Polarization-Dependent Locking in SOA Harmonic Mode-Locked Fiber Laser

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

***Abstract*—Polarization-dependent states of the output pulse train generated from an active harmonic mode-locked fiber laser by exploiting the birefringence of the fiber ring is reported for the first time. There exist two different fundamental frequencies for each polarization-mode lasing and hence the laser can be forced to mode-locking states of the two orthogonal polarization regimes by tuning or detuning the modulation frequency. Theoretical equations for predicting the tuning frequencies are described and good agreement with experimental results is obtained.**

***Index Terms*—Birefringence, fiber laser, mode lock, polarization, semiconductor optical amplifier (SOA).**

I. INTRODUCTION

ACTIVE mode locking has attracted widespread attention in recent years due to its potential of producing short and high repetition rate pulse sequence, low timing jitter, and ease of synchronization to a stable electronic clock signal [1], [2]. However, stability of the laser is one of the critical issues, especially when harmonic mode locking is required to obtain a repetition rate as high as tens of gigahertz or higher. Super mode noise can cause fluctuation in the amplitude of pulses generated from this kind of laser. In addition, dynamic energy competition which cause pulse dropout and giant pulse locking have been reported [3], [4]. Several techniques have been proposed to improve the stability of the lasers such as intracavity filtering, regenerative mode locking, phase lock-loop feedback control, etc.[2], [5], [6]. However, there are no reports to date addressing the polarization switching phenomena in an active harmonic mode-locked fiber laser. In this paper, we report a new phenomenon that the polarization of the mode-locked pulse can be switched between two orthogonal eigenstates by tuning or detuning the modulation frequency. The matching of the modulation frequency to the harmonic of fundamental frequency of each eigenstate determines the polarization state of the laser. Rigorous theoretical prediction of the separation between two mode-locking modulation frequencies of the polarization states gives reasonable agreement with experimental results.

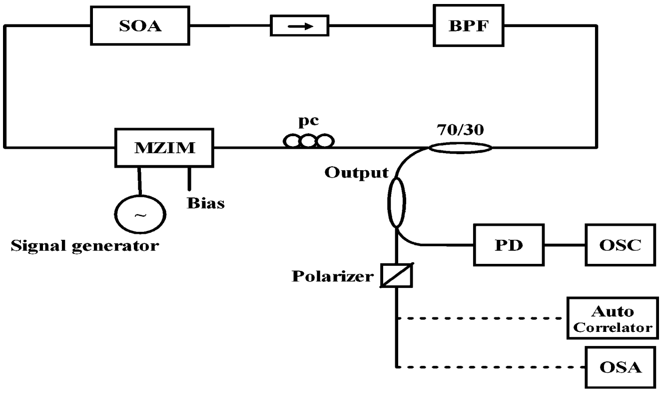

Fig. 1. SOA-based harmonic mode-locked fiber laser. BPF: bandpass filter. PD: photodiode. OSC: oscilloscope. OSA: optical spectrum analyzer.

II. EXPERIMENTAL SETUP

Fig. 1 shows the experimental setup of the semiconductor optical amplifier (SOA)-based active mode-locked fiber laser. The ring configuration incorporating an isolator is used to ensure unidirectional lasing. The optical gain is provided by an SOA with a small signal gain of 18.2 dB and a saturation power of 11.3 dBm. A thin-film 1.2-nm tunable optical bandpass filter is used to tune the lasing wavelength. Mode locking of the lasing lightwave is obtained through amplitude modulation process by incorporating in the ring a $\mathrm{LiNbO_3}$ Mach–Zehnder intensity modulator (MZIM) with the insertion loss of 3 dB. As large as 30% of the optical power in the ring can be coupled to the output port through a 70 : 30 coupler.

The output signal is split into two paths for simultaneous monitoring and characterization. One is amplified and fed into a high-speed photodiode (45-GHz 3-dB bandwidth) for conversion into the electrical signal and then monitored by a high-speed 50-GHz sampling oscilloscope. The other path is analyzed by a polarizer followed by an autocorrelator and/or an optical spectrum analyzer with resolution of 0.01 nm.

III. RESULTS AND DISCUSSION

The fundamental frequency of the ring, estimated as the inverse of the round-trip period of the lightwave traveling in the ring with total length of 17 m, is about 12 MHz. Fig. 2(a) shows the harmonic mode-locked pulse train at a repetition rate of 10 GHz generated when the modulation frequency is set at

Manuscript received March 13, 2006; revised September 19, 2006. This work was supported in part by the Agency for Science, Technology and Research (A*STAR), Singapore, and Open Fund of Key Laboratory of Optical Communication and Lightwave Technologies, Beijing University of Posts and Telecommunications, Ministry of Education, China.

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Color versions of Figs. 4 and 6 are available at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2006.886136

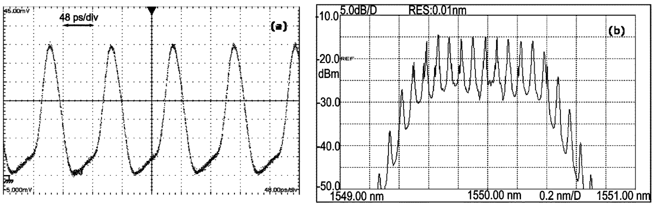

Fig. 2. (a) H-mode pulse trace and (b) its optical spectrum.

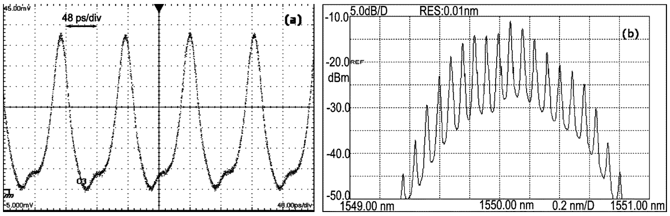

Fig. 3. (a) V-mode pulse trace and (b) its optical spectrum.

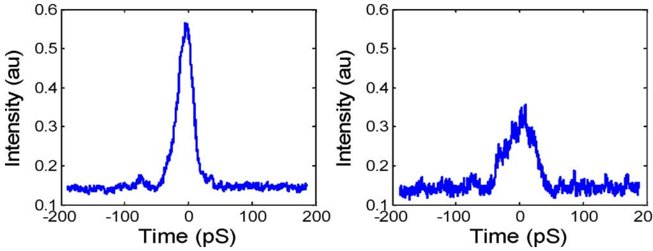

Fig. 4. Autocorrelation traces of H-mode pulses: (a) x-axis component, (b) y-axis component.

10.008426 GHz, according to the 834th harmonic of the fundamental frequency. The pulse sequence optical spectrum shown in Fig. 2(b) clearly shows lasing longitudinal mode spacing of 0.08 nm. The 3-dB bandwidth of the spectrum envelop has been measured as large as 0.77 nm. The locking range is about 260 kHz. However, when the modulation frequency is tuned to 10.009106 GHz, or 680 kHz away from 10.008426 GHz, a stable well-defined mode-locked pulse train appears again as shown in Fig. 3. The 3-dB bandwidth is estimated to be 0.36 nm under this condition. It is interesting that the polarization state of the pulse sequence in this case is orthogonal to that of the previous one, which is mode locked at 10.008426 GHz. Hence, we denote the two polarization locking states as the V- *and* H-mode regimes, respectively. It should be noted that the polarization controller (PC) is first adjusted to get the laser mode locked in the H-mode regime. After that, the polarization of the lasing signal is switched between two orthogonal modes by tuning the modulation frequency without any adjustment to the PC. This is achieved for the first time, to the best of our knowledge, that switching of the polarization in an active mode-locked fiber laser has been reported.

A. H-Mode Regime

Fig. 4(a) and (b) shows the autocorrelation traces of the x- and y-polarization component, respectively, of the H-mode pulse sequence. Higher power on the x-axis demonstrates that the pulse has the major polarization state aligning along this axis. This is confirmed by the optical spectra of the two orthogonal polarization components shown in Fig. 5. The central wavelength modes of the pulse polarize along the x-axis, and hence, pass through the x-axis polarizer without attenuation whereas suffering as much as 10-dB loss when passing through the y-axis polarizer. It is noted that the sideband modes far from the central wavelength do not have strong x-polarized state as the central wavelength. They have equal powers on both axes.

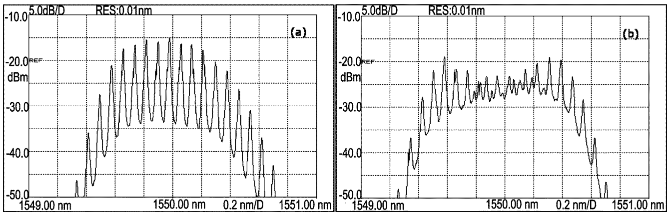

Fig. 5. Optical spectra of H-mode pulses: (a) x-axis component, (b) y-axis component.

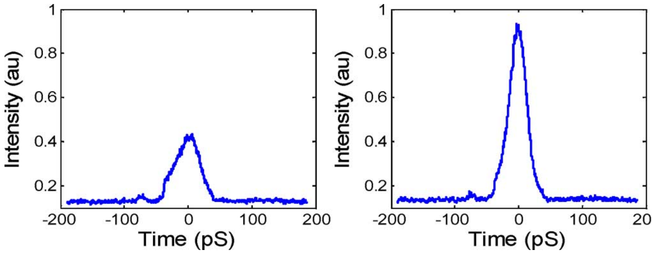

Fig. 6. Autocorrelation traces of V-mode pulses: (a) x-axis is component, (b) y-axis component.

The pulsewidth of the y-axis component is slightly larger than that of the x-axis. The pulse full-width at half-maximum of 24.8 and 19.8 ps have been achieved, assuming Gaussian shape, for the y- and x-components, respectively.

B. V-Mode Regime

The polarization state of the mode-locked pulse is now switched to the other orthogonal state, the V-mode regime, by tuning the modulation frequency to 10.009106 GHz. The autocorrelation traces shown in Fig. 6 indicate that the pulse power is distributed more on the y-axis than on the x-axis, hence contrasting to that observed in the H-mode regime. In addition, the optical spectra shown in Fig. 7 also show that the central wavelength is polarized along the y-axis and has not been affected by the y-axis polarizer. However, there is a slight difference of the polarization state of the sideband modes from the H-mode regime. The sideband modes are now polarized along the axis orthogonal to the polarization axis of the central wavelength and significantly attenuated when passing through the y-axis polarizer.

Similar to the H-mode regime, the pulsewidth of the major axis (the higher power axis) component is slightly narrower than that of the minor axis. The pulsewidth is 29.4 and 19.1 ps for the x- and y-axis components respectively. This can be easily understood that the minor axis component is detuned while the major axis component is tuned to its locking frequency.

It is also noted that the time bandwidth products are very large in both locking regimes. This indicates that the pulses are

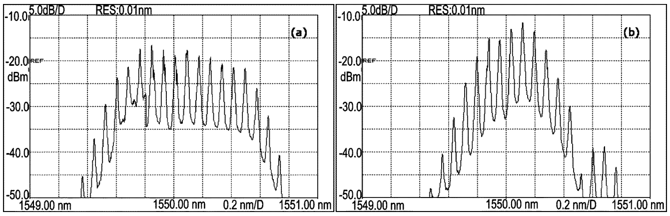

Fig. 7. Optical spectra of V-mode pulses: (a) x-axis component, (b) y-axis component.

heavily chirped and can be linearly compressed externally. The reason causing such a large chirp, especially in H-mode regime, is still under investigation. It may be due to the cavity dispersion and the chirping induced by the z-cut LiNbO$_3$ MZIM.

The switching of the polarization of the mode-locked pulse train can be attributed to the birefringence property of the laser cavity. Since the lightwaves traveling in the y-axis sees an effective refractive index n_x different from n_y when traveling in the y-axis, the traveling round-trip time of the ring is thus different from x- to y-axis. The laser can thus resonate at two different fundamental frequencies, f_{Rx} for the x-axis and f_{Ry} for the y-axis, instead of a single fundamental frequency as reported in [2]–[5]. When the modulation frequency is equal to an integer number multiple of f_{Rx}, the laser is excited and mode locked in the x-axis, resulting in the output pulse has x-polarized state. On the other hand, when the modulation frequency is equal to an integer number multiple of f_{Ry}, harmonic mode locking in the y-axis is obtained.

In our laser cavity, the major contribution to the birefringence is the 3.2 m *length* of the polarization-maintaining (PM) fiber pigtail of the LiNbO$_3$ Mach–Zehnder modulator; the rest are standard SMF. The birefringences of other devices are low and thus ignored in the following theoretical calculation. The refraction index difference between the fast and slow axes of the PM fiber can be calculated as [7]

$$\Delta n = \frac{\lambda}{L_b} \tag{1}$$

where λ is the operating wavelength and L_b is the beat length of the fiber. The round-trip traveling time difference and the difference between the two fundamental frequencies f_{Rx} and f_{Ry} are thus given by

$$\Delta T = L_{\mathrm{PM}} \times \frac{\Delta n}{c} \tag{2}$$

$$\begin{aligned}\Delta f_R &= f_{Ry} - f_{Rx} = \frac{1}{T_{Ry}} - \frac{1}{T_{Rx}} = \frac{\Delta T}{T_{Ry}T_{Rx}}\\ &= \Delta T \times f_R^2\end{aligned} \tag{3}$$

where L_{PM} is the length of the PM fiber, c is the speed of light, T_{Rx}, T_{Ry} is the round-trip time of the light traveling in the x- and y-axes, respectively, and f_R is the average fundamental frequency $f_R = \sqrt{f_{Rx} f_{Ry}}$. From (1)–(3), one can obtain

$$\Delta f_R = \frac{L_{\mathrm{PM}} \lambda f_R^2}{L_b c}. \tag{4}$$

When the laser is locked to an Nth-order harmonic mode of the fundamental frequency, the difference between two modulation frequencies, f_{mx} and f_{my}, for locking the laser ring into the two orthogonal regimes is

$$\Delta f_m = f_{mx} - f_{my} = N \Delta f_R = N \frac{L_{\mathrm{PM}} \lambda f_R^2}{L_b c} \tag{5}$$

In our experiment, $L_{\mathrm{PM}} = 3.2$ m, $L_b = 3.5$ mm, $\lambda = 1550$ nm, $f_R = 12$ MHz, $N = 834$, the fundamental frequency difference and the modulation frequency difference is thus estimated as $\Delta f_R = 680$ Hz and $\Delta f_m = 567$ kHz. These values give a reasonable agreement with the experimental result where the modulation frequencies for x- and y-polarized mode-locking states are $f_{mx} = 10.008426$ GHz and $f_{my} = 10.009106$ GHz, respectively. The difference is $\Delta f_m = 680$ kHz. The small discrepancy might be due to the residual birefringence of the fiber and other components in the ring, and partly due to the error when determining the locking modulation frequencies and estimation of the beat length

IV. CONCLUSION

Switching of the polarization state of the output pulse sequence of an active harmonic mode-locked fiber laser due to birefringence in the ring has been reported for the first time. Since there are two different fundamental frequencies according to the resonance of the two orthogonal polarized regimes, the polarization state of the laser can be switched between two orthogonal states by tuning the modulation frequency. Theoretical equations for predicting the tuning frequency has been developed and show good agreement with the experimental results. This phenomenon is useful to analyze the dynamics of the mode-locked lasers and can be exploited to generate polarization switch able optical pulses and to control the polarization stability of the mode-locked laser.

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