Polarization rotation locking of vector solitons in a fiber ring laser

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Abstract: Polarization rotation of vector solitons in a fiber ring laser was experimentally studied. It was observed that the period of vector soliton polarization rotation could be locked to the cavity roundtrip time or multiple of it. We further show that multiple vector solitons can be formed in a fiber laser, and all the vector solitons have the same group velocity in cavity, however, their instantaneous polarization ellipse orientations could be orthogonal.

OCIS codes: (060.5530) Pulse propagation and temporal solitons; (140.1540) Chaos; (190.3100) Instabilities and chaos.

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1. Introduction

Due to the fact that single mode fibers actually support two polarization modes, pulse propagation in single mode fibers can exhibit complicated polarization dynamics, which have been the subject of extensive theoretical and experimental researches. Cutis R. Menyuk first numerically showed that two orthogonally polarized solitons with different group velocities could trap together and propagate as a nondispersive unit under the effect of cross-phase modulation [1, 2]. D. N. Christodoulides et al. have theoretically predicted the formation of a

#93563 - $15.00 USD Received 7 Mar 2008; revised 14 Apr 2008; accepted 14 Apr 2008; published 23 Jun 2008

class of vector solitons in birefringent nonlinear dispersive media [3]. N. Akhmediev et al have shown the existence of stationary elliptically polarized solitons [4]. Pulse propagation in a fiber laser is much more complicated than pulse propagation in single mode fibers. Apart from propagation in the single mode fibers that form part of a laser cavity, a pulse circulating in a fiber laser is also subjected to actions of other cavity components, such as the saturable absorber, laser gain and output coupler. However, it was recently demonstrated that vector solitons could still be formed in passively mode-locked fiber lasers [5]. Both the polarization locked vector solitons (PLVSs) and the group velocity locked vector solitons (GVLVSs) have been obtained [6, 7]. Nevertheless, previous studies [5-7] have only focused on the single vector soliton operation of the lasers and the associated vector soliton features, the multiple vector soliton features of the lasers were untouched. Neither the polarization rotation dynamics of the observed GVLVSs was studied.

Another obvious difference between light propagation in single mode fibers and in a fiber laser is that light propagation in a laser cavity must also satisfy the cavity boundary condition. Previous studies on solitons formed in lasers have shown that cavity boundary condition could synchronize the soliton pulsation dynamics [8]. In this paper we report on other novel effects of the vector solitons formed in a passively mode-locked fiber laser. We show that under suitable conditions the polarization rotation of vector solitons formed in the lasers can be locked by the cavity. Consequently, the period of vector soliton polarization rotation is fixed at the multiple of the cavity roundtrip time. Moreover, we show that multiple vector solitons can be formed in a passively mode-locked fiber lasers, especially, the formed multiple vector solitons exhibit the so-called “soliton energy quantization effect” of the scalar soliton fiber lasers [9]. However, different from the formation of multiple scalar solitons, the formed multiple vector solitons could have orthogonal polarization ellipse orientations, an effect that could be traced back to the spatial gain hole burning in the fiber cross section caused by the special polarization evolution of the vector solitons in the fiber laser cavity.

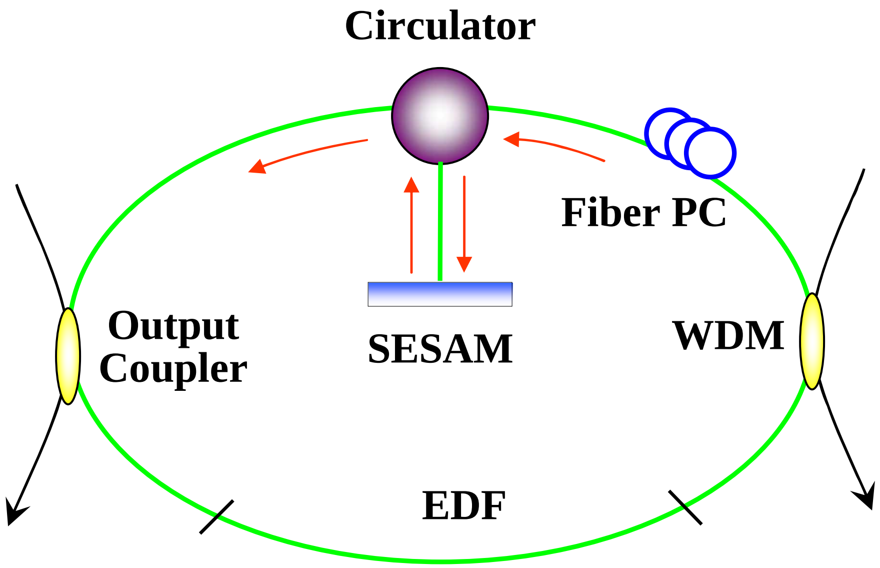

Fig. 1. Schematic of the fiber laser. SESAM: semiconductor saturable absorber mirror; PC: polarization controller; WDM: wavelength-division multiplexer; EDF: erbium-doped fiber.

2. Experimental setup and results

The fiber laser used is schematically shown in Fig. 1. Different from the linear cavity scheme used in Ref. 5-7, the laser has a ring cavity. The fiber laser is mode locked by a semiconductor

#93563 - $15.00 USD Received 7 Mar 2008; revised 14 Apr 2008; accepted 14 Apr 2008; published 23 Jun 2008

saturable absorber mirror (SESAM). We used 2.63m erbium-doped fiber (StockerYale EDF-1480-T6) as the gain medium, the other fibers used were the standard single mode fibers (SMFs). A 3-port polarization-independent circulator was used to force the unidirectional operation of the laser and simultaneously incorporate the saturable absorber into the cavity. A fiber-based polarization controller was inserted in the cavity to control the net birefringence of the cavity. The laser was pumped by a 1480 nm Raman fiber laser with maximum output of 220 mW and the pump was coupled to the cavity with a reverse pumping theme to avoid overdriving of the SESAM by the residual pump power. The laser beam was coupled out of the cavity through a 10% fiber coupler. The SESAM has a saturable absorption of about 8% and a recovery time of 2 ps.

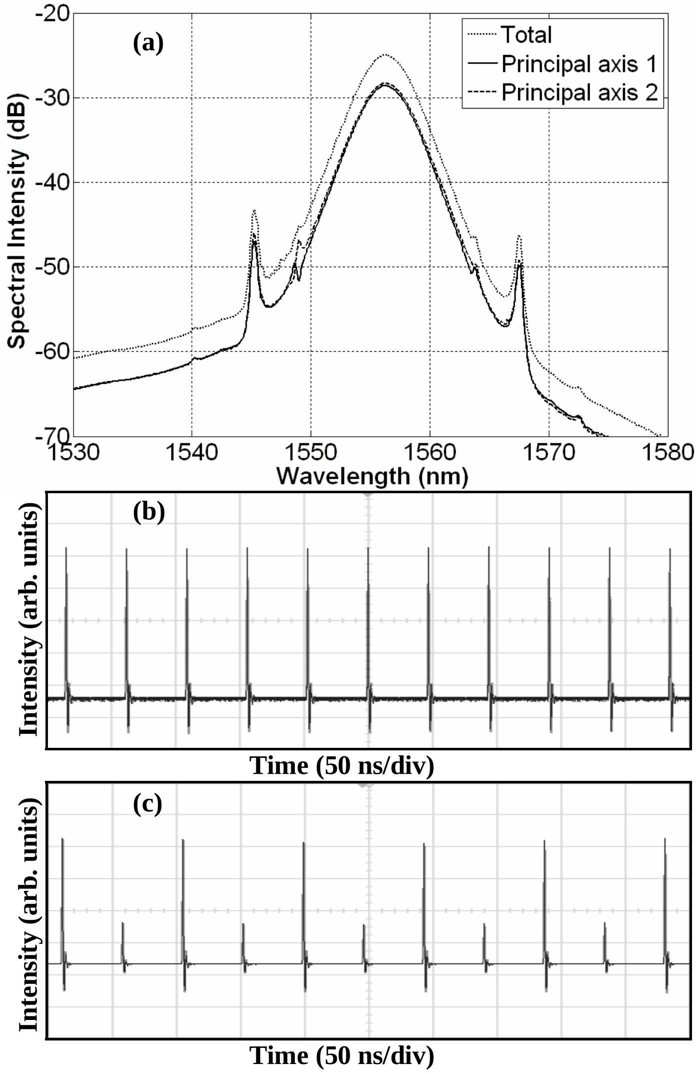

Fig. 2. The optical spectra (a) and corresponding oscilloscope traces (b) before polarizer; (c) after polarizer.

Self-started mode-locking of the laser was achieved by simply increasing the pump power above the mode-locking threshold. Initially, multiple mode-locked pulses were always observed. However, through carefully controlling the pump power, the number of pulse in cavity could be controlled. Vector soliton operation of the laser was obtained by rotating the paddles of the polarization controller. Figure 2 shows for example a state of the vector soliton operation of the laser with one soliton in cavity. Figure 2(a) shows the optical spectrum of the pulse. The soliton feature of the pulse is confirmed by its soliton sidebands [10]. Figure 2(b) and Fig. 2(c) show the oscilloscope traces of the soliton pulse measured without passing and passing through an external polarizer, respectively. Without passing through an external polarizer, all the pulses in the trace have equal intensity. However, after passing through an external polarizer, the pulse intensity then alternated between two values, indicating that the polarization of the soliton is rotating in the cavity and the period of the soliton polarization rotation is 2 (P2) times of the cavity roundtrip time.

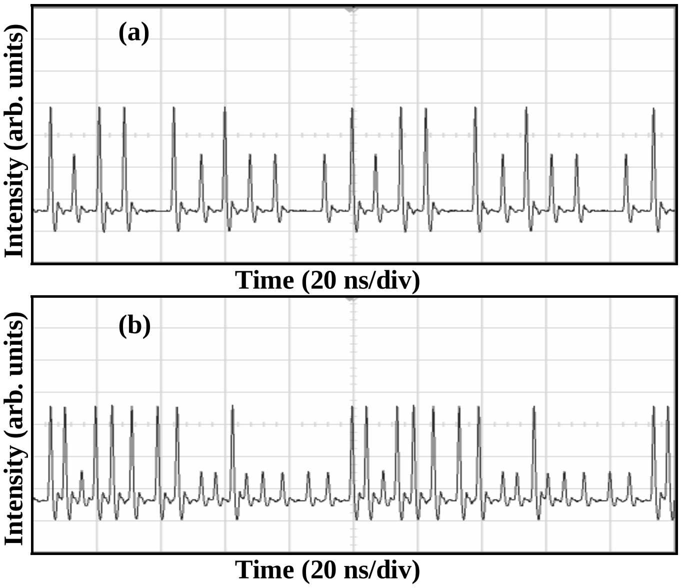

Fig. 3. Period-doubling of multiple vector solitons. (a) five vector solitons and (b) eight vector solitons in cavity.

To get an insight into the property of each of the coupled polarization components of the vector soliton, we also measured the spectra of the vector soliton along two orthogonal polarization directions by passing it through an external polarizer. Guided by the pulse intensity in the oscilloscope, we first orientated the external polarizer to a direction that the pulse intensity measured in all odd number of roundtrips has a maximum value. We denoted the direction as zero degree polarizer orientation and recorded the soliton spectrum. Fixed all other parameters we then turned the external polarizer by 90° and recorded the projection of soliton spectrum along the orthogonal direction. As the polarization ellipse of the vector soliton alternates between two states at the laser output position and the measured optical spectrum is an averaged result over the device response time, the spectral measurement cannot give the exact soliton spectra along each of the principal birefringence axes. However, as with orthogonal external polarizer orientation the projection of the long and short axis of the soliton polarization ellipse on the polarizer is different, sufficient information about the two-coupled components of the vector soliton at the output position could still be obtained. The results are shown in Fig. 2(a). It is to see that while with the 0° external polarizer orientation a spectral peak was observed on the soliton spectrum, at the 90° external polarizer orientation, a spectral dip appeared at the same spectral position of the measured soliton spectrum, suggesting that coherent energy exchange (CEE) between the two polarization components exists. In another paper we have reported the effect of four-wave-mixing between the two

#93563 - $15.00 USD Received 7 Mar 2008; revised 14 Apr 2008; accepted 14 Apr 2008; published 23 Jun 2008

orthogonal polarization components of a vector soliton formed in the fiber lasers [11]. It was found that as far as the linear cavity birefringence of the lasers was not zero or near zero, coherent energy exchange between the two orthogonal polarization components of a vector soliton always occurred, and the effect manifested as the appearance of extra spectral sidebands on the polarization resolved vector soliton spectra. In particular, if on the spectrum of one polarization component the extra sideband was a spectral peak, at the same position a spectral dip appeared on the spectrum of the orthogonal polarization component. The polarization resolved spectra shown in Fig. 2(a) exhibited the same feature.

It is well-known that the polarization rotation of a vector soliton along a weak birefringence fiber is caused by both the linear and nonlinear birefringence of the fiber. Moreover, the nonlinear polarization rotation is proportional to the soliton intensity. A soliton formed in a laser in essence is a dissipative soliton, whose pulse intensity is actually the net laser gain dependent. However, experimentally we observed that whenever the polarization rotation of the formed vector solitons became synchronized with the cavity length, increasing the pump strength of the laser did not destroy the synchronization but only change the number of solitons in the cavity. Figure 3(a) and Fig. 3(b) shows for example the cases where five or eight vector solitons coexist in the cavity, respectively. The states were obtained by carefully increasing the pump strength from the state shown in Fig. 2(b). It is clearly observed that the polarization of all solitons rotates. After every 2 cavity-roundtrips their polarization states return to the previous states. Obviously the polarization rotation of all solitons is the same as a result of the soliton energy quantization and cavity locking effect. However, carefully examining the pulse intensity variation, it turned out that the polarization ellipse orientations of the solitons were not the same. There exist actually two sets of solitons in cavity, represented by the existence of two different pulse intensities within one cavity roundtrip time in the measured oscilloscope trace. Solitons in each set have the same polarization ellipse orientation. To determine the relative polarization ellipse orientation between the solitons in the two sets, we studied the relative soliton intensity variation by rotating the external polarizer. It was observed that while pulse intensity of the solitons in one set increased, the pulse intensity of the solitons in the other set decreased. When pulse intensity of the solitons in one set reached the maximum, the pulse intensity of solitons of the other set was at the minimum, which suggested that the polarization ellipses of the two sets of solitons were orthogonal to each other. Despite of the fact that two sets of vector solitons with orthogonal polarization ellipse orientations coexist, the relative positions of the vector solitons are stable in the cavity, indicating that all solitons move with exactly the same group velocity.

To explain the formation of two sets of vector solitons with orthogonal polarization ellipse orientations, we note that the polarization rotation of a vector soliton along the cavity is actually a kind of swing of the polarization ellipse with respect to a certain direction in the fiber cross section [12]. As in the fiber laser the laser gain is polarization independent, such a vector soliton polarization rotation then causes spatial gain hole burning in the fiber cross section. When multiple vector solitons are formed in cavity, as a result of the laser gain competition some solitons will have polarization ellipse orientation orthogonal to the others. To support our explanation, we note that we also experimentally studied the formation of new vector solitons in our laser. Starting from the state shown in Fig. 2, as the pump power was increased a new vector soliton was formed. We found that the new vector soliton always had a polarization ellipse orthogonal to that of the original vector soliton. However, with more solitons in cavity the polarization ellipse orientation of the new soliton then could be either of the two existing vector soliton polarization ellipse orientations. From the state shown in Fig. 3, if the soliton number was reduced, it was found that the last two vector solitons in cavity always had orthogonal polarization ellipse orientations.

Experimentally soliton polarization rotation locking to the 3 (P3) and 4 (P4) times of the cavity roundtrip time had also been observed. Figure 4(a) shows for example the case of a P3 state with one soliton in cavity. The state was obtained by changing the net linear cavity birefringence of our fiber laser. Like the case of P2 states, increasing pump strength did not destroy the polarization rotation locking state but increase the number of solitons in cavity, as

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shown in Fig. 4(b), where two vector solitons coexist in cavity and after every three cavity roundtrips, their polarization states return to the previous orientations.

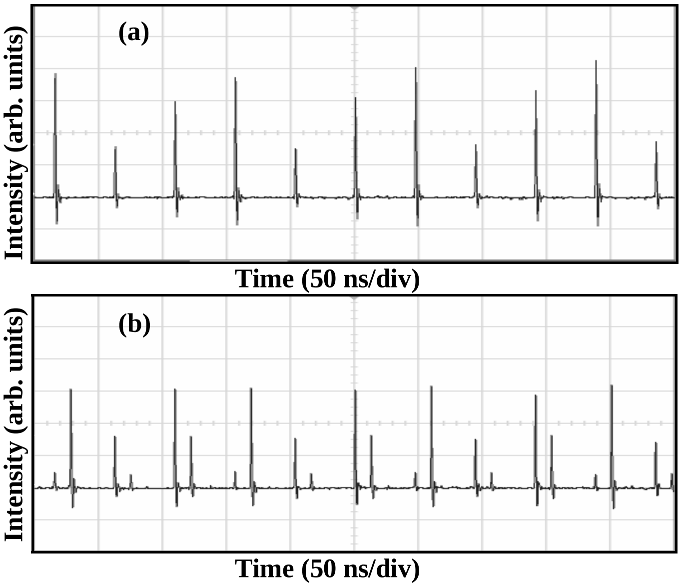

Fig. 4. Period-tripling of (a) single vector soliton and (b) two vector solitons in cavity.

3. Conclusion

In conclusion, polarization rotation of the vector solitons formed in a passively mode-locked fiber laser was experimentally studied. It was found that when the period of the soliton polarization rotation is close to the multiple of the cavity roundtrip time, the cavity boundary condition could lock the soliton polarization rotation. Eventually at a fixed cavity position the solitons have only a fixed or alternate discrete polarization states. We have also experimentally shown that due to the laser gain competition two sets of vector solitons with orthogonal polarization orientations can be formed. However, despite of their polarization difference they have identical group velocity in the cavity.

Acknowledgment

This project is supported by the National Research Foundation Singapore under the contract NRF-G-CRP 2007-01.