Coexistence of polarization-locked and polarization-rotating vector solitons in a fiber laser with SESAM

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We report the experimental observation of the coexistence of polarization-locked vector solitons (PLVSs) and polarization-rotating vector solitons (PRVSs) in a fiber laser mode locked with a semiconductor saturable absorber mirror. It was found experimentally that interaction between the PLVSs in a fiber laser could lead to formation of bound states of PRVSs. Moreover, the bound PRVSs as a unit have the same group velocity as that of the PLVSs in the cavity. © 2009 Optical Society of America

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Dissipative solitons are stable localized waves formed in the nonlinear dissipative systems [1]. Different from the classical solitons formed in the conservative systems, dissipative solitons possess a number of new features, which are the focus of current soliton studies. A fiber laser is a typical dissipative system, as light circulating in the laser cavity is subject to cavity losses and gain. Optical soliton formation and dynamics in mode-locked fiber lasers has been extensively investigated. However, emphasis has been given to scalar dissipative solitons. It is well known that because of the intrinsic technical limitation on fabricating a fiber with a perfect circular core and/or the random mechanical stresses affecting a fiber, a practical single-mode fiber (SMF) always supports two polarization eigenmodes. Except when polarization-maintaining fibers are used, the cavity of a fiber laser is always weakly birefringent. Therefore, it is necessary to consider the vector feature of the dissipative solitons formed in a fiber laser.

Theoretical work on vector soliton (VS) formation in SMFs was pioneered by Menyuk [2,3], who predicted trapping of two orthogonally polarized solitons in a SMF. Other types of VS, such as polarization-rotating VSs (PRVSs) [4], polarization-locked VSs (PLVSs) [5], and the phase-locked black–white VSs [6], were also theoretically predicted in weakly birefringent SMF. However, except for the soliton trapping, the various types of theoretically predicted VS in SMF were not experimentally confirmed. A challenge for experimentally observing the PLVSs in SMFs is that the birefringence of the fibers must be kept small over a long distance, which in practice is difficult to realize. In contrast, both the PLVSs and the PRVSs were experimentally observed in mode-locked fiber lasers [7–9]. A main difference of soliton propagation in a fiber laser cavity from that in a SMF is that the soliton propagation in a fiber laser cavity must further satisfy the cavity boundary condition. A consequence of the difference is that the features of the laser solitons are not determined by the localized cavity parameters but by the averaged cavity parameters. Experimentally one can easily control the averaged birefringence of a fiber laser cavity to be near zero.

Multiple soliton formation is a generic feature of soliton fiber lasers under strong pumping [10]. For the scalar soliton fiber lasers, it was found that the formed multiple solitons have identical soliton parameters, which is known as the soliton energy quantization feature. For the VS fiber lasers the orientation of the VS provides an extra degree of freedom. It would be interesting to know whether under multiple VS operation the soliton energy quantization feature could still be maintained. In a recent experiment we have shown an effect of so-called polarization rotation locking of VSs [11]. It was found that multiple PRVSs could coexist in a fiber laser cavity and propagate with the same group velocity. Moreover, the instantaneous polarization ellipse orientations of the solitons could keep an orthogonal relationship. In this Letter, we report another novel multiple VS operation state of the fiber lasers. We show that both the PLVSs and the PRVSs could coexist in a laser cavity. In particular, the interaction between two PLVSs could lead to formation of a bound state of PRVSs, and the bound PRVSs as a unit have the same group velocity in the cavity as that of the PLVSs of the laser.

The fiber laser used has the same cavity configuration as reported in [11], except that the cavity length is now 15.2 m and the erbium-doped fiber has a length of 5.5 m. Self-started mode locking of the laser occurred at a pump power of around 140 mW. Immediately after mode locking, multiple soliton pulses were always initially formed in the cavity. Through appropriately setting the polarization controller, multiple VSs, either in the form of the PLVSs or the group-velocity-locked VSs [12], were then obtained. Figure 1 shows a state of the multiple PLVSs of the laser. The polarization-locking feature of the VSs is verified by the measurement of the polarization evolution frequency [7]. We connected the output of the laser to a fiber-based polarization beam splitter (PBS), where the incoming branch of the PBS is made of a standard SMF and the two outgoing

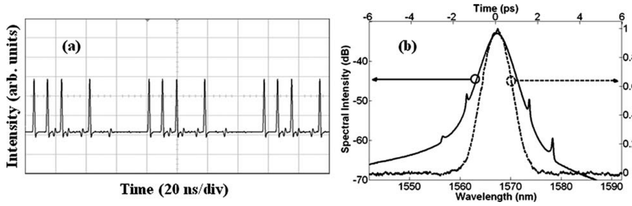

Fig. 1. A state of multiple PLVS operation of the laser. (a) The oscilloscope trace. (b) The corresponding optical spectrum and autocorrelation trace.

branches are made of polarization-maintaining fibers, and measured the output signal from each branch of the PBS. For the case of a PLVS state, the polarization evolution frequency was zero. Figure 1(b) shows the optical spectrum of the state and the autocorrelation trace of the PLVSs. The optical spectrum has clear and sharp spectral sidebands. There were 4 PLVSs coexisting in the cavity as shown in Fig. 1(a), and they were far apart. The pulse width of the PLVS is about 1.10 ps if a sech^2 pulse profile is assumed, and its pulse energy is about 226 pJ. When the incoming branch of the PBS was randomly twisted, all the pulses after the PBS simultaneously have the same pulse intensity variations.

Figure 2 shows a state of multiple PRVSs of the laser: there were four PRVSs coexisting in the cavity, and the separations among the solitons are fixed, which means that all the solitons have exactly the same group velocity in the cavity. Unlike the state of multiple PLVSs, measured after the PBS the intensity of the pulses periodically varied with the cavity round trips, indicating that the polarization of the solitons were rotating [8]. Figure 2(b) shows that the polarization rotation of the VSs was locked at twice the cavity round-trip time. The pulse energy of a PRVS is about 222 pJ.

Apart from the above multiple VS states where all the solitons are either PLVSs or PRVSs, experimentally we found that the two types of VS could also coexist in the laser cavity as illustrated in Fig. 3. Figure 3(a) shows the oscilloscope trace of the laser output pulse train before the PBS. Figure 3(b) shows those after the PBS. There were five VSs coexisting in the cavity. Among them, three were far apart, and two had a pulse separation <50 ps and formed a bound state of VSs in the cavity. By randomly twisting the incoming branch of the PBS, which corresponds to randomly changing the linear birefringence of the branch fiber, we found that the three widely separated VSs project equal weight in either of the orthogonally polarized directions, while the bound solitons as a unit exhibited polarization rotation in the cavity. The polarization rotation was locked to the twice the cavity round-trip time.

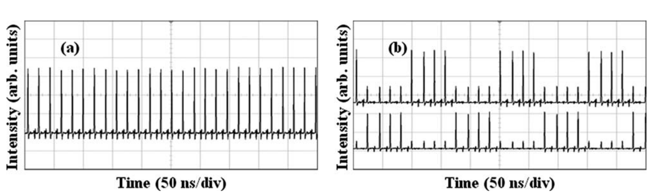

Fig. 2. State of multiple PRVS operation of the laser measured (a) before PBS and (b) after PBS.

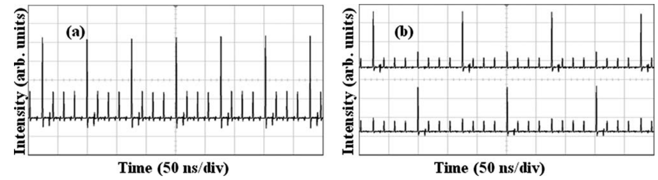

Fig. 3. Coexistence of PLVSs and PRVSs in the laser measured (a) before PBS and (b) after PBS.

The internal structure of the bound VSs was further studied with a high-speed oscilloscope (Agilent 86100A) and a 45 GHz photodetector (New Focus 1014). Figure 4 shows the bound VSs in two adjacent cavity roundtrips. It was found that the polarization of each of the bound VSs rotated during propagation, and their polarization rotation was locked to twice the cavity round-trip time. When the incoming branch of the PBS was purposely twisted so that one of the bound VSs reached its maximum, the other one always reached its minimum, indicating that the instantaneous polarization ellipse orientations of the two bound VSs were orthogonal.

To show how these states of multiple VSs were formed in the laser, we have taken two video clips of their formation processes. The output pulse trains after the PBS were monitored. Video A (Media 1) shows the changes of the laser output pulse train when the pump power was increased. Starting from a state with two PLVSs, as the incoming branch of the PBS was randomly twisted, the soliton intensity exhibited synchronous variation; when pump power was increased while keeping all the other operation conditions fixed, a new PLVSs was generated; with a further increase in the pump power, under the perturbation of a CW background, all VSs first approached one another and then redistributed over the cavity. At the same time the fourth PLVS was formed in the cavity; on further increasing the pump power, after an attracting procedure, three VSs bound together, and the other two PLVSs distributed far apart. Enlarging the bound state of VSs with the high-speed oscilloscope, as shown in Fig. 5, it is seen that three VSs interacted with each other in the state. Each of the VSs in the bound state now became a PRVS, and moreover the instantaneous polarization ellipse of one PRVS is always orthogonal to that of the other two PRVSs. Video B (Media 2) shows the case of the VS evolution in the cavity when the pump power was decreased from the end state of Video A (Media 1). Four PLVSs were first obtained, then 3 PLVSs, then 2 PLVSs, then 1 PLVS; finally, no VS survived.

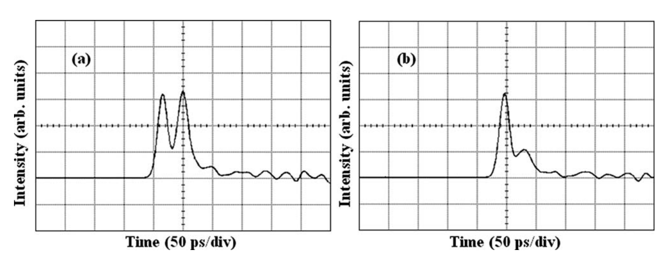

Fig. 4. Zooming-in of the bound VSs shown in Fig. 3. (a) and (b) were measured in two subsequent cavity roundtrips and after PBS.

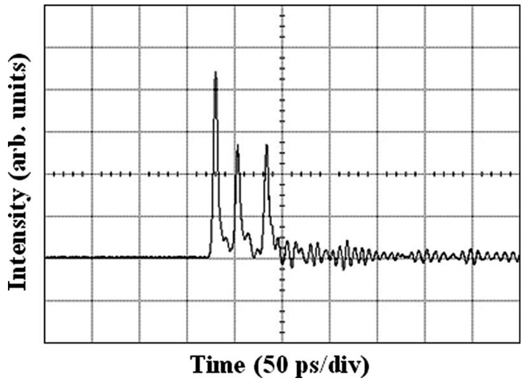

Fig. 5. Zooming-in of the bound state of VSs observed in Video A (Media 1) (2954 KB) and Video B (Media 2) (2892 KB).

The formation of multiple identical PLVSs or PRVSs in a fiber laser can be easily understood based on the soliton energy quantization effect of the scalar solitons. However, the coexistence of the PLVSs and PRVSs and that both solitons propagate with the same group velocity in the cavity are beyond our expectation. We note that Grelu and Akhmediev reported an effect of group interaction of scalar solitons [13]. It was shown that, owing to the coupling of solitons, the bound scalar solitons as a unit had a different group velocity from that of the single scalar solitons. Obviously, interaction between the VSs is more complicated than that between the scalar solitons. To understand the formation of the bound VSs in our laser, we note that the saturable absorption of a SESAM exhibits two recovery times, a fast one with strong absorption and a slow one with weak absorption, and a recovery time extending to ~100 ps [14]. We believe that the observed bound VSs could be formed because of a feature of the SESAM. When the pump power is increased, the same as the scalar soliton case [10], a new VS will be generated. If the new VS emerges far from the original VS, the SESAM will totally recover. Therefore, the same type of VS will be generated. However, if the new VS appears close to the existing VS, so that the SESAM cannot fully recover, the SESAM will introduce a coupling force between the VSs and lead to the formation of the bound VSs. The interaction between the VSs changes the phase of the VSs and further causes their polarization rotation. It is plausible that the coupling of the solitons could compensate for the group-velocity difference between the PLVS and the PRVS.

In conclusion, we have experimentally observed a novel state of multiple VS operation in a passively mode-locked fiber laser. It was shown that coupling among the PLVSs may result in the formation of bound states of PRVSs and, moreover, compensate for the group-velocity difference between the PLVS and the PRVS in the cavity. Our experimental results clearly show that the VS interaction has much more complicated dynamics than that of the scalar solitons.

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