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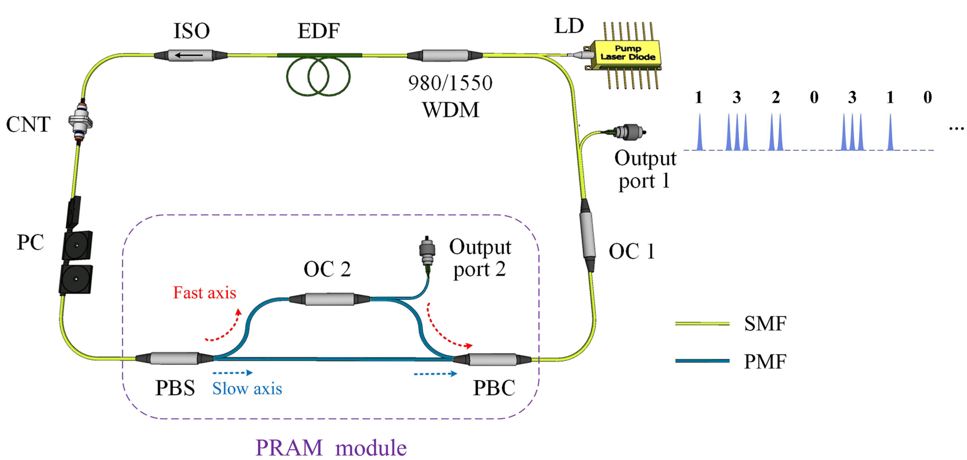

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Manipulation of Soliton Bunches Generated From a Polarization-Route-Assisted Vector Fiber Laser

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Abstract: In this article, we report robust vector soliton bunches arising in a passively mode-locked fiber laser based on carbon nanotube (CNT). By introducing a polarization-route-assisted module (PRAM) and finely adjusting the cavity birefringence, the soliton bunches can be flexibly manipulated to operate with controllable soliton numbers and positions. Moreover, the potential bandwidth resource provided by the concept of soliton bunches for the ease of breaks a new path for the enhancement of data-carrying capacity. Our research is helpful to extend the theory of vector soliton dynamics in fiber lasers and promotes the promising application in optical communication systems.

Index Terms: Fiber lasers, mode-locked lasers, ultrafast technology.

1. Introduction

Passively mode-locked fiber laser as a flexible source of ultrafast optical pulses has been widely investigated over past decades, due to its advantages of compact size, high stability, and simple configuration [1]. In addition, such lasers also act as a convenient experimental platform for the investigation of nonlinear waves subject to periodic boundary conditions [2]. Optical solitons, a typical nonlinear wave, normally result from the balance between intra-cavity dispersion and nonlinearity during its propagation over single mode fibers (SMFs). In a fiber laser cavity where gain and loss are also taken into account, the soliton evolution governed by Ginsburg-Landau equation

(GLE) shows more complex dynamic characteristics. Intra-cavity solitons can hardly be obtained without the mode-locked mechanism. To achieve mode-locking, a great variety of techniques and materials have been proposed, including the nonlinear polarization rotation (NPR) [3], nonlinear optical loop mirror (NOLM) [4], nonlinear amplifier loop mirror (NALM) [5], semiconductor saturable absorber mirror (SESAM) [6], and various two-dimensional optical materials [7]–[10]. Recently, with the extensive usage of diverse novel saturable materials, the investigation and application of solitons have entered into a brand-new period. Among the rapid development, polarization diversity and soliton interaction have always been research hotspots that can further enrich the understanding of soliton nonlinear dynamics.

As a SMF is capable of supporting two orthogonal polarization modes, for a fiber laser cavity without any polarization sensitive devices, it can generate vector solitons that contain two orthogonal components on two orthogonal polarization axes of SMF. According to the strength of intra-cavity fiber birefringence, various types of vector solitons have been successfully generated in fiber lasers, including group velocity locked vector soliton (GVLVS) [11], [12], polarization locked vector soliton (PLVS) [13], [14], and polarization rotation locked vector soliton (PRLVS) [15], [16]. Various vector solitons, with attractive physical features, provide new tools and insights to further understand the light polarization, which is a traditional but always active feature of laser physics [17], [18].

Apart from single soliton state, multi-soliton operation and soliton interaction will occur when pulse energy is relatively high. Over the decades, related nonlinear phenomenon has been widely studied, including harmonic mode-locking [19], bound-state solitons [20], soliton rain [21], macroscopic solitons [14]. Soliton bunch, as a typical and attractive inter-soliton behavior, has been reported in many mode-locked fiber lasers. Stable soliton bunch, consist of numerous solitons, can be regarded as a unit and a localized wave [22]–[26]. It is a naturally suitable data carrier for data encoding in optical communication system, allowing an increase in the bit-rate of data transmission. The encoding concept of soliton bunch suggests a data stream using symbols characterized by soliton numbers within the bunch, such as logical zero, one (single soliton), two (two-soliton bunch), and three (three-soliton bunch). Such a quaternary coding scheme ($M = 4$) doubles the data-carrying capacity of existing binary systems ($M = 2$), according to $\log_2 M$ law. With more solitons bunched together, it is desirable that the bit-rate could be further upgraded. So far, researches on soliton bunch have mainly focused on scalar fiber lasers where the solitons are generated from one single polarization axis. We notice it is difficult for these soliton bunch states to maintain for a long time, because the number of solitons and their positions are extremely sensitive to the disturbance of pump power and polarization state, which hinders the development of practical applications.

In this paper, we report a novel all-fiber vector mode-locked laser cavity which contains a polarization-route-assisted module (PRAM) for the ease of manipulating the structure of soliton bunches. The number of solitons within the soliton bunch can be flexibly tuned from one to six. Owing to the polarization beam splitter and combiner in the cavity, the solitons generated from two orthogonal polarization axes propagate along different paths every round trip. This structure greatly weakens the interaction among solitons and improve the robust operation of soliton bunch state, leading to an excellent long-term stability, which makes it ideal for practical uses.

2. Experimental Setup

The experimental setup of proposed fiber laser is shown in Fig. 1. A 976-nm laser diode (LD) with maximum output power of 400 mW introduces the pump light into the laser cavity via a 980/1550 nm wavelength division multiplexer (WDM). A 2.5-m EDF (Nufern, SM-ESF-7/125) is used as the gain medium. A polarization insensitive isolator (PI-ISO) operating at 1550 nm is used to ensure the unidirectional operation and suppress the detrimental reflections. The self-starting mode-locked operation can be achieved by a carbon nanotube (CNT) saturable absorber, which is attached between the end surface of two standard FC/PC fiber connectors. The CNT possesses low-intensity absorption of 20% at the wavelength of 1550 nm, modulation depth of 4%. In order to generate and manipulate the soliton bunches, a polarization-route-assisted module (PRAM) is

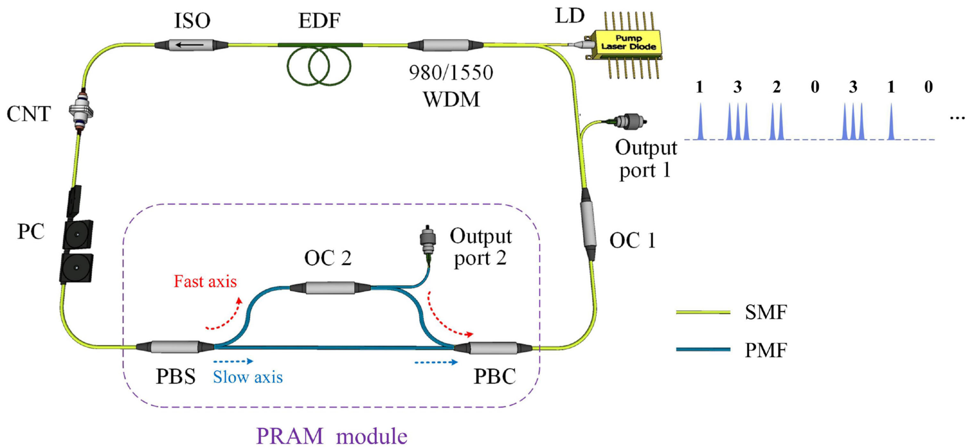

Fig. 1. Schematic diagram of proposed fiber laser configuration. WDM: wavelength division multiplexer, EDF: Erbium-doped fiber, LD: laser diode, CNT: carbon nanotube, ISO: isolator, PC: polarization controller, OC: optical coupler, PBS: polarization beam splitter, PBC: polarization beam combiner, SMF: single mode fiber, PMF: polarization maintaining fiber.

deliberately inserted in the fiber cavity, which consists of a polarization maintaining (PM) fiber pigtailed polarization beam splitter (PBS) and a polarization beam combiner (PBC). The PRAM divides the lights into two orthogonal polarization components (along fast axis and slow axis), and then re-combines them after propagating through different paths. The laser output is extracted via a 20:80 optical coupler (OC). Another 20:80 OC, with around 2-m PM fiber pigtail, is set into the fast-axis branch path to characterize output features along this axis, as well as introduce a distinct length difference between two orthogonal paths. A polarization controller (PC) is used to control the intro-cavity linear birefringence and adjust the polarization states of lights before the PRAM. Apart from the PRAM with PM structure, all the other components are pigtailed with single mode fibers (SMFs). The total cavity length is estimated around 17 m along fast axis and 15 m along slow axis. At the output port, an optical spectrum analyzer (OSA, Yokogawa AQ6370C) with a resolution of 0.02 nm is used to measure the optical spectrum. A sampling oscilloscope (OSC, Siglent SDS3052E) together with a 1-GHz photodetector (PD) is used to monitor the soliton pulse train.

3. Experimental Results

3.1 Traditional Polarization Rotation Locked Vector Solitons

Before inserting the PRAM, the proposed fiber laser is a fundamental passively vector mode-locked fiber laser, where typical vector solitons are expected to be obtained. Self-started mode-locking can be achieved by simply increasing the pump power above the mode-locking threshold. Different PRLVSs are easily obtained by slightly adjusting PC. The temporal characteristics of the PRLVSs measured after the PBS are presented in Fig. 2(a), (b) and (c), illustrating evident double-period, triple-period and six-time-period phenomenon characterized by the periodic intensity fluctuation between the two orthogonal polarization components. The corresponding optical spectra are shown in Fig. 2(d), (e) and (f). Among those spectra, we notice that apart from Kelly sidebands, there also exists an extra pair of spectral sidebands. This pair of sidebands will shift their position remarkably when we carefully either adjust the PC or alter the pump power. At the position of the extra sidebands after polarization resolved measurement, a peak is observed at one polarization component, while a dip is observed at the other. This peak-dip pair clearly indicates that the extra sidebands is generated due to the coherent energy exchange between two orthogonal polarization components [16]. The above observation on the polarization rotation dynamics of the PRLVSs

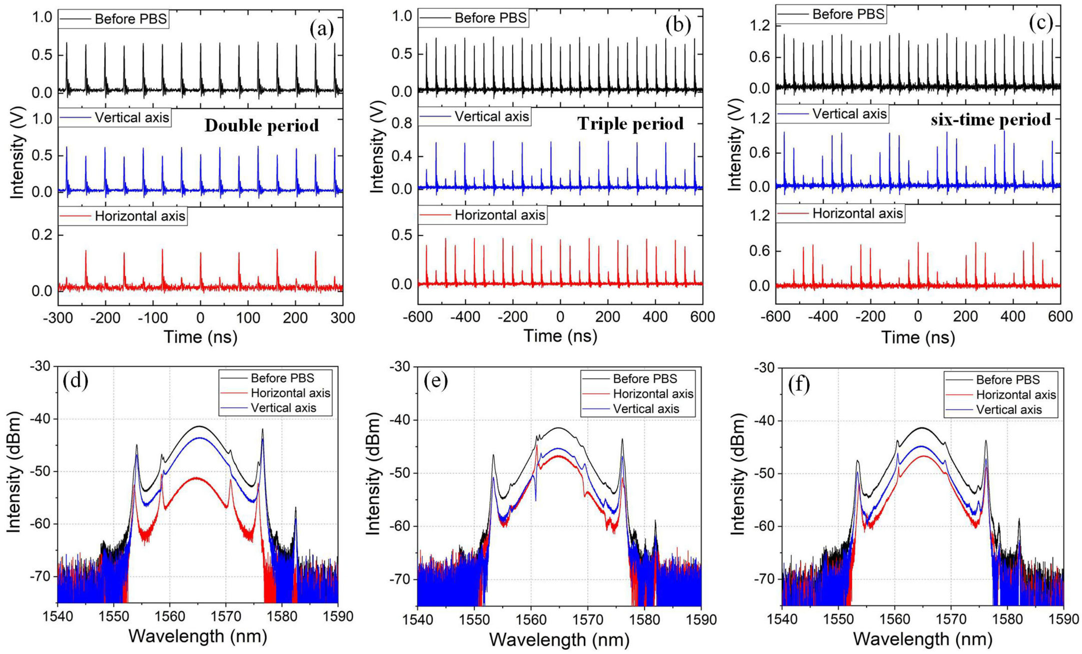

Fig. 2. Vector characteristics of PRLVSs. The polarization resolved pulse trains with double (a), triple (b), and six-time (c) period. (d)(e)(f) The corresponding optical spectra before (black lines) and after (red and blue lines) passing through the PBS.

shows that such laser can support abundant vector characteristics, lying the foundation for our following study on the generation and manipulation of vector soliton bunches.

3.2 Single Soliton With Alternate Roundtrip Time

In order to obtain soliton bunches, the previous common approach is simply increasing pump power. Normally, in a fiber laser, higher pump power leads to higher pulse energy, so that both pulse duration and peak power could rise. Due to the peak power limitation inside cavity, the fiber laser could evolve to single-pulse regime with wider pulse duration (such as peak power clamping effect [27]) or multi-pulse regime to reduce peak power. For the cavities operated in traditional anomalous dispersion regime with relatively low nonlinearity, the single pulse with large energy tends to split into multiple pulses to reduce its peak power, leading to multi-soliton operations within the laser cavity. However, for these soliton bunches, the newly-generated solitons normally move randomly without fixed positions [21]. This makes soliton bunch an attractive physical phenomenon, but neither controllable nor reliable for practical applications.

In our experiment, a PRAM is deliberately inserted into the cavity to weaken the interaction among solitons. It takes different time for the soliton to pass through the fast-axis branch and the slow-axis branch due to the different optical lengths. By connecting one brunch and disconnect the other, we separately measure the two round trip time along different brunch paths. The mode-locked thresholds of these two conditions are 100 mW (slow-axis connected) and 110 mW (fast-axis connected), respectively. Two oscilloscope traces are shown in Fig. 3. Thus, the repetition rates of two output pulse trains are 85 ns (for fast-axis brunch) and 75 ns (for slow-axis brunch), respectively.

Next, we connect both brunches so that the pulses can propagate along two polarization axes. Since the two OCs are placed at SMF section and fast-axis branch, respectively, the pulses propagating along slow-axis can be easily inferred. By increasing the pump power to 100 mW and adjusting PC, single soliton with alternate roundtrip time, is obtained as shown in Fig. 4.

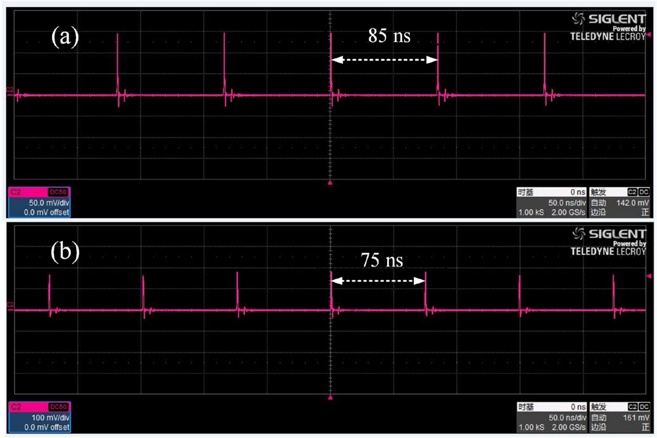

Fig. 3. Oscilloscope traces with (a) fast-axis brunch and (b) slow-axis brunch connected.

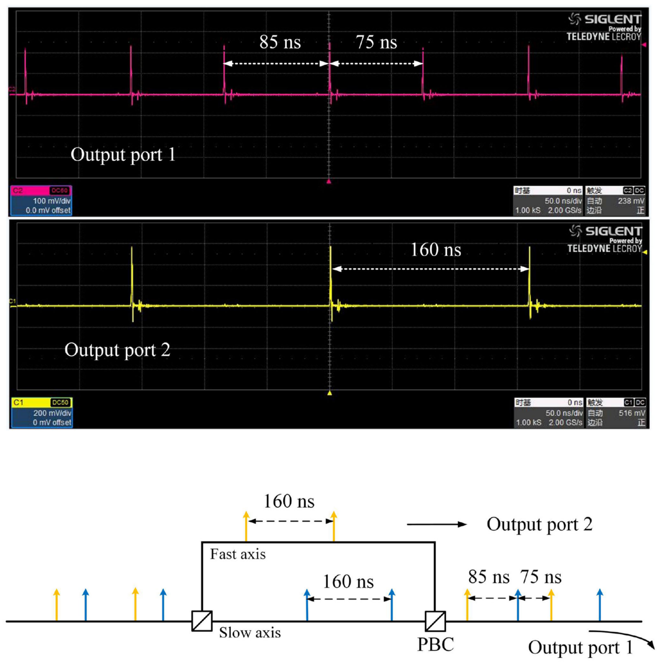

Fig. 4. Oscilloscope traces from output port 1 (red) and output port 2 (yellow) in "1+1" soliton state. The schematic diagram under the screenshot demonstrates soliton transmission process within the PRAM, in which yellow and blue arrows represent solitons that linearly polarized along two orthogonal directions.

The pulse-train from output port 2 (yellow) shows a period of 160 ns while the one from output port 1 (red) shows 85-ns and 75-ns alternate repetition rate. This result indicates that the soliton propagates along different branches every round trip, as shown in the each bottom diagram, where the yellow and blue arrows represent solitons with orthogonal linear polarized direction. We can further conclude that after passing through the SMF section of cavity (from PBC to PBS), the state of polarization (SOP) of solitons always experience a 90° rotation. If the 160-ns repetition rate from OC2 is regarded as the fundamental repetition rate, the output from OC1 can be considered "1+1" soliton state, which contains two 160-ns period pulse-trains. In fact, this type of soliton is similar to period-doubling PRLVS in principle, where the soliton returns to its original SOP every two round trip time. However, with the help of PRAM based configuration, the solitons with orthogonal

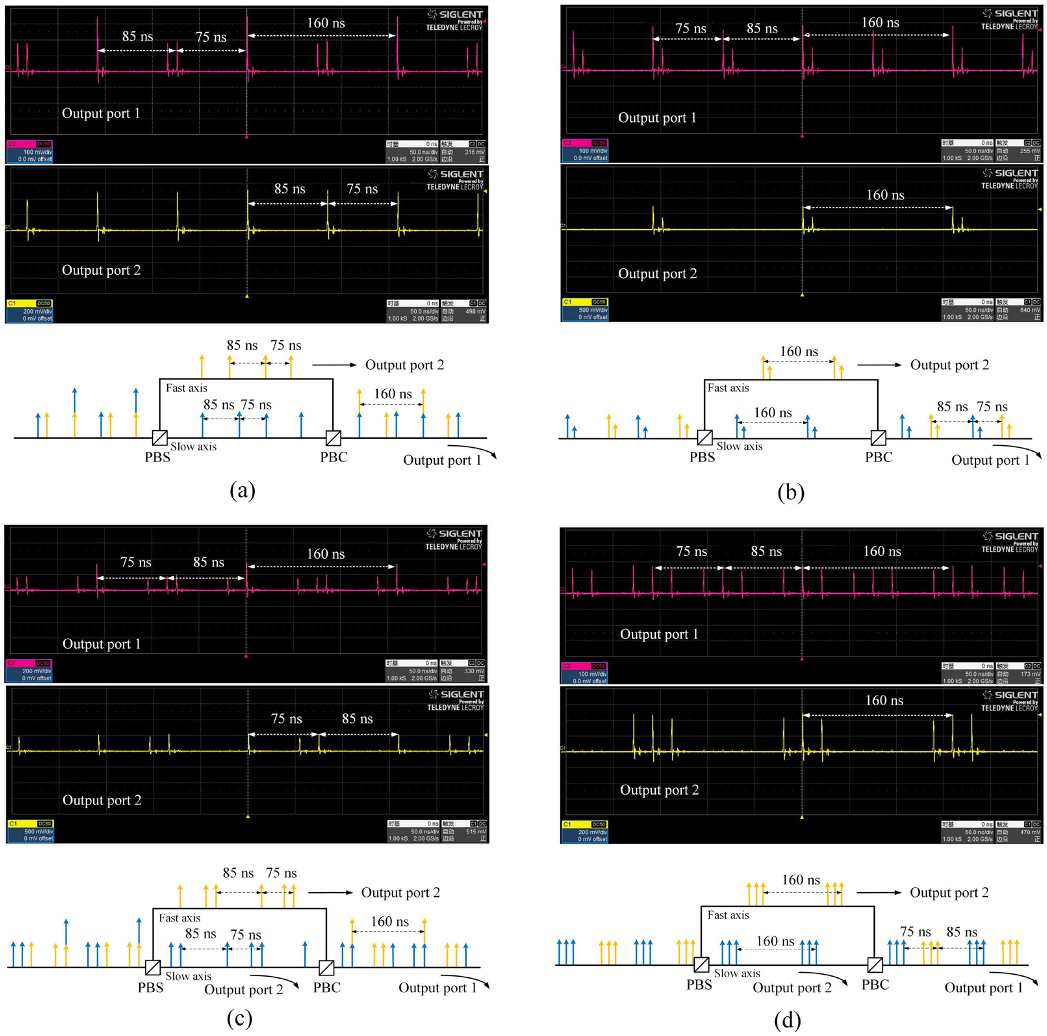

Fig. 5. The oscilloscope traces of different soliton bunches from output port 1 (red) and 2 (yellow): (a) 3-soliton (b) 4-soliton (c) 5-soliton (d) 6-soliton.

polarization direction propagate along different brunches, which greatly weakens the interaction among these solitons and improve the robustness of soliton bunch state, leading to an excellent long-term stability.

3.3 Vector Soliton Bunches

In order to increase the number of solitons and obtain soliton bunches, the pump power is slightly increased from 100 mW to 120 mW to realize pulse splitting. It is worth noting that in this case, the nonlinear phase shift (NPS) is also changed with increasing pulse energy. Therefore, the PC has to be slightly rotated to compensate the NPS by linear birefringence, so as to ensure the 90° rotation of SOP every round trip in the SMF section. Otherwise, the pulses would evolve to a random and disordered regime. Based on the principle of peak-power-clamping [6], soliton bunch state is easily obtained as long as the pump power is sufficient. In order to investigate the detailed transmission process within the PRAM, we simultaneously monitor the pulse trains output from output port 1 and output port 2. Fig. 5 shows the screen snapshot of oscilloscope for “1+2”, “2+2”, “2+3” and “3+3” soliton states which can all stably operate for at least eight hours under laboratory condition.

Under each snapshot, a diagram helps illustrate the transmission process of solitons. Therefore, the structure of the generated vector soliton bunches can be flexibly manipulated with the assistance of the PRAM. From the above results, the number of solitons within the soliton bunch increases with pump power, while the position of newly generated solitons is closed related to the length difference between the two branches. Theoretically, to generate more solitons within the soliton bunch, we just need to increase the roundtrip time and decrease the brunch length difference. This controllable feature distinguishes the generated soliton bunches from traditional soliton bunches with random soliton positions.

In the experiment, we also attempt to realize 180° or 360° rotation of SOP for both axes, so that the solitons can maintain fixed transmission route along fast- or slow-axis, and we may able to obtain two pulse-trains with an evident repetition rate difference [28], [29]. However, no matter how to adjust PC and pump power, the solitons can only stably operate at "axis-shift" state. We infer that although all the components used in the cavity are both-axis working or polarization insensitive, which supports the pulses along two orthogonal polarization axes, there still exists residual polarization dependent loss (PDL) within cavity [16]. This PDL may cause different pulse energy on two polarization axes, further making the NPS differ from one another. Therefore, the linear phase shift (LPS) adjusted by PC cannot compensate the NPS difference between two axes simultaneously.

4. Conclusion

In summary, we present robust vector soliton bunches arising in a passively mode-locked fiber laser based on CNT. With the help of a PRAM, the soliton bunches can be flexibly manipulated to operate with controllable soliton numbers from one to six. We believe that these results may greatly enrich the understanding of soliton dynamics. On the other hand, this new polarization-related regime can also find potential applications in the fields of optical communications, three-dimensional display, polarization multiplexing transmission, etc, especially for data encoding in optical communication allowing a bit-rate increment.

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