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Observation of dark-bright vector solitons in fiber lasers

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We report the experimental observation of coherently coupled dark-bright vector solitons in single mode fiber lasers with either normal or anomalous cavity dispersion. The properties of these vector solitons were found to agree well with theoretical predictions based on the coherently coupled nonlinear Schrödinger equations. The experimental results clearly confirmed the existence of a fundamentally new form of optical solitons in coupled nonlinear systems. © 2019 Optical Society of America

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Solitons as localized nonlinear waves that can propagate long distance in a dispersive medium without changing the shape are ubiquitous in nonlinear physical systems and have been widely studied [1-4]. In nonlinear optics, soliton formation and dynamics in single mode fibers (SMFs) have also attracted great attention [5-8]. Light propagation in single mode fibers is governed by the nonlinear Schrödinger equation (NLSE), where solitons are formed as a result of the natural balance between the fiber dispersion and the self-phase modulation [5, 6]. Specifically, the bright solitons are formed in the anomalous dispersion fibers, and the dark solitons, represented as an intensity-dip embedded in a CW light background, are formed in the normal dispersion fibers [7, 8].

However, in reality a single mode fiber always has slight birefringence due to imperfections, strain in the fiber, or the effects of fiber bending. A linearly birefringent single mode fiber supports two orthogonal polarization modes. Taking into account the coupling between the two orthogonally polarized modes, light propagation in SMFs can be described by the coupled NLSEs [9], where in addition to self-phase modulation, cross-polarization phase modulation also plays a role. Theoretical studies have shown that cross-polarization coupling could lead to the formation

of a group of novel solitons with two mutually coupled polarization components, known as vector solitons [10-14].

Two groups of vector solitons have been predicted from coupled NLSEs. The first group has a close relation to their scalar, single component counterparts. Examples of these vector solitons include the group-velocity-locked bright vector solitons [9], the phase-locked bright-bright vector solitons [10-12], and the dark-dark vector solitons [13]. These vector solitons have the characteristic that each of their polarization components can exist as a scalar soliton even when there is no coupling. They have been experimentally observed [15-18]. The second group of vector solitons has no scalar, one-component counterparts. Examples of these solitons are the polarization-domain wall solitons [19] and the dark-bright vector solitons [14]. Formation of these vector solitons is purely a result of cross-polarization coupling. They therefore constitute a fundamentally new type of optical solitons. Previously, S. Pitois et al. have reported the experimental observation of the polarization domain wall solitons by mixing two intense counter-propagation laser beams in a spun fiber [20]. In a previous paper we have also shown polarization-domain wall solitons in a single mode fiber laser [21]. However, to the best of our knowledge, there is so far no experimental confirmation of the coherently coupled dark-bright vector solitons in SMFs.

To better understand the dark-bright vector solitons, we first briefly review some of their features following the work of Christodoulides [14]. The light propagation in a weakly birefringent SMF is governed by the coupled NLSEs:

$$\begin{aligned} i \frac{\partial u}{\partial z} - \frac{\beta_2}{2} \frac{\partial^2 u}{\partial \tau^2} + \gamma \left(|u|^2 + \frac{2}{3} |v|^2 \right) u + \frac{\gamma}{3} v^2 u^* \exp(-4i\rho z) &= 0 \\ i \frac{\partial v}{\partial z} - \frac{\beta_2}{2} \frac{\partial^2 v}{\partial \tau^2} + \gamma \left(|v|^2 + \frac{2}{3} |u|^2 \right) v + \frac{\gamma}{3} u^2 v^* \exp(4i\rho z) &= 0 \end{aligned} \quad (1)$$

where u, v are the normalized slowly varying optical fields along the two orthogonal polarization eigenmodes of the fiber, β_2 is the group velocity dispersion coefficient, γ is the nonlinear coefficient

of the fiber, and z is the propagation distance along the fiber and τ is the time in a coordinate system that moves at the average group velocity, $\rho = \frac{\pi}{\lambda_0}(n_x - n_y)$ is the birefringence of the fiber.

The coupled NLSEs admit the formation of coupled dark-bright vector solitons of the form:

$$u(z, \tau) = U_0 \text{sech}(\tau/\tau_0) \exp[i(\sigma - \rho)z] \quad (2)$$

$$v(z, \tau) = V_0 \tanh(\tau/\tau_0) \exp[i(\sigma + \rho)z] \quad (3)$$

where

$$\tau_0^2 = \frac{\beta_2}{4\rho} = \frac{\lambda_0 \beta_2}{4\pi(n_x - n_y)} \quad (4)$$

$$U_0^2 = \frac{\lambda_0}{\pi n_2}(\sigma - 3\rho) \quad (5)$$

$$V_0^2 = \frac{\lambda_0}{\pi n_2}(\sigma + \rho) \quad (6)$$

In equations (2)–(6), U_0 and V_0 are the amplitude of the bright and dark solitons, respectively, τ_0 is the temporal soliton pulse width, and σ is an arbitrary constant. To illustrate, we have drawn in Fig. 1 and Fig. 2 the dark-bright soliton profiles at different σ values and the soliton pulse width variation with fiber birefringence, respectively.

Fig. 1. The dark-bright vector solitons formed in the anomalous dispersion regime at different σ . The solid-lines are the bright solitons and the dashed-lines are the dark solitons. Here $\beta_2 = -1.55 \text{ ps}^2/\text{km}$,

$\delta n = 1 \times 10^{-9}$, $n_2 = 1.2 \times 10^{-22} (\text{m/V})^2$, the effective cross-section area of the fiber is $S = 20 \times 10^{-12} \text{ m}^2$, and $\lambda = 1580 \text{ nm}$. The full width at half maximum (FWHM) of the solitons is $\tau_{FWHM} = 770 \text{ fs}$.

The vector solitons have the following unique characteristics: i) their formation is a result of the coherent cross-polarization coupling of light in SMFs; ii) vector solitons can be formed in either normal ($\beta'' > 0$) or anomalous ($\beta'' < 0$) dispersion fibers. While in the anomalous dispersion regime the bright soliton polarizes along the fast birefringence axis, in the normal dispersion regime it polarizes along the slow birefringence axis. In normal dispersion fibers, $V_0^2 > U_0^2$, while in the anomalous dispersion fibers, $U_0^2 > V_0^2$; iii) the pulse widths of the dark and bright solitons are always the same. Under fixed fiber group velocity dispersion, they are uniquely determined by the birefringence of the fiber. These features of the dark-bright vector solitons are different from their scalar NLSE soliton counterparts, as well as those vector solitons

so far experimentally observed [15–18]. This makes these vector solitons unique and interesting.

However, the experimental observation of this type of vector solitons is challenging. If we consider using a standard SMF to generate these vector solitons at $1.55 \mu\text{m}$, from Eqs. (4) – (6), to form a soliton with 1ps pulse width, the fiber birefringence would need to be as small as $\sim 3 \times 10^{-9}$, and the CW beam power at least $\sim 20 \text{ W}$ to support the dark soliton. In practice, it is difficult to find fibers with such small birefringence over long lengths. In principle one could use strong pulsed light to reduce the required fiber length, as S. Pitois *et al.* did for observing polarization-domain wall solitons [20]. However a drawback to this approach is the generation of other nonlinear effects that could mire the interpretation.

Fig. 2. The dependence of soliton pulse width on the fiber birefringence Δn at different GVDs. $n_2 = 1.2 \times 10^{-22} (\text{m/V})^2$, $S = 50 \times 10^{-12} \text{ m}^2$, and $\lambda = 1580 \text{ nm}$. Inset in the panel is the zoom-in of the lower birefringence region.

We introduce an innovative approach to solve this problem. Instead of traversing light over a long fiber length, we circulate the light in an active fiber ring cavity. It can be theoretically shown that under suitable conditions the average dynamics of light circulating in an active fiber ring cavity is equivalent to light propagation along an endless fiber [22]. Moreover, the approach has the advantage that the average dynamics of the light is governed by the averaged cavity dispersion and birefringence. By using cavity dispersion and birefringence management, one can fine-tune the effective cavity dispersion and birefringence and even make them close to zero. Using this same technique we have previously successfully demonstrated experimentally phase locked and polarization rotation bright vector solitons, whose formations also require coherent cross-polarization coupling of light in weakly birefringent fibers [16, 18].

We constructed a fiber ring laser as shown in Fig. 3 for the experiment. Briefly, it comprises 3.0 m erbium-doped fiber with a group velocity dispersion (GVD) coefficient of $63.6 \text{ ps}^2/\text{km}$, a 13.4 m long standard single mode fiber (SMF28) with a GVD coefficient of $-23.8 \text{ ps}^2/\text{km}$, and 12.9 m of dispersion-shifted fiber (DSF) with a GVD coefficient of $5.3 \text{ ps}^2/\text{km}$. A fiber pigtailed polarization insensitive isolator was used to force the unidirectional operation of the fiber ring. A polarization controller (PC) was used in the cavity to finely adjust the cavity net birefringence. The output was obtained through a 10% fiber output coupler. A fiber pigtailed polarization beam splitter was used to separate the two

polarizations of the laser emission. The polarization resolved beams were simultaneously measured with a high-speed electronic detection system comprising two 40 GHz photodetectors and a 33 GHz bandwidth real-time oscilloscope. In constructing the laser cavity, special care was taken to ensure the cavity had low birefringence and negligible polarization dependent losses.

Fig. 3. Schematic of the fiber laser setup. EDF: erbium-doped fiber; DSF: dispersion shifted fiber; SMF: single mode fiber; PC: polarization controller; PBS: polarization beam splitter; OSC: oscilloscope.

The fiber laser cavity had very small net birefringence, reflected by the fact that the laser emission along the two orthogonal polarization directions of the cavity had a very small wavelength difference of less than 1 nm. As a consequence, incoherent cross-polarization coupling always occurred with the laser emission alternating between the two orthogonal polarization modes [22]. Starting from such an initial laser operational state, the pump power was fixed, and the net cavity birefringence was then carefully reduced through appropriately setting the intra cavity PC. Phase locking between the two orthogonal polarization-modes was eventually achieved, which switched the mode coupling to the coherent regime.

Experimentally, a number of interesting laser operation states were obtained under coherent polarization coupling. Figure 4 shows one of such states observed with a cavity that had an averaged dispersion coefficient of $\sim 2.1 \text{ ps}^2/\text{km}$ and close to zero net birefringence. The two traces shown are the polarization resolved laser emissions. It clearly demonstrates that while along one polarization direction the laser emitted bright soliton pulses, along the orthogonal polarization direction it emitted simultaneously a dark soliton pulse. Many coupled dark-bright pulse pairs were formed in the cavity, and in particular, all the pairs had almost identical pulse parameters.

Depending on the pumping strength, phase locking between the two orthogonal polarization-modes could be achieved in a certain range of the net cavity birefringence, where the coupled dark-bright pulse pair emission was always obtained. However, at different net cavity birefringence the pulse width could change significantly. The pulses shown in Fig. 4 had broad pulse width so that they could be well detected by our detection system. Unfortunately such a state was very sensitive to the net cavity birefringence. Slight turning the orientation of the intra cavity PC to one direction, the state would suddenly terminate, while turning it to the opposite direction, the pulse width as well as the number

of pulses in the cavity would quickly decrease, and eventually the dark pulses became undetectable.

Fig. 4. Coupled dark-bright pulse pair emission of the fiber laser measured at an estimated net cavity birefringence of $\Delta n < 10^{-10}$. The intra cavity beam power: $\sim 700 \text{ mW}$.

We experimentally characterized the features of the dark-bright pulse pairs at relatively large net cavity birefringence where the pulse width is insensitive to small net cavity birefringence change. Figure 5(a) shows again the polarization resolved emissions of the laser. Five pairs of the dark-bright pulses coexisted in the cavity, and they repeated with the cavity roundtrip time. Figure 5(b) is the corresponding optical spectra. Both the Kelly sidebands [23] and the coherent energy exchange spectral sidebands [24] are obviously observable in the spectra, which clearly shows that both the bright and dark pulses are solitons. Using a commercial autocorrelator we measured the width of the bright pulses. It had a FWHM width of 1.53 ps. Assuming that the pulse had a sech^2 profile, its width was estimated $\sim 990 \text{ fs}$, as shown in Fig. 5(c). We note that the central wavelength of the solitons was at 1580 nm, which is different from that of the CW light. Due to the low repetition rate of the pulses, the width of the dark solitons couldn't be measured with the autocorrelation method. However, the Kelly sidebands of the dark solitons had exactly the same positions as those of the bright solitons, indicating that they should have the same pulse width and properties.

We have also constructed fiber lasers with different net cavity dispersions by varying the lengths of the SMF and DSF. Independent on the sign of the net cavity dispersion and the cavity length, the dark-bright vector solitons were always obtained as far as strong coherent cross polarization coupling was achieved. Through measuring the total laser output, we could also confirm that in the net normal cavity dispersion regime, the dark solitons have stronger pulse intensity than the bright solitons, while in the anomalous cavity dispersion regime, it is reversed. All features of the observed dark-bright vector solitons were found well in agreement with those of the coherently coupled dark-bright vector solitons theoretically predicted by D. N. Christodoulides [14].

We note that different from the conventional bright-bright vector soliton fiber lasers where a saturable absorber is inserted in the cavity and the vector solitons are formed through pulse shaping of the mode locked pulses, in our fiber lasers no any mode locker exists in the cavity. Experimentally we observed that before the dark-bright vector solitons were formed, a kind of antiphase periodic intensity modulation between the two orthogonal polarization components of the laser emission always occurred. The periodic intensity modulation quickly evolved into a periodic dark-bright pulse train, which is eventually shaped into a train of

the dark-bright vector solitons with random soliton separations, as shown in Fig. 4. In cases of too large net cavity dispersion and/or insufficient pumping strength, only the induced dark solitons [25] or the polarization domain wall solitons [21] could be obtained. In-phase periodic intensity modulations were also frequently obtained in our lasers. However, they were shaped into the phase locked bright-bright vector solitons. Based on our experimental observations we attribute the formation of the low frequency antiphase periodic intensity modulation to the polarization modulation instability effect [26, 27].

Fig. 5. Dark-bright pulse pair emission of the fiber laser measured at a relatively larger net cavity birefringence than the state shown in Fig. 4. (a) Polarization resolved laser emissions. (b) Optical spectra. (c) Autocorrelation trace of the bright solitons. The intra cavity beam power: $\sim 700\text{mW}$.

Finally, it is worth discussing the relationship between the dark-bright vector solitons and the polarization domain wall vector solitons. Both types of vector solitons were theoretically predicted under coherent cross-polarization coupling. A subtle difference between them is that the bright soliton in a polarization domain wall vector soliton is on top of a CW background [19, 21]. Both phenomena were experimentally obtained in our fiber lasers under the coherent cross-polarization coupling, which is in consistent with the theoretical prediction. However, we found experimentally that through varying the pumping power one could switch between the two types of vector solitons, suggesting that they could physically be equivalent.

In summary, we have first experimentally observed dark-bright vector solitons in single mode fiber lasers with either a net normal or a net anomalous dispersion cavity. The observed dark-bright vector solitons exhibited properties exactly as those theoretically predicted by D. N. Christodoulides based on the coupled NLSEs under coherent cross-polarization coupling. To the best of our knowledge, this is the first experimental confirmation on the existence of the vector solitons in SMFs. Given that the coupled NLSEs describe the nonlinear wave properties of a wide range of physical systems, and the vector soliton formation constitutes a fundamentally new phenomenon of the nonlinear wave dynamics, we expect that the experimental result will shine insight on the multi-component soliton formation in other physical systems and trigger extended experimental study of them.

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