-order optical pulse trains with a wavelength tuning range of 1535 nm –1560 nm,” in *Int. Topical Meeting on Microwave Photonics (MWP 2001)*, Long Beach, CA, 2002.

[3] H. A. Haus, “Mode-locking of lasers,” *IEEE J. Sel. Topics Quantum Electron.*, vol. 6, no. 6, pp. 1173–1185, Nov./Dec. 2000.

[4] M. Horowitz, C. R. Menyuk, T. F. Carruthers, and I. N. Duling, III, “Theoretical and experimental study of harmonically modelocked fiber lasers for optical communication systems,” *J. Lightw. Technol.*, vol. 18, no. 11, pp. 1565–1574, Nov. 2000.

[5] H. Q. Lam, P. Shum, L. N. Binh, and Y. D. Gong, “Polarization-dependent locking in SOA harmonic mode locked fiber laser,” *IEEE Photon. Technol. Lett.*, vol. 19, no. 22, pp. 2404–2406, Nov. 15, 2006.

[6] G. Zhu and N. K. Dutta, “Dispersion effects on the detuning properties of actively harmonic mode-locked fiber lasers,” *Opt. Express*, vol. 13, p. 2688, 2005.

[7] K. Tamura and M. Nakazawa, “Dispersion-tuned harmonically mode-locked fiber ring laser for self-synchronization to an external clock,” *Opt. Lett.*, vol. 21, pp. 1984–1986, 1996.