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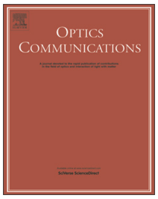

Polarization of vector solitons generated in break-up process in twisted fiber

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ABSTRACT

We study experimentally the polarization of the radiation resulting from the pulse break-up process in a SMF-28 twisted fiber. The fiber twist causes circular birefringence and also mitigates the linear birefringence. The twisted fiber may be considered for nonlinear effect as fiber without linear birefringence, which allows the investigation of polarization properties which cannot be studied in common fibers because of the random residual birefringence. We found that the polarization of the formed solitons is more stable when the input pump polarization has elliptical polarization with big angle of ellipticity. At input polarization close to linear we observed that the polarization ellipticity angle tends to be higher than the polarization ellipticity angle of the input pump. The fluctuation of the polarization grows when the input polarization approaches to the linear.

1. Introduction

Solitons as the exact solution of the Nonlinear Schrödinger Equation (NLSE) can be found for linearly or circularly polarized light [1] in fibers without birefringence. In practice the polarization is not conserved along the fiber because of fiber birefringence. However, even in the fiber with birefringence the pulse can propagate stably in the form of the vector soliton. The concept of vector soliton has been intensively discussed. It was shown that the nonlinear coupling between orthogonally polarized modes allows their envelopes to propagate without temporal walk-off forming the so-called group-velocity locked vector soliton [2, 3]. Also the phase locked vector soliton was found [4, 5]. The concept of the vector solitons was considered for fiber lasers [6–8]. In the papers cited above a single vector soliton propagating in the fiber was discussed.

A pulse with power much higher than the soliton in a fiber with anomalous dispersion becomes instable and transforms into a number of solitons. The initial dynamic of this process depends on pulse duration and for long pulses (ps and longer) modulation instability plays an important role. In the time domain, these processes induce a fast modulation of the pump envelope which can subsequently break up into a train of femtosecond solitons. The fact that the initial dynamics is seeded from noise results in random fluctuation of the solitons parameters. The pulse break-up is one of the principal mechanisms of formation of supercontinuum [9] and also may play important role in the formation of noise-like pulses in fiber lasers [10–12]. The mechanism of the formation of noise like pulses is not yet well established.

The polarization properties of vector solitons generated in the break-up process have been investigated in relation with SC generation because the polarization stability can be an important issue for applications [13–17]. Numerical simulations for the fiber with low birefringence [13] show that the output polarization depends randomly on the wavelength even without imposed noise if the input polarization is aligned at an angle of 45° to the slow axis. When the input was linearly polarized close to the slow axis the SC output had the slow axis polarization dominant, with few components present in the fast mode. However, for input polarized close to the fast axis the output polarization was random. The noise imposed on the pulse results in random polarization at the fiber output. The fluctuations depend on pulse duration and become lower when the pulse is shorter. The calculations were done for pulses with durations of 150 fs and shorter.

A commonly accepted way to stabilize the polarization of SC is the use of fibers with high birefringence [15, 17].However the application of hi-bi fibers may be limited. One example is provided by mode-locked fiber lasers where the principal mechanism of mode-locking is nonlinear polarization rotation [18, 19]. Another

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way to provide polarization stability is introducing circular birefringence by fiber twist. In combination with the linear birefringence, elliptical birefringence results and causes a rather complicated evolution of the polarization [20, 21]. However, if the circular birefringence is much higher than the linear birefringence, the linear birefringence is mitigated and the fiber has circular birefringence. Moreover for nonlinear processes the twisted fiber may be considered as a perfectly isotropic fiber [22] useful for the investigation of nonlinear processes. The investigation of soliton formation and soliton propagation in a twisted fiber may reveal effects that are normally disguised by the presence of residual linear birefringence.

However, there are only a few papers where the formation and evolution of vector solitons in a twisted fiber were investigated. One of the new effects discovered recently was reported in [23]. It was shown theoretically that the polarization of Raman solitons evolves towards circular during the propagation in a fiber with circular birefringence if the vectorial nature of the Raman effect is taken into account. The comparison of the polarization of the radiation formed in a twisted fiber and in a fiber without intentionally introduced twist was discussed previously in [22]. In fibers without twist and hence with residual linear birefringence the polarization was completely random at any input polarization. In contrast, the polarization of the radiation in twisted fibers shows some stability especially if input polarization is circular. It was also suggested that if the input polarization is close to linear the output polarization tends to have an ellipticity angle greater that the ellipticity angle of the input pulse. In this paper ns pulses were used for pumping. In that case the number of pulses formed by pulse break-up is very large and the time separation between pulses with different wavelengths is less than the pump pulse duration. So the process of the formation of separate solitons was not terminated.

In the present paper we used 0.7-ps pulses generated by a fiber ring laser. The calculations show that for sub-ps pulses the longer-wavelength part of the spectrum at the fiber output consists of solitons separated in space. We measured the polarization of solitons at the end of a 500-m twisted SMF-28 fiber using a single shot technique. This technique also allows measuring the fluctuations of the polarization. To the best of our knowledge it was never done before. We find that solitons have a more stable polarization if the input pulses have polarization close to circular. At input pulse polarization close to linear the fluctuation grows significantly and the output ellipticity tends to be greater than the input ellipticity.

2. Experimental setup

The experimental setup is presented in Fig. 1a. As a source of signal we used a mode-locked fiber ring laser based on nonlinear polarization rotation, Fig. 1b. The laser cavity consists of a 3-m EDF with normal dispersion and 10 m of the standard fiber Corning SMF-28. The cavity also includes a WDM, the output coupler and free space elements: a half wave plate (HWP), a polarization-dependent isolator and a quarter wave plate (QWP). The configuration is typical for soliton lasers. The length of the cavity is 14 m with a total anomalous dispersion estimated as -0.25 ps^2. The rotation of the HWP and QWP changes the generation regime. We used pulses with spectra shown in the Fig. 2a and Fig. 2b. In the first case the spectrum bandwidth was 5.5 nm with 1544 nm central wavelength and the autocorrelation function of 1.3 ps. The spectrum assumes that the pulse may have some internal structure or chirp. The spectrum shown in the Fig. 2a is typical for soliton lasers. The central wavelength is 1532 nm; bandwidth is 7.3 nm. The FWHM of the autocorrelation function is 0.4 ps.

The pulses from the laser were stretched by the 12-m SMF-28 fiber and then amplified by an EDFA with maximum amplification of 150 times. The pulses from the amplifier output pass through a polarization controller (PC), a polarizer, and a quarter wave retarder (QWR1). Rotation of the QWR1 allows stable polarization with desirable ellipticity at the input of the twisted SMF-28 fiber. It has to be note that the spectra generated in the twisted fiber were different for two regime of the laser. The pulse with spectrum shown in the Fig. 2a generated the broadband flat spectrum consisting of multiple solitons, while the pulse with the spectrum shown in the Fig. 2b generated one or few number of well separated solitons. The details will be discussed below. We used two spans of the fibers with lengths of 500 m and 200 m. The fiber in both spans were twisted with a twist rate of 7 turns/meter and placed on a cylinder with a diameter of 46 cm. The dispersion of the fiber is 25 ps^2/km and nonlinearity is approximated by 1.5 (W-km)$^{-1}$. For our purpose the linear birefringence has to be mitigated by the fiber twist. To do this the circular birefringence has to be much larger than the linear. It was shown [20] that the twist introduces an optical activity proportional to the twist:

$$\alpha = g\tau L, \tag{1}$$

where τ is the fiber twist rate. The coefficient g was calculated from the elastooptic tensor for silica glass to be approximately of 0.16. This value depends slightly on the doping concentration. However even for highly doped fiber it gives a good correspondence with experimental results [21]. The difference between refractive indexes for orthogonal circularly polarized beams is defined by:

$$\Delta n_c = \frac{\lambda}{2\pi} g\tau, \tag{2}$$

where Δn_c is the difference between refractive indexes for orthogonal circularly polarized waves. This equation yields the value of Δn_c equal to 1.7×10^{-6} for a wavelength of 1.55 μm and a twist rate of 7 turns/m. The beat length for the same fiber without bending was measured as 15 m [25] that corresponds to a value of Δn_l for orthogonal linearly polarized beams equal to 10^{-7}. Fiber twist also causes polarization mode dispersion. It can be calculated from:

$$\Delta t_c = \frac{L}{c}\tau\frac{dg}{dk}, \tag{3}$$

where k is the wave number. Using the dependence of the coefficient "g" on the wavelength [26] we obtain that for the twist rate of 7 turns/m the polarization mode dispersion is equal to 0.3 ps/km.

Linear birefringence in single-mode optical fibers results also from fiber bend [27]. For the bend diameter of 46 cm Δn_l is equal to 3.4×10^{-8}. We can see that for our coil the circular birefringence resulting from twist is at least one order of magnitude higher than linear birefringence. However, there may be some additional effects such as additional stress in the process of coiling which can causes the linear birefringence. However it is impossible to cancel completely the linear birefringence and ellipticity of the pulse is change slightly in the fiber. It is not very important for circular input polarization because the polarization along all fiber length remains close to circular, however in may be very important for linear input polarization because even small ellipticity changes can change the sigh of the ellipticity angle.

The fiber output is connected to a circular polarizer formed by QWR2 and a polarizer. The QWR2 converts orthogonally polarized circular components at the fiber output into orthogonally polarized linear components. The linearly polarized components are then splitted by a fiber polarization beam splitter (PBS). The pulses