Vector Soliton Fiber Lasers

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Abstract

Experimental observation of different types of vector solitons such as the brigth-bright, dark-dark, and dark-bright vector soltions in single mode fiber lasers is reported. Experimental techniques for observing each of the vector solitons are explained. Special features of the vector solitons in fiber lasers are numerically simulated and compared with the experiments.

Soliton as a stable localized nonlinear wave that can propagate long distance without waveform distortion has been extensively investigated. Optical solitons were first experimentally observed in single mode fibers (SMFs) by Maulenauer et al. in 1980 [1]. Due to their potential applications in optical long distance communications and optical signal processing, optical solitons formed in SMFs have attracted great attention. It is now well-known that formation of optical solitons in SMFs is due to the balance between the fiber dispersion and fiber nonlinear optical Kerr effect, which is mathematically described by the nonlinear Schrödinger equation (NLSE). Moreover, it has also been theoretically shown that in the anomalous dispersion SMFs, dark optical solitons could be formed. When birefringence of a SMF is considered, various types of vector solitons characterized as solitons comprising two orthogonal polarization components, could also be formed. Among them the group velocity locked bright-bright vector soliton had been experimentally confirmed previously [2].

A fiber laser is mainly made of SMFs. Experimentally it has been shown that optical solitons could be automatically formed in the mode-locked erbium-doped fiber lasers. As the erbium-doped fiber lasers operate at the 1.55 μm, which is the fiber optical communication wavelength, the soliton operation of the erbium doped fiber lasers as well as the properties of the emitted solitons have been extensively investigated. However, previous studies on the soliton fiber lasers have mainly been focused on the NLSE type of scalar solitons. In this talk we show that, apart from the scalar solitons, various types of vector solitons, which are governed by the coupled NLSEs, can also be formed in the erbium-doped fiber lasers. We have experimentally observed different types of vector solitons in the erbium-doped fiber lasers, these include the group velocity locked bright-bright, dark-dark vector solitons, the phase locked bright-bright, dark-dark and dark-bright vector solitons, and the polarization rotation bright-bright vector solitons. Numerical simulations could also well reproduce our experimental observations.

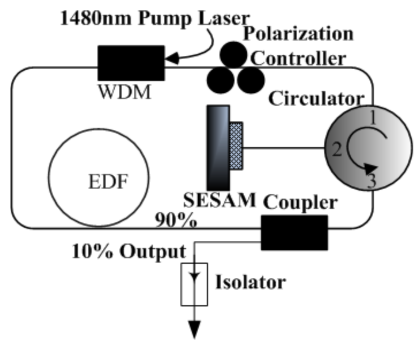

Figure 1: Configurstion of a fiber laser used for various bright-bright types of vector soliton generation.

We have designed different erbium-doped fiber lasers to fulfill the conditions required for generating different types of vector solitons, e. g. we have designed a passively mode locked fiber ring laser as shown in Fig. 1 for the generation of the various types of bright-bright vector solitons. The ring fiber cavity consists of 4.6 m Erbium-doped fiber (EDF) with group velocity dispersion parameter 10 ps/km/nm, and a total length of 5.4 m standard single mode fiber (SMF) with group velocity dispersion parameter 18 ps/km/nm. Mode-locking of the laser was achieved with a commercial semiconductor saturable absorber mirror (SESAM). A characteristic of the laser is that it has a negative dispersion cavity and no any polarization dependent components are inserted in the cavity. Therefore, the laser emits simultaneously along its two principal polarization directions. After mode locking the mode locked pulses are automatically shaped into the bright-bright vector solitons due to the intrinsic balance between the negative cavity dispersion and the fiber nonlinear optical Kerr effect. Depending on the strength of the cavity birefringence, the various types of bright-bright vector solitons, these are the group velocity locked bright-bright vector solitons, the phase locked fundamental and a high order bright-bright vector solitons, the polarization rotation bright-bright vector solitons, are automatically formed in the laser.

Removing the SESAM from the cavity or replace it with a saturable absorber of sufficiently weak saturable absorption, polarization domain walls and the fundamental domain-wall solitons in the form of phase-locked dark-bright vector solitons are then observed in the fiber laser, an example is shown in Fig. 2. The domain wall soliton is a stable localized structure that separates the adjacent regions of the two polarization states of the laser.

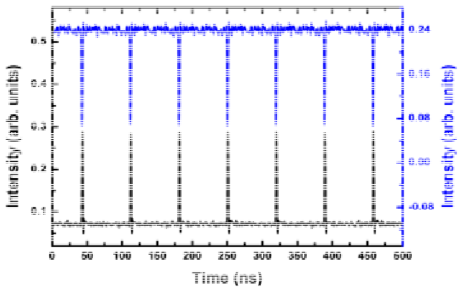

Figure 2: Oscilloscope trace of an experimentally observed dark-bright vector soliton.

Its formation is due to the strong coupling between the two polarization modes. Like the conventional scalar bright and dark solitons formed in fiber lasers, multiple dark-bright vector solitons could also simultaneously appear in a fiber laser. The dark-bright vector soliton has also been observed in the positive dispersion fiber lasers, suggesting its formation in the fiber lasers is independent the sign of cavity dispersion. In addition, in a positive dispersion fiber laser we have also observed a type of elliptically polarized dark-dark vector soliton. It constitutes another type of fundamental domain-wall solitons that has been theoretically predicted [3]. With a weak saturable absorber in the purely positive dispersion cavity fiber laser we have also experimentally revealed a type of group-velocity locked dark-dark vector soliton, whose formation mechanism could be traced back to the balance between the cavity group velocity and nonlinear phase modulation of the pulses.

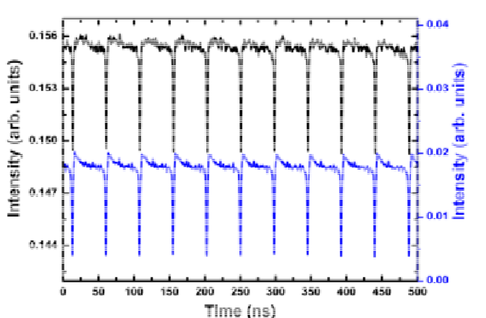

Figure 3: Oscilloscope trace of an experimentally observed dark-dark vector soliton.

To confirm our experimental observations, we also numerically simulated the operation of the fiber lasers with a technique as reported in [4]. Briefly, we circulate the light within a calculation window in the laser cavity. Whenever the light encounters a discrete cavity component, we multiply the Jones matrix of the cavity component with the light field. The light propagation in the cavity fibers is described by the coupled Ginzburg-Landau equations. The features of the erbium-doped fiber as well as the saturbale absober used were numerically considered. Numerically we could reproduce almost all the experimentally observed vector solitons. Fig. 4 shows for example a numerically calculated phase locked dark-bright vector soliton. The features of the numerically simulated vector solitons well match to those of the experimental observations.

In summary, we have experiemntally observed various types of vector solitons in the erbium-doped fiber lasers operating in the 1.5μm wavelength region. Through carefully design of the fiber laser cavity and selecting its parameters, we have shown that the various types of vector soltions threoretically predicted could be obtained in fiber lasers. Numerical simulations have also well reproduced our experimental results. It is shown that the erbium-doped fiber lasers are an attractive vector soliton generation source as well. As a soliton fiber laser mimics a miniature soliton fiber communication system, and birefringence is an intrinsic feature of the optical fibers, we believe that apart from scientific importance, our results could also be of practical importance.

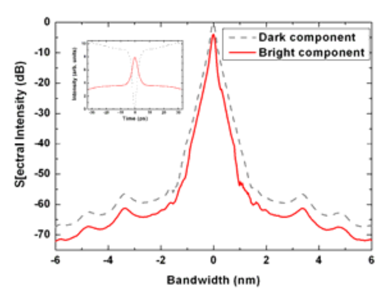

Figure 4: Polarization resolved soliton spectra of a numerically calculated dark-bright vector soliton. Inset: the calculated dark-bright vector solitons.

References:

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