Vector dark domain wall solitons in a fiber ring laser

H. Zhang, D. Y. Tang*, L. M. Zhao and R. J. Knize

School of Electrical and Electronic Engineering, Nanyang Technological University, 639798 Singapore
**edytang@ntu.edu.sg*

Abstract: We observe a novel type of vector dark soliton in a fiber ring laser. The vector dark soliton consists of stable localized structures separating the two orthogonal linear polarization eigenstates of the laser emission and is visible only when the total laser emission is measured. Numerical simulations based on the coupled complex Ginzburg-Landau equations have well reproduced the results of the experimental observation.

OCIS codes: (060.4370) Nonlinear optics, fibers; (060.5530) Pulse propagation and temporal solitons; (140.3510) Lasers, fiber.

References and links

1. I. N. Iii, “All-fiber ring soliton laser mode locked with a nonlinear mirror,” Opt. Lett. **16**(8), 539–541 (1991).
2. N. Akhmediev, J. M. Soto-Crespo, and G. Town, “Pulsating solitons, chaotic solitons, period doubling, and pulse coexistence in mode-locked lasers: complex Ginzburg-Landau equation approach,” Phys. Rev. E Stat. Nonlin. Soft Matter Phys. **63**(5), 056602 (2001).
3. D. Y. Tang, L. M. Zhao, and B. Zhao, “Soliton collapse and bunched noise-like pulse generation in a passively mode-locked fiber ring laser,” Opt. Express **13**(7), 2289–2294 (2005).
4. H. Zhang, D. Y. Tang, L. M. Zhao, X. Wu, and H. Y. Tam, “Dissipative vector solitons in a dispersionmanaged cavity fiber laser with net positive cavity dispersion,” Opt. Express **17**(2), 455–460 (2009).
5. C. R. Menyuk, “Stability of solitons in birefringent optical fibers. I: equal propagation amplitudes,” Opt. Lett. **12**(8), 614–616 (1987).
6. N. N. Akhmediev, A. V. Buryak, J. M. Soto-Crespo, and D. R. Andersen, “Phase-locked stationary soliton states in birefringent nonlinear optical fibers,” J. Opt. Soc. Am. B **12**(3), 434–439 (1995).
7. S. Trillo, S. Wabnitz, E. M. Wright, and G. I. Stegeman, “Optical solitary waves induced by cross-phase modulation,” Opt. Lett. **13**(10), 871–873 (1988).
8. D. N. Christodoulides, and R. I. Joseph, “Vector solitons in birefringent nonlinear dispersive media,” Opt. Lett. **13**(1), 53–55 (1988).
9. Y. S. Kivshar, and S. K. Turitsyn, “Vector dark solitons,” Opt. Lett. **18**(5), 337–339 (1993).
10. M. Haelterman, and A. P. Sheppard, “Polarization domain walls in diffractive or dispersive Kerr media,” Opt. Lett. **19**(2), 96–98 (1994).
11. S. Pitois, G. Millot, and S. Wabnitz, “Polarization domain wall solitons with counterpropagating laser beams,” Phys. Rev. Lett. **81**(7), 1409–1412 (1998).
12. E. Seve, G. Millot, S. Wabnitz, T. Sylvestre, and H. Maillotte, “Generation of vector dark-soliton trains by induced modulational instability in a highly birefringent fiber,” J. Opt. Soc. Am. B **16**(10), 1642–1650 (1999).
13. C. Milián, D. V. Skryabin, and A. Ferrando, “Continuum generation by dark solitons,” Opt. Lett. **34**(14), 2096–2098 (2009).
14. Q. L. Williams, and R. Roy, “Fast polarization dynamics of an erbium-doped fiber ring laser,” Opt. Lett. **21**(18), 1478–1480 (1996).
15. B. Meziane, F. Sanchez, G. M. Stephan, and P. L. François, “Feedback-induced polarization switching in a Nd-doped fiber laser,” Opt. Lett. **19**(23), 1970–1972 (1994).
16. D. Y. Tang, L. M. Zhao, B. Zhao, and A. Q. Liu, “Mechanism of multisoltion formation and soliton energy quantization in passively mode-locked fiber lasers,” Phys. Rev. A **72**(4), 043816 (2005).
17. B. A. Malomed, “Optical domain walls,” Phys. Rev. E Stat. Phys. Plasmas Fluids Relat. Interdiscip. Topics **50**(2), 1565–1571 (1994).
18. B. A. Malomed, A. A. Nepomnyashchy, and M. I. Tribelsky, “Domain boundaries in convection patterns,” Phys. Rev. A **42**(12), 7244–7263 (1990).
19. B. A. Malomed, “Domain wall between traveling waves,” Phys. Rev. E Stat. Phys. Plasmas Fluids Relat. Interdiscip. Topics **50**(5), R3310–R3313 (1994).

1. Introduction

Soliton operation of mode locked fiber lasers has been extensively investigated previously. It has been shown that the dynamics of the solitons formed in an anomalous dispersion cavity

#121302 - $15.00 USD Received 10 Dec 2009; revised 6 Feb 2010; accepted 6 Feb 2010; published 18 Feb 2010

fiber laser could be well described by the nonlinear Schrödinger equation (NLSE) [1]. Generally speaking, formation of a soliton in fiber lasers is a result of the mutual nonlinear interaction among the laser gain and losses, cavity dispersion and fiber nonlinearity, as well as the cavity effects. The dynamics of the soliton should be governed by the complex Ginzburg-Landau equation (CGLE) [2]. However, it was noticed that solitons formed in an anomalous dispersion cavity fiber laser normally have a narrow spectral bandwidth, which is far narrower than the laser gain bandwidth. Consequently, no gain bandwidth filtering effect practically exists in the laser, and the effect of laser gain is mainly to balance the cavity losses. It was confirmed experimentally when the effect of spectral filtering on the pulse shaping could no longer be ignored, dynamics of the solitons formed in a fiber laser could not be described by the NLSE but the CGLE [3]. Solitons whose dynamics are governed by the CGLE are also called the dissipative solitons. Recently, formation of dissipative solitons in fiber lasers has attracted considerable attention [4].

In addition to gain, the vector nature of light also needs to be considered for fiber lasers whose cavity consists of no polarizing components. In these fiber lasers the dynamics of the formed solitons are governed by the coupled NLSEs or CGLEs. Theoretical studies on the coupled NLSEs have shown that due to the cross polarization coupling, new types of solitons, such as the group velocity locked vector solitons [5], phase locked vector solitons [6], induced solitons [7], high order phase locked vector solitons [8], and incoherently coupled vector dark solitons [9] could be formed. Indeed, these solitons were experimentally observed in fiber lasers. Moreover, polarization domain walls (PDWs) and novel types of vector dark PDW solitons were also theoretically predicted using coupled NLSEs [10]. Here a PDW refers to a localized structure that separates the two stable polarization eigenstates of a birefringent laser cavity. Phenomena related to PDWs and PDW soliton have been observed in passive fibers using two counter-propagating laser beams [11] and by polarization modulation instability [12]. However, they have not been observed in fiber lasers. It was anticipated that dark pulse trains could find applications in the optical continuum generation [13]. In this paper we report the first experimental observation of the vector dark PDW solitons in a fiber ring laser.

2. Experimental Setup

Our experiment was conducted on a fiber laser schematically shown in Fig. 1. The ring cavity is made of all-anomalous dispersion fibers, consisting of 6.4 m erbium-doped fiber (EDF) with group velocity dispersion (GVD) of 10 (ps/nm)/km and an erbium-ion doping concentration of 2880 ppm, and 5.0 m single mode fiber (SMF) with GVD of 18 (ps/nm)/km. A polarization insensitive isolator was employed in the cavity to force the unidirectional operation of the ring, and an in-line polarization controller (PC) was used to fine-tune the linear cavity birefringence. A 10% fiber coupler was used to output the signal. The laser was pumped by a high power Fiber Raman Laser source of wavelength 1480 nm. An in-line polarization beam splitter (PBS) was used to separate the two orthogonal polarizations of the laser emission, and they were simultaneously measured with two identical 2GHz photo-detectors and monitored in a multi-channel oscilloscope.

#121302 - $15.00 USD Received 10 Dec 2009; revised 6 Feb 2010; accepted 6 Feb 2010; published 18 Feb 2010

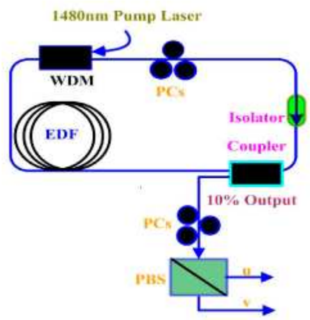

Fig. 1. Schematic of the experimental setup. EDF: Erbium doped fiber. WDM: wavelength division multiplexer. SMF: single mode fiber. PC: polarization controller. PBS: polarization beam splitter.

3. Experimental results

A similar configuration fiber laser was previously investigated by Williams and Roy [14]. They observed a type of fast antiphase square pulse emission along the two orthogonal principal polarization directions of the cavity. They interpreted the observed fast antiphase square pulse emission as caused by the gain competition between the two cavity polarization modes and the cavity feedback. Feedback induced polarization switching in a fiber laser was also reported in [15]. The fast antiphase square pulse emission along the two orthogonal polarization cavity modes was also observed in our laser. However, different from the previous observation [14] the square pulse width varied with the cavity birefringence. Figure 2 shows an experimentally measured square-pulse width variation with the orientation of one of the PC paddles. In a range of the paddle's orientation the laser emitted square pulses, and the square pulse width could be continuously changed as the paddle's orientation was varied. At the two ends of the orientation range, the laser emitted stable CW, whose polarization is linear and orthogonal to each other, indicating that they are the two stable principal polarization states of the laser emission. We then fixed the orientation of the paddle at a position within the stable square pulse emission range and further studied the features of the laser polarization switching with the pump strength change. At a weak pumping, stable antiphase polarization switching could still be obtained. It was found that the antiphase intensity variation along the two orthogonal polarizations perfectly compensated each other. When the total laser emission intensity was measured, almost no signature of the polarization switching could be observed. However, as the laser emission intensity was increased, the antiphase polarization switching was no longer compensated.

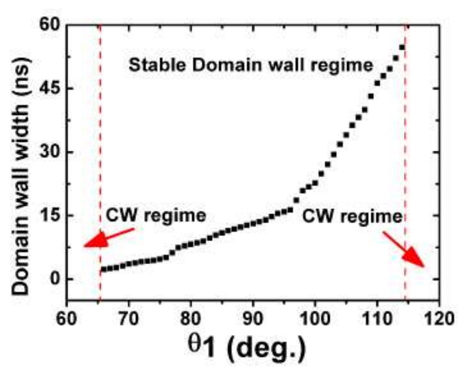

Fig. 2. Duration variation of the square pulses versus the orientation angle of one of the paddles of the intra-cavity PC.

#121302 - $15.00 USD Received 10 Dec 2009; revised 6 Feb 2010; accepted 6 Feb 2010; published 18 Feb 2010

Figure 3(a) shows an example of the laser emission measured along two orthogonal polarization directions. It clearly shows that along each polarization direction the laser emitted square pulses, and the square pulses between the two orthogonal polarization directions were antiphase.

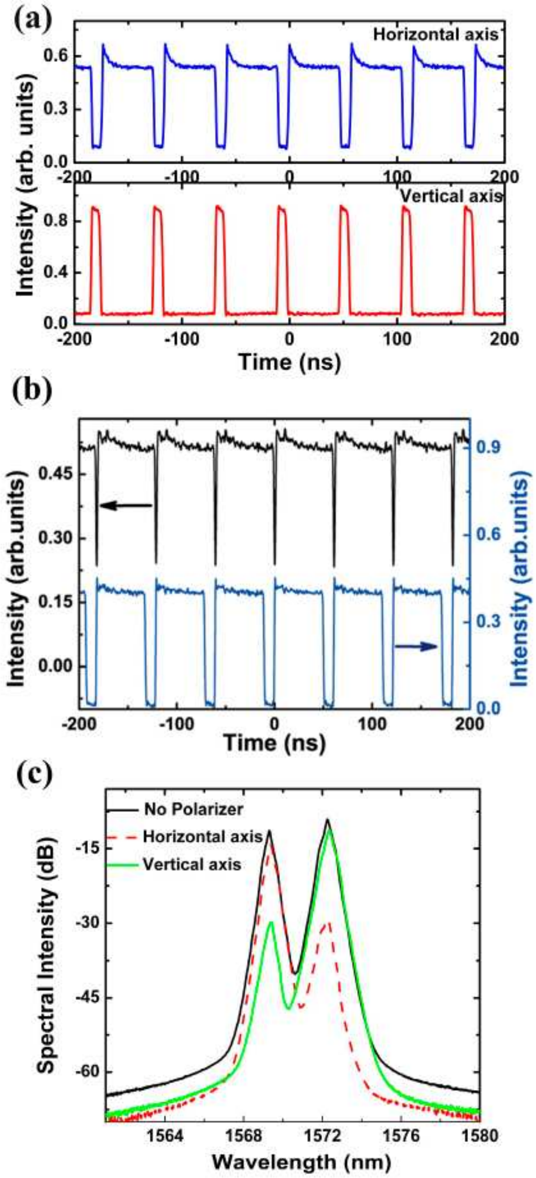

Fig. 3. Vector dark polarization domain wall soliton emission of the laser. (a) Polarization resolved oscilloscope trace: horizontal axis (upper trace) and vertical axis (lower trace). (b) Total laser emission (upper trace) and one of the polarized laser emissions (lower trace). (c) The corresponding optical spectra.

Figure 3(b) shows the total laser emission and one of the polarized emissions of the laser under strong pumping. Within one cavity roundtrip time there is one square-pulse along each polarization direction. Associated with the laser emission switching from one polarization to the other, an intensity dip appeared on the total laser emission. The profile of the intensity dip is stable with the cavity roundtrips, and each dip separates the two stable linear polarization

#121302 - $15.00 USD Received 10 Dec 2009; revised 6 Feb 2010; accepted 6 Feb 2010; published 18 Feb 2010

states of the laser emission. Figure 3(c) shows the corresponding optical spectra of the laser emissions. Laser emissions along the two orthogonal polarization directions have obvious different wavelengths and spectral distributions, showing that the coupling between the two polarization components is incoherent. In our experiments the cavity birefringence could be altered by rotating the paddles of the PC or carefully bending the cavity fibers, eventually the wavelength separation between the two spectral peaks could be changed. However, independent of the wavelength difference, the intensity dip could always be obtained. Moreover, the width and depth of the dip varied with both the cavity birefringence and the pumping strength. The stronger the pumping, the narrower and deeper is the dip. At even higher pump strength, splitting of the square pulse could occur. Within one cavity roundtrip another square pulse could suddenly appear. The new square pulse was found unstable. It slowly moved in the cavity and eventually merged with the old one.

4. Numerical simulation

The intensity dips possess the characteristics of vector dark PDW soliton predicted by Haelterman and Shepperd [10], despite of the fact that the two stable polarization domains are now orthogonal linear polarizations instead of circular polarizations. To confirm that such PDWs could exist in our laser, we further numerically simulated the operation of the laser, using the model as described in [16] but with no polarizer in cavity. To make the simulation possibly close to the experimental situation, we used the following parameters: γ=3 $W^{-1}km^{-1}$, Ω_g =16 nm, k''_{SMF}= –23 ps^2/km, k''_{EDF}= –13 ps^2/km, k'''= –0.13 ps^3/km, E_{sat}=10 pJ, cavity length L= 11.4 m, cavity linear birefringence of L_b=L, where $L_b = \lambda / \left| n_x - n_y \right|$ and G=120 km^{-1}. To favor the creation of an incoherently coupled domain wall, a polarization switching between the two orthogonal polarization components of the laser inside the simulation window was set in the initial condition. This corresponds to the initial existence of the linear polarization switching in our laser caused by the laser gain competition and cavity feedback.

A stable PDW soliton separating the two principal linear polarization states of the cavity could be numerically obtained, as shown in Fig. 4. Figure 4(a) and Fig. 4(b) show the stable propagation of the two linear orthogonal polarization components with the cavity roundtrips. The two polarization components are conjointly trapped in the time domain. Figure 4(c) shows the domain walls along each of the polarizations and Fig. 4(d) is the total laser emission intensity. An intensity dip appears on the total laser intensity and propagates undistorted with the cavity roundtrips. We have also plotted the polarization ellipticity degree of the intensity dip in Fig. 4(d). We adopted the definition of ellipticity degree q= (μ-ν)/(μ+ν), where q=±1 represents the two orthogonal linearly polarized states and q=0 refers to a circularly polarized state [10]. Obviously the intensity dip separates the two linear orthogonal polarization states, suggesting that it is a vector dark PDW soliton. Numerically it was observed that even with very weak cavity birefringence, e.g. Lb=100L, stable PDW soliton could still be obtained. However, if the cavity birefringence becomes too large, e.g. larger than Lb=0.5L, no stable PDWs could be obtained.

Therefore, based on the numerical simulation and the features of the experimental phenomenon, we interpret the intensity dips shown in Fig. 3(c) as a type of vector dark PDW soliton. To understand why the PDWs and vector dark soliton could be formed in our laser, we note that Malomed had once theoretically studied the interaction of two orthogonal linear polarizations in the twisted nonlinear fiber [17–19]. It was shown that PDWs between the two orthogonal linear polarizations of the fiber exist, and the fiber twist could even give rise to an effective force driving the domain walls. Considering that both the gain competition and the cavity feedback could have the same role as the fiber twist, e.g. cavity feedback also introduces linear coupling between the two orthogonal cavity polarization modes of a laser [15], not only the domain walls but also the moving of the domain walls could be explained.

#121302 - $15.00 USD Received 10 Dec 2009; revised 6 Feb 2010; accepted 6 Feb 2010; published 18 Feb 2010

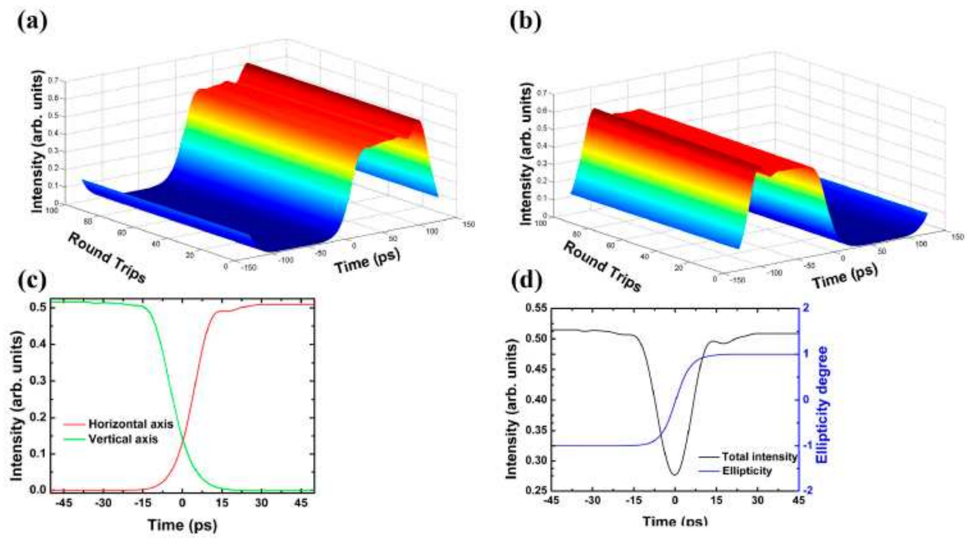

Fig. 4. Polarization domain wall numerically calculated. Evolution of the polarization domain wall with the cavity roundtrips: (a) Horizontal polarization, (b) Vertical axis, (c) Domain wall profiles at particular roundtrip, (d) The vector domain wall soliton and its ellipticity degree at particular roundtrip.

4. Conclusion

In conclusion, we have reported the experimental observation of PDWs and vector dark PDW solitons in a linear birefringence cavity fiber ring laser. The domain walls and solitons are found to separate the two stable orthogonal linear principal polarization states of the laser cavity. We have further shown that the cavity feedback and the gain competition could have played an important role on the formation of such PDWs and the vector dark domain wall solitons.

Acknowledgements

Authors are indebted to Professor Boris A. Malomed, Sergei Turitsyn for useful discussions. This project is supported by the National Research Foundation Singapore under the contract NRF-G-CRP 2007-01.