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Suppression and Compensation of the Third-Order Dispersion Effect on Polarization Modes in Birefringent Fibres *

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The influence of the third-order dispersion (TOD) on the polarization mode dispersion (PMD) is investigated. It is found that the TOD effect destroys orthogonal polarization modes in optical birefringent fibres. A new method is proposed to compensate for the PMD by means of cascading the fibres with the positive and negative TOD. This has proven to be practicable in long transmissions.

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Polarization mode dispersion (PMD) is regarded as the ultimate limitation in fibre-optic communication systems. Recently, many papers have focused on the characteristics of polarization modes and PMD in high bit-rate fibre systems.[1−5] As the bit-rate continues to increase, the impairments caused by PMD become serious, especially for dispersion shift fibres (DSFs). Due to four-wave mixing (FWM), wavelength-division multiplexing (WDM) is not suitable for DSF, whereas the capacity in the case of using time-division multiplexing (TDM) for DSFs is also limited because most of the installed DSFs have a high PMD. For the past decade, great efforts have been made to understand the effects of PMD on optical system performance and to find methods to overcome them. Fortunately, it has been proven that optical solitons have inherent robustness to PMD due to the nonlinear effect even in DSFs.[6−9] However, as is known, group velocity dispersion (GVD) of DSFs is very small in the optical communication regime, and the third-order dispersion (TOD) will affect soliton propagation in optical fibres. The purpose of this letter is to discuss some simulation results in order to further deepen understanding of TOD effects on PMD in a soliton system. It is shown that TOD destroys polarization modes in DSFs and results in soliton instability in optical fibres. We propose a new method to suppress and compensate for PMD degraded by TOD effects in birefringent fibres.

We consider the propagation of orthogonal polarization modes with picosecond widths in birefringent fibres. The normalized coupled nonlinear Schrödinger equations in an anomalous dispersion regime take the form:[10]

$$\begin{aligned}&\frac{\partial u}{\partial \xi}+\delta_w^{'}\frac{\partial u}{\partial \tau}-\frac{\mathrm{i}}{2}\frac{\partial^2 u}{\partial \tau^2}-\delta_P\frac{\partial^3 u}{\partial \tau^3}+\Gamma u\\ &=\mathrm{i}\gamma N^2\left(|u|^2+\frac{2}{3}|v|^2\right)u,\\ &\frac{\partial v}{\partial \xi}-\delta_w^{'}\frac{\partial v}{\partial \tau}-\frac{\mathrm{i}}{2}\frac{\partial^2 v}{\partial \tau^2}-\delta_P\frac{\partial^3 v}{\partial \tau^3}+\Gamma v\\ &=\mathrm{i}\gamma N^2\left(|v|^2+\frac{2}{3}|u|^2\right)v,\end{aligned}\qquad(1),(2)$$

where u and v are the slow and fast polarization solitons respectively, which input along polarization principal axes at the same time. The parameters satisfy the following relation:

$$\begin{aligned}\delta_w^{'}&=\frac{(\beta_x-\beta_y)\,T_0}{(2(|\beta_2|)},\\ \delta_{\mathrm{P}}&=\frac{\beta_3}{2|\beta_2|T_0},\\ N&=\left(\frac{\gamma P_0 T_0^2}{|\beta_2|}\right)^{1/2},\qquad \Gamma=\frac{\alpha}{2}L_{\mathrm{D}},\end{aligned}\qquad(3)$$

where $\delta_w^{'}$ is the normalized birefringent coefficient of the fibre, δ_{P} is the third-order dispersion parameter, N is the parameter related to optical soliton order in the fibre anomalous regime, Γ is the normalized loss parameter, and ξ and τ are the normalized distance and time, respectively. The third and fourth terms on the left-hand side of Eqs. (1) and (2) indicate the GVD and TOD effects. The two terms on the right-hand side of Eqs. (1) and (2) represent self-phase modulation and cross-phase modulation respectively. The fibre loss is neglected for simplification in this letter.

We first study the TOD effects on polarization modes in birefringent fibres. Figure 1 shows that optical pulses propagate over 50 normalized distances by the polarization multiplexing technique without the TOD effect in single-mode fibres (SMFs). The parameters are selected as follows: $N=1$, $\delta_w^{'}=0.5$. The solid line represents a slow soliton, and the dashed line a fast soliton. The figure shows that polarization pulses retain their envelopes in long transmissions except that their peak intensities vary slightly. Two orthogonal polarization solitons move at a common group velocity and trap one another without walking off, though the fibres have PMD. This phenomenon is referred to as soliton self-trapping (SST).[11,12] It is

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shown that SST is due to cross-phase modulation of two polarized components. As SST expresses robustness to PMD, it was suggested for use in suppressing PMD in soliton transmission and has been investigated extensively.[6−12] Figure 2 shows that optical pulses propagate over the same distance as that in Fig. 1 with the TOD effect. The third-order dispersion parameter is $\delta_{\rm P} = 0.03$ and the other parameters are similar to those in Fig. 1. From Fig. 2, we know that the slow and fast modes exhibit different behaviours, which is different from Fig. 1. The slow soliton is compressed while the fast soliton radiates a dispersion wave and is destroyed during the transmission. The TOD effect reduces the two component trapping and results in the large delay of two polarization solitons in the time domain. If the pulse wavelength is exactly a zero dispersion wavelength ($\beta_2 = 0$) in DSFs, we find that the two polarization modes are severely destroyed and distorted even though they propagate over a short transmission distance.

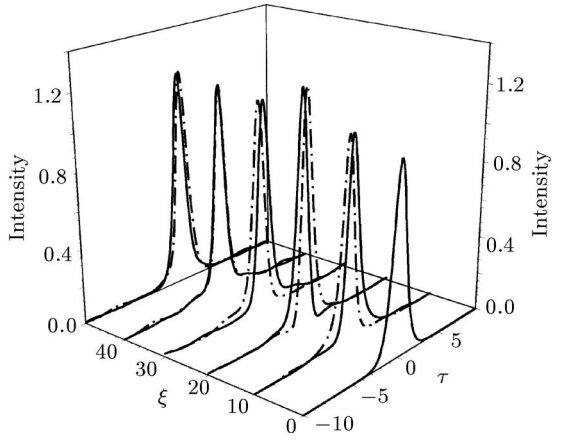


Fig. 1. Pulse evolution of a fundamental soliton without the third-order dispersion for the case of $\delta_w^{'} = 0.5$. The solid curve represents a slow soliton and the dot-dashed line a fast soliton.

In order to understand the dispersion effects on PMD, we calculated the time delay of two polarization components in different birefringent fibres. We found that dispersion-flatten fibres (DFFs) can be used to suppress the TOD effect. The difference between DFFs and SMFs shows that the GVD and TOD values of DFFs are much smaller than those of SMFs. Typically, the GVD and TOD coefficients of DFFs are $D = 1\,{\rm ps/nm{\cdot}km}$ and $\beta_3 = 1.6 \times 10^{-2}\,{\rm ps^3/km}$ at a $1.55\,\mu{\rm m}$ optical regime. Figure 3 shows that the two polarization pulses propagate over 50 normalized distances in DFFs. It clearly shows that the destructive degree of two polarization components in DFFs is much slighter than that in DSFs at the same transmission distance. Our numerical simulation results also show that the destruction of the TOD effect on PMD is still evident over a fibre distance of more than 200 normalized distances. That is to say, DFFs can be used to suppress the TOD effect on PMD in a certain transmission distance.

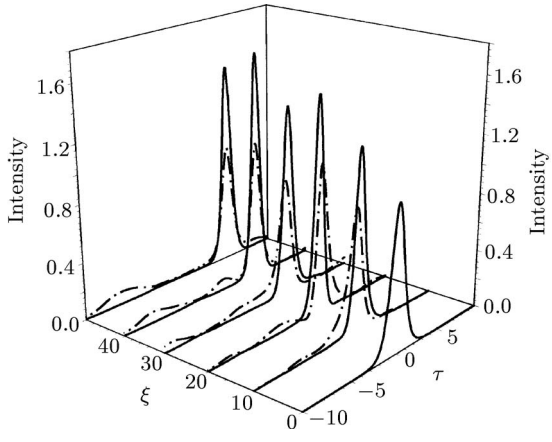


Fig. 2. Pulse evolution of the fundamental soliton with the third-order dispersion. The parameters are $\delta_w^{'} = 0.5$, $\delta_{\rm P} = 0.03$ and $N = 1$. The solid curve represents a slow soliton and the dot-dashed line a fast soliton.

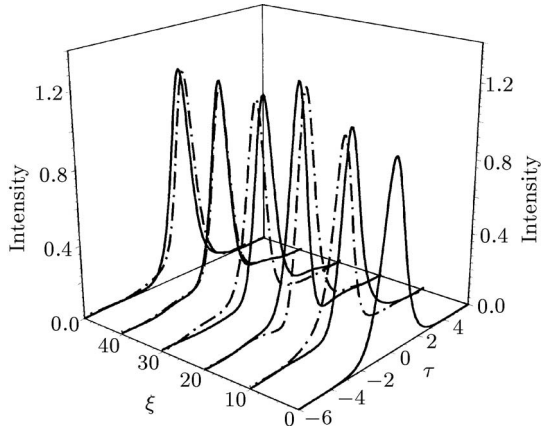


Fig. 3. Pulse evolution of the fundamental soliton with the third-order dispersion in DFFs. The solid curve represents a slow soliton and the dot-dashed line a fast soliton.

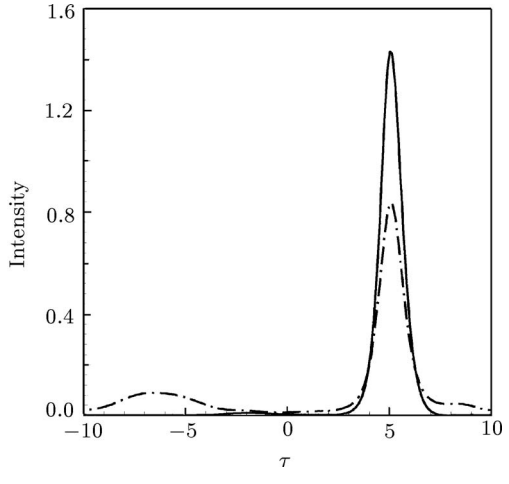


Fig. 4. Pulse shape of fundamental soliton with positive value of third-order dispersion. The third-order dispersion parameter is $\delta_P = 0.03$. The solid curve represents a slow soliton and the dot-dashed line a fast soliton.

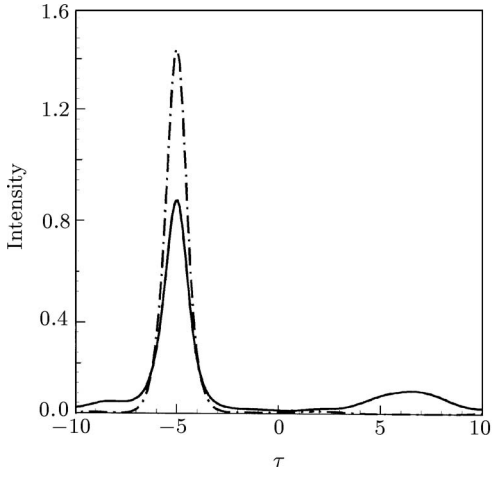


Fig. 5. Pulse shape of the fundamental soliton with negative value of the third-order dispersion. The third-order dispersion parameter is $\delta_{\mathrm{P}} = -0.03$. The solid curve represents a slow soliton and the dot-dashed line a fast soliton.

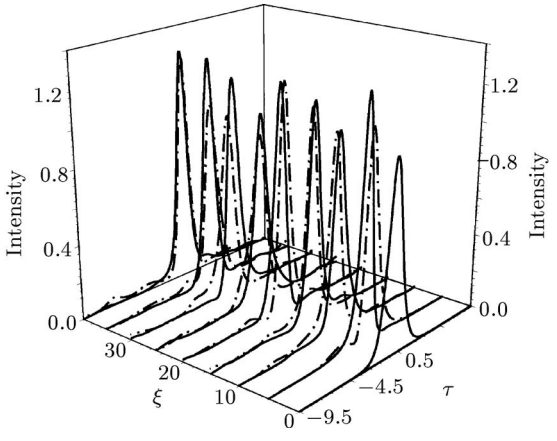


Fig. 6. Pulse evolution of the fundamental soliton for the case of compensation of the third-order dispersion. The solid curve represents a slow soliton and the dot-dashed line a fast soliton.

In order to overcome TOD effects on PMD, we propose a method based on dispersion management scheme[13] to compensate for the destruction of the TOD effect on two polarization modes. The principal idea is that the long transmission system is made up of several fibres with positive and negative TOD. The length of each fibre segment is the same, and the absolute TOD value is equal. This compensation technique is based on the following phenomena: when the TOD value is positive, TOD destroys the fast mode and compresses the slow mode. The intensity of the fast mode is much smaller than that of the slow mode due to the radiated wave of the fast mode induced by the TOD effect. When the value of TOD is negative, the results are opposite. Figures 4 and 5 show the envelopes of polarization modes after propagating 50 normalized distances in fibres with positive and negative TOD respectively. The propagation of orthogonal polarization solitons in fibres with the TOD compensation technique is shown in Fig. 6. The parameters are the same as those of Fig. 2 except that the value of TOD is positive or negative. Figure 6 clearly shows that the polarization modes are destroyed and re-constituted periodically. Our numerical results show that the compensation technique can eliminate the TOD effect on PMD in long transmissions.

In conclusion, we have studied the propagation of orthogonal polarization modes in birefringent fibres and found that dispersion-flattened fibres can be used to suppress the third-order dispersion effect on PMD to some extent. As the destruction of the TOD effect is still evident in long transmissions in dispersion-flattened fibres, we propose a new method to compensate for it by means of cascading fibres with positive and negative TOD. Our simulation results show that the compensation technique is practicable in long distance communications.

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