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Simulative demonstration of soliton pulse stability over the nonlinear regime in a birefringent optical fiber

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Abstract

In this paper, the results of numerical analysis are demonstrated for sech pulse (soliton) propagation in a birefringent optical fiber using computer modeling and simulation. Here, the initial pulse is polarized linearly and guided into the fiber at an angle of 45° to its polarization axes. The birefringence-induced time delay of 200 and 440 ps between X and Y polarization components has been reported at a fiber length of 631.72 km (10 soliton periods) by considering linear and nonlinear regimes, respectively. The Kerr nonlinearity, which stabilizes solitons against spreading due to GVD, also stabilizes them against splitting due to birefringence. A similar fact is true for the birefringent walk-off. Above a certain soliton order (N_{th}), the evolution scenario is qualitatively different and two orthogonally polarized components of the soliton move with a common group velocity despite their different modal indices or polarization mode dispersion (PMD) at a fiber length of 631.72 km (10 soliton periods) and 1264.344 km (20 soliton periods) over a nonlinear regime at $\theta \neq 45^\circ$. The physical effect responsible for this type of behavior is the cross-phase modulation (XPM) between the two polarization components.

Keywords: Solitons; Birefringent fibers; Kerr nonlinearity; GVD

1. Introduction

The “single-mode” fibers are actually bimodal because of the presence of birefringence. This means that the group velocity is different for pulses polarized along the two principal axes. If the pulse contains both polarization components, in addition to spreading due to GVD, the partial pulses will tend to split apart because of birefringence [1,2].

Optical birefringence of an optical fiber, exhibited by the dependence of the refractive index on the state of polarization of a propagating light wave, is a feature characteristic of every existing fiber. The fiber birefringence causes the linearly polarized electric field, guided into an actually existing single-mode optical fiber, to break up into two orthogonal components, between which unpredictable coupling occurs, which leads to an uncontrollable change of the state of polarization along the fiber length [1–4].

Highly birefringent fibers possess a distinguished pair of orthogonal symmetry axes (birefringence axes), along which the two orthogonal components of the fundamental mode are polarized, which can propagate for any

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given wavelength, but with two different phase velocities. If the direction of polarization of the input electrical field (the direction of polarization of the input pulse) coincides with the one of the birefringence axis, then the direction of polarization will be maintained over the whole length of the fiber (the fiber maintains the polarization).

In [5], the results of numerical analysis were reported for ultrashort pulse propagation in a highly birefringent optical fiber for a super Gaussian initial pulse. From the calculations carried out, it follows that when both orthogonally polarized components of the fundamental mode of a highly birefringent single mode fiber are excited to the same degree by a pulse in the shape of a super Gaussian function, then, for a given value of the birefringence parameter (δ), the manner in which the pulse components propagate is determined by the amplitude of the initial pulse. But the numerical analysis reported above needs to be supported by simulative or experimental validations.

Here, the results of numerical analysis are established for sech pulse (soliton) propagation in a birefringent optical fiber using computer modeling and simulation with OptiSystem$^{\mathrm{TM}}$. The theory is discussed in Section 2. The results are reported in Section 3 and concluding remarks are mentioned in Section 4.

2. Theory

In high-birefringence fibers, the group velocity mismatch between the fast and slow components of the input pulse cannot be neglected. Such a mismatch would normally split a pulse into its two components polarized along the two principal axes if the input polarization angle θ deviates from 0° or 90°.

The propagation of a pulse and the effects of group velocity mismatch in linear birefringent fibers with an arbitrary polarization with respect to the principal polarization axes are described by the following system of coupled NLS equations:

$$\mathrm{i}\left(\frac{\partial u}{\partial \xi}+\delta\,\frac{\partial u}{\partial \tau}\right)+\frac{1}{2}\frac{\partial^2 u}{\partial \tau^2}+(|u|^2+B|v|^2)u=0$$

and

$$\mathrm{i}\left(\frac{\partial v}{\partial \xi}-\delta\,\frac{\partial v}{\partial \tau}\right)+\frac{1}{2}\frac{\partial^2 v}{\partial \tau^2}+(|v|^2+B|u|^2)v=0, \tag{1}$$

where u and v are the normalized amplitudes of the field components polarized linearly along the X and Y axes, respectively.

In Eq. (1), B is the cross-phase modulation parameter ($B=2/3$ for linearly birefringent fiber), $\delta=(\beta_{1x}-\beta_{1y})T_0/(2|\beta_2|)$ is the normalized group velocity and governs the mismatch between the two polarization components $\tau=(t-\bar{\beta}_1 z)/T_0$ is the normalized time, where $\bar{\beta}=\frac{1}{2}(\beta_{1x}+\beta_{1y})$ is inversely related to the average group velocity and $z=\xi L_{\mathrm{D}}$, where $L_{\mathrm{D}}=T_0^2/|\beta_2|$is the dispersion length and T_0 is a measure of the pulse width.

These equations generalize the scalar NLS equation to the vector case for birefringent fibers and can be solved numerically using the split–step Fourier method [1,2,5].

The electric field envelopes are normalized according to $(u,v)=\sqrt{\gamma L_{\mathrm{D}}}(E_x E_y)$.

The initial conditions (at $z=0$) used are in the form

$$u(z=0,\tau)=N\cos\theta\,\mathrm{sech}(\tau)$$

and

$$v(z=0,\tau)=N\sin\theta\,\mathrm{sech}(\tau), \tag{2}$$

where N is the soliton order and can be derived from the relation

$$N^2=\frac{L_{\mathrm{D}}}{L_{\mathrm{NL}}}=\frac{\gamma P_0 T_0^2}{|\beta_2|}. \tag{3}$$

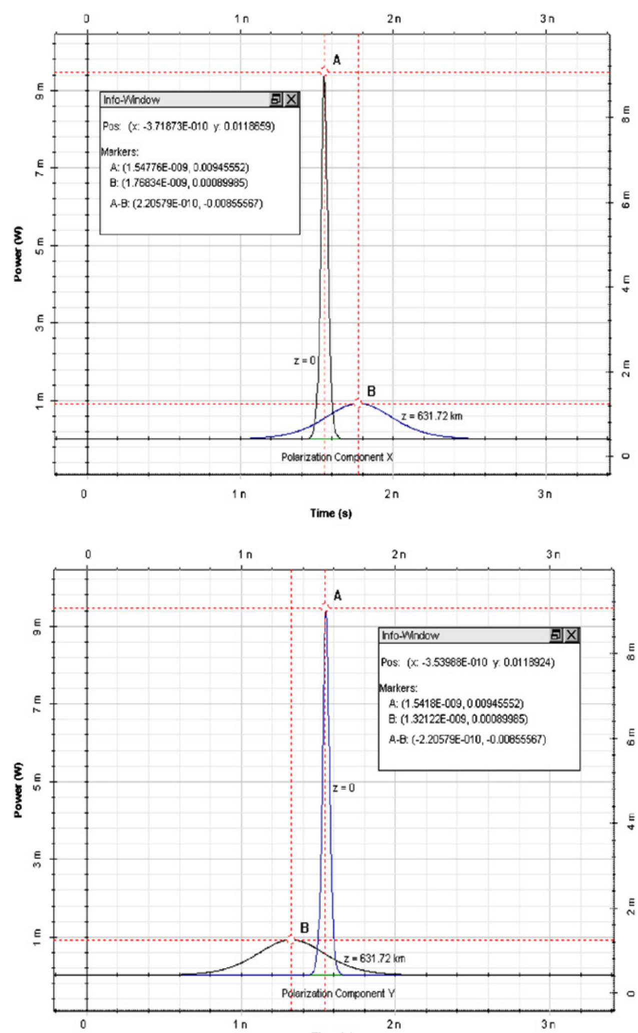

Fig. 1. Polarization components X and Y for a sech pulse at the input and at a transmission distance of 631.72 km (10 soliton periods) in the linear regime.

3. Results

The parameters used in our simulation model are: bit rate = 10 Gb/s, pulse width = 0.5 bit (50 ps) and $n_2 = 3 \times 10^{-20}\,\mathrm{m}^2/\mathrm{W}$, $A_{\mathrm{eff}} = 93\,\mu\mathrm{m}^2$, $\beta_2 = -20\,\mathrm{ps}^2/\mathrm{km}$. The power necessary to launch the fundamental soliton (corresponding to 1550 nm, in the anomalous GVD regime of the fiber) is calculated to be $P_0 = 19.0155$ mW, and the soliton period is $Z_0 = 63.172$ km. We set the value of the birefringence to $\Delta n = n_x - n_y = 2.1187 \times 10^{-7}$, where n_x and n_y are the effective mode indices for X and Y polarized components, respectively.

The difference in the group delays per unit fiber length between both polarization components is then $\Delta n/c = 0.7067$ ps/km. Since $T_0 = 28.3607$ ps, the value of the group velocity mismatch parameter δ is $\delta = 0.5$. To see the birefringence-induced time delay between both polarization components, we set azimuth in the optical sech pulse generator equal to 45° and fiber length to equal 631.72 km (10 soliton periods).

Fig. 1 shows the input and output partial pulses after 631.72 km propagation in a loss-free fiber along polarization components X and Y. Both partial pulses are broadened by GVD and shifted in time by 440 ps with respect to each other, which corresponds to a difference in the arrival times of 0.7 ps for 1 km of fiber length. This shift can be attributed to the birefringence.

When the nonlinearity is taken into account, the two polarization components remain bound together if N in Eq. (2) exceeds some critical value N_{th} that increases with the increase in δ. For $\delta = 0.5$, this value is $N_{\mathrm{th}} \approx 1$ [1,2]. For this, we took into account the nonlinear effects in the fiber component. The output pulses for 631.72 km of propagation are shown in Fig. 2.

Comparing Figs. 1 and 2, we can see that the impact of the nonlinearity is double-fold: Nonlinear effects reduce the GVD-induced pulse broadening for each of

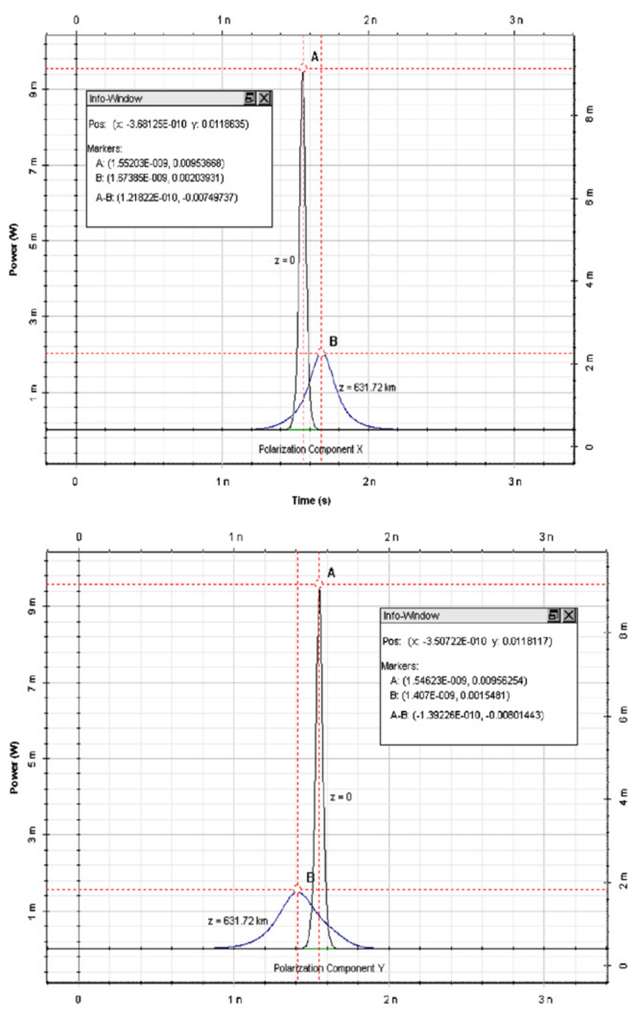

Fig. 2. Polarization components X and Y for a sech pulse at the input and at a transmission distance of 631.72 km (10 soliton periods), taking into account the nonlinear effects.

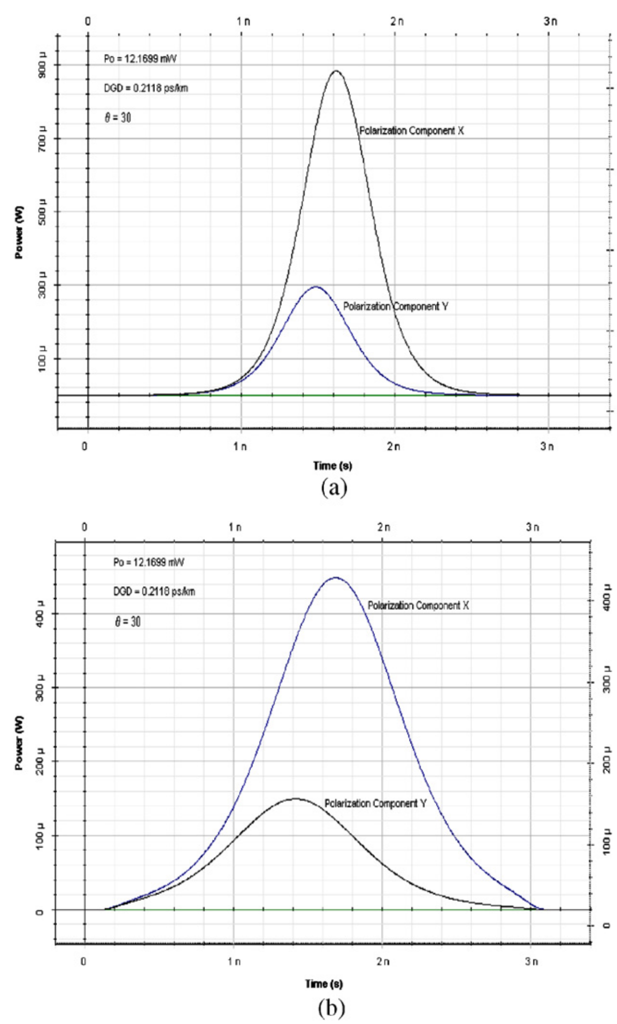

Fig. 3. Polarization components X and Y for a sech pulse in linear regime at transmission distances of (a) 631.72 km (10 soliton periods) and (b) 1264.344 km (20 soliton periods).

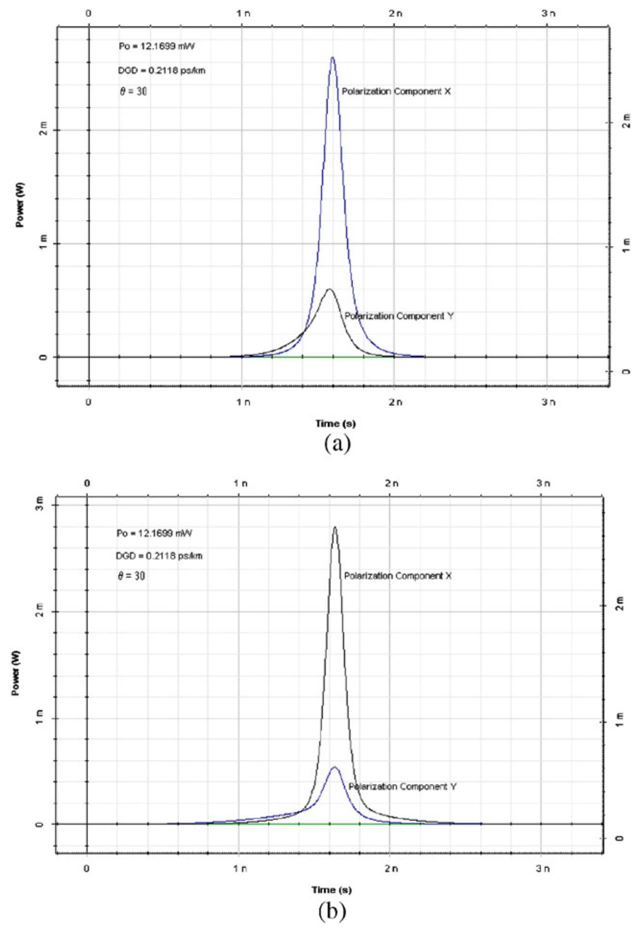

Fig. 4. Polarization components X and Y for a sech pulse taking into account the nonlinear effects at transmission distances of (a) 631.72 km (10 soliton periods) and (b) 1264.344 km (20 soliton periods).

the polarization components, and the time delay between both is reduced with respect to the case of linear propagation (i.e. without nonlinear effects). When the nonlinear effects are taken into account, the time delay is roughly 200 ps, which is much smaller (more than a factor of two) compared to the case of linear-regime propagation. It can be concluded that Kerr nonlinearity reduces the birefringent walk-off.

Hence, as a result of the action of the cross-phase modulation between both polarization components (the last terms in the system Eq. (1)), the faster polarization component is slowed down while the slower polarization component is accelerated and consequently the birefringent walk-off is reduced.

When $\theta \neq 45^\circ$ in Eq. (2), the two components have different amplitudes initially. In this case, when N exceeds N_{th}, the evolution scenario is qualitatively different, depending on the value of the birefringence (δ-parameter in Eq. (1)). With $\theta = 30^\circ$, this is illustrated in Figs. 3 and 4 for different values of the birefringence.

For the case $\delta = 0.15$ corresponding to a differential group delay of 0.2118 ps/km as shown in Fig. 4, the smaller pulse is captured by the larger and the two move together. However, when $\delta = 0.5$, the larger one captures a fraction of the energy in the smaller pulse and the rest of it is dispersed away with propagation. The results shown in Figs. 3 and 4 indicate that, under certain conditions, the two orthogonally polarized components of the soliton move with a common group velocity despite their different modal indices or polarization mode dispersion (PMD).

4. Conclusions

In this paper, the birefringence-induced time delay between both polarization components has been observed using an optical sech pulse generator at polarization angles equal to 45° and 30° and fiber lengths equal to 631.72 km (10 soliton periods) and 1264.344 km (20 soliton periods) for both linear and nonlinear soliton transmission. Further, it is noted that the spectrum of the X-polarization component acquires a blue shift, while that of the Y-polarization component turns out to be red-shifted. The birefringence-induced time delay between X and Y polarization components reduces to 200 from 440 ps when the nonlinear effects are taken into account at polarization angle $\theta = 45^\circ$. In the nonlinear regime when $\theta = 30^\circ$ and N exceeds N_{th}, the evolution scenario is qualitatively different; depending on the value of the δ-parameter, two orthogonally polarized components of the soliton move with a common group velocity despite their different modal indices or polarization mode dispersion (PMD).

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