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Enhanced pulse compression induced by the interaction between the third-order dispersion and the cross-phase modulation in birefringent fibres*

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In this paper, we report on the enhanced pulse compression due to the interaction between the positive third-order dispersion (TOD) and the nonlinear effect (cross-phase modulation effect) in birefringent fibres. Polarization soliton compression along the slow axis can be enhanced in a birefringent fibre with positive third-order dispersion, while the polarization soliton compression along the fast axis can be enhanced in the fibre with negative third-order dispersion. Moreover, there is an optimal third-order dispersion parameter for obtaining the optimal pulse compression. Redshifted initial chirp is helpful to the pulse compression, while blueshifted chirp is detrimental to the pulse compression. There is also an optimal chirp parameter to reach maximum pulse compression. The optimal pulse compression for TOD parameters under different N-order solitons is also found.

Keywords: pulse compression, third-order dispersion, cross-phase-modulation, birefringent fibre, initial chirp

PACC: 4265S, 4281

1. Introduction

Nonlinear pulse propagation in fibres has long been considered as a promising technique for the compression of optical pulses. This technique produces, in both visible and near-infrared regions, ultra-short optical pulses that last for a duration of only a few optical cycles. However, when third-order dispersion (TOD) is considered, the quality of the pulse compression decreases. It is well known that TOD distorts the pulse shape so that it becomes asymmetric with an oscillatory structure near one of its edges. Positive TOD makes oscillations appear near the trailing edge of the pulse, while negative TOD makes oscillations appear near the leading edge of the pulse.[1−3] Recently, it has been reported that the interaction between negative TOD and Raman self-scattering effects can enhance the pulse compression.[4−7] However, the interaction between positive TOD and Raman self-scattering effects is found to be useless for pulse compression. In this paper, for the first time as far as we know, we report that the interaction between the positive TOD and the nonlinear effect (the cross-phase modulation (XPM) effect) in birefringent fibres can enhance the pulse compression along the slow polarization axis. We find that there is an optimal TOD parameter for obtaining a maximum compression ratio. When initial chirp is considered, the optical pulse with redshifted chirp can be compressed further and there is also an optimal chirp parameter to enhance the pulse compression. Furthermore, the TOD parameter can be selected appropriately to achieve a maximum compression for a certain order soliton.

2. Theoretical model

We consider the propagation of orthogonal polarization modes with picosecond width in birefringent fibres. The coupled-nonlinear Schrödinger equations in an anomalous dispersion regime take the forms[8]

$$\frac{\partial u}{\partial z}+\delta_w\frac{\partial u}{\partial \tau}-\frac{i}{2}\frac{\partial^2 u}{\partial \tau^2}-\delta_p\frac{\partial^3 u}{\partial \tau^3} =\mathrm{i}\gamma N^2\left(|u|^2+\frac{2}{3}|v|^2\right)u, \tag{1}$$

$$\frac{\partial v}{\partial z}-\delta_w\frac{\partial v}{\partial \tau}-\frac{i}{2}\frac{\partial^2 v}{\partial \tau^2}-\delta_p\frac{\partial^3 v}{\partial \tau^3} =\mathrm{i}\gamma N^2\left(|v|^2+\frac{2}{3}|u|^2\right)v, \tag{2}$$

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where the second, third and fourth terms on the left-hand side of the above two equations represent the time delay of two polarization modes, group velocity dispersion (GVD), and the TOD, respectively. The two terms on the right-hand side are self-phase modulation (SPM) and XPM. γ, δ_w and δ_p are the nonlinear coefficient, the normalized birefringent parameter and the normalized TOD parameter, respectively. We also have the parameter $\delta_p = \dfrac{\beta_3}{2|\beta_2|T_0}$. In addition, β_2 and β_3 are GVD and TOD coefficients, respectively, and T_0 is the initial pulse width. In Eqs.(1) and (2), N is the soliton order, while u and v are pulse envelopes of the polarization mode along the slow and fast axes, respectively. τ is the normalized time and z is the propagation distance. Fibre loss is neglected here for simplicity.

The normalized incident field associated with a hyperbolic-secant pulse is in the forms

$$u = \sec h(\tau)\exp\left(-\frac{\mathrm{i}C\tau^2}{2}\right),$$
$$v = \sec h(\tau)\exp\left(-\frac{\mathrm{i}C\tau^2}{2}\right), \qquad (3)$$

where the chirp parameter C controls the initial chirps.

3. Numerical results and discussion

3.1. Enhanced pulse compression induced by the interaction between TOD and XPM

We study the propagation properties of the fifth-order soliton pulses, which are input along orthogonal polarization principal axes synchronously by the polarization multiplexing technique in birefringent fibres. The compression ratios[9] of two orthogonal polarization solitons are the same without the effect of TOD, their values are 16.7. When TOD is considered, the interaction between TOD and XPM affects the propagation of the two polarization solitons. Figure 1 shows the pulse shape of a polarization soliton along the slow polarization axis over a distance z/z_0=0.08 without and with the positive TOD, where z_0 is the soliton period, $z_0 = \dfrac{\pi}{2}\cdot\dfrac{T_0^2}{|\beta_2|}$. The parameters of the pulse evolution in fibres are as follows: $\beta_2 = -20\mathrm{ps}^2/\mathrm{km}$, β_3=0.1ps^3 and T_0=20ps. Therefore, the soliton period z_0=31.42km and the optimal compression distance z=0.08 z_0=2.51km. Curve 1 represents the pulse shape without the effect of TOD (δ_p=0), and curve 2 represents the pulse shape under the effect of TOD (δ_p=0.005). Curves 1 and 2 in Fig.2 depict the pulse compression ratios corresponding to curves 1 and 2 in Fig.1. The maximum compression ratios for curves 1 and 2 are 16.7 and 21.5 respectively. It is evident that the pulse compression is enhanced by the effect of the positive TOD. Oscillations induced by positive TOD are also displayed in the pulse trailing edge according to curve 2 in Fig.1.

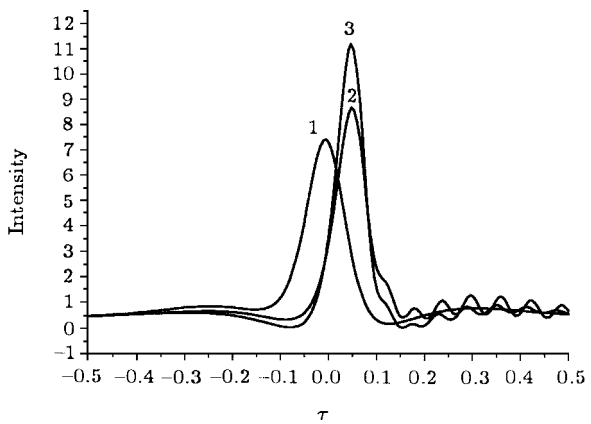


Fig.1. Pulse shapes of a polarization soliton propagating along the slow polarization axis over the distance z/z_0=0.08 with the effect of positive TOD. The parameters are as follows: N=5; δ_w=0.5; curve 1, δ_0=0, C=0; curve 2, δ_p=0.005, C=0; curve 3, δ_p=0.005 C=–0.5.

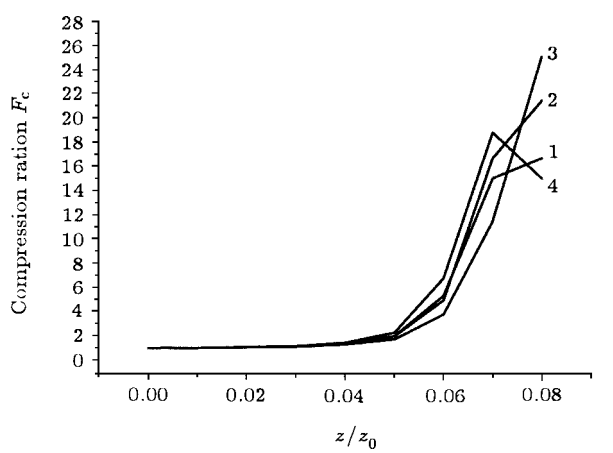


Fig.2. The pulse compression ratios versus the normalized transmission distance along the slow axis: curve 1, δ_p=0, C=0; curve 2, δ_p=0.005, C=0; curve 3, δ_p=0.005, C=–0.5; curve 4, δ_p=0.005, C=0.5.

We have investigated the effect of TOD on the compression of a polarization soliton along the slow and fast axes. Figures 3 and 4 show the pulse peak intensities of polarization solitons over the distance

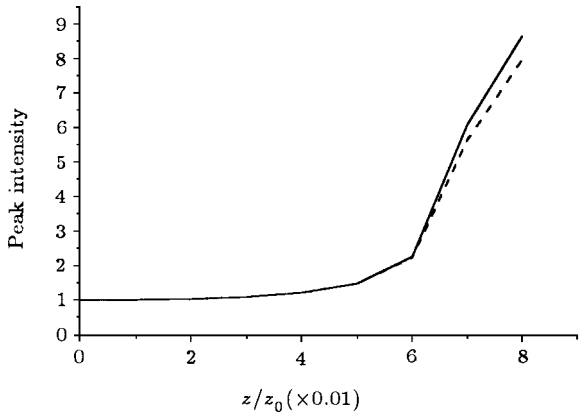


Fig.3. Pulse peak intensity of a polarization soliton after compression versus the distance z/z_0 with the TOD parameter δ_p=0.005. The other parameters are the same as those in Fig.1. The solid curve represents the soliton along the slow axis and the dashed curve represents the soliton along the fast axis.

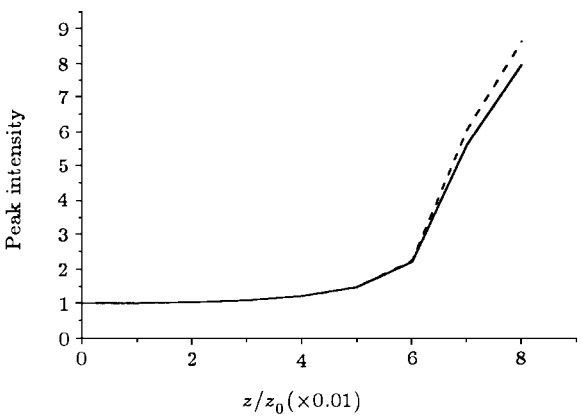


Fig.4. Pulse peak intensity of polarization soliton after compression versus the distance z/z_0 with the TOD parameter δ_p=–0.005. The other parameters are the same as those in Fig.1. The solid curve represents the soliton along the slow axis, and the dashed curve represents the soliton along the fast axis.

with the TOD parameters δ_p=0.005 and δ_p=–0.005, respectively. The solid curve represents the peak intensity of the polarization soliton along the slow axis, while the dashed curve represents the peak intensity of the polarization soliton along the fast axis. The figures show that the peak intensity of the polarization soliton along the slow axis is higher than that of the polarization soliton along the fast axis in the case of positive TOD, but is lower than that along the fast axis in the case of negative TOD. The results mean that the polarization soliton compression along the slow axis is enhanced and that along the fast axis it is suppressed in the fibres with positive TOD. When negative TOD is considered, the results are reversed. That is, the polarization soliton compression along the fast axis is enhanced and that along the slow axis is suppressed. The compression ratios of the enhanced pulse compression are the same in these two cases; the value is about 21.5.

3.2. Physical mechanism of the enhanced pulse compression

The physical mechanism of the pulse enhanced compression by the combined action of TOD and XPM can be explained as follows. When two solitons are input along polarization principal axes by the polarization multiplexing technique, under a certain condition in birefringent fibres, two polarization solitons can trap each other and move with a common group velocity in spite of different birefringence. This phenomenon is referred to as soliton self-trapping.[10] It is the XPM-induced nonlinear coupling between the two polarization solitons that allows the two solitons to propagate with a common group velocity. Physically, two polarization solitons shift their carrier frequencies in opposite directions to reach such a temporal synchronization. This means that the carrier frequency of a soliton along the slow polarization axis shifts towards the blueshifted frequency band, and the carrier frequency of the other soliton along the fast polarization axis shifts towards the redshifted frequency band (as shown in Fig.5). The solid curve represents the frequency shift of the soliton along the slow axis and the dashed curve shows the frequency shift of the soliton along the fast axis. According to the definition of TOD, we have

$$\beta_3 = \frac{\mathrm{d}\beta_2}{\mathrm{d}\omega}, \tag{4}$$

when the soliton pulse propagates along the slow axis. Its carrier frequency shifts towards the blueshifted frequency band, indicating $\mathrm{d}\omega > 0$. When positive TOD is considered ($\beta_3 > 0$), then $\mathrm{d}\beta_2 > 0$. This indicates that $|\beta_2|$ decreases in the anomalous dispersion region. The nonlinear effect is correspondingly strengthened with the reduction of $|\beta_2|$. Therefore, the compression of the soliton along the slow axis is enhanced. However, when the soliton pulse propagates along the fast axis, $\mathrm{d}\omega < 0$, and when $\beta_3 > 0$, we have $\mathrm{d}\beta_2 < 0$. This means that $|\beta_2|$ increases in the anomalous dispersion region. The soliton compression along the fast axis is suppressed due to the reduction of the nonlinear effect. When negative TOD is considered, the results are contrary to those in the case of positive TOD. The pulse compression along the fast axis is enhanced, while the pulse compression along the slow axis is suppressed.

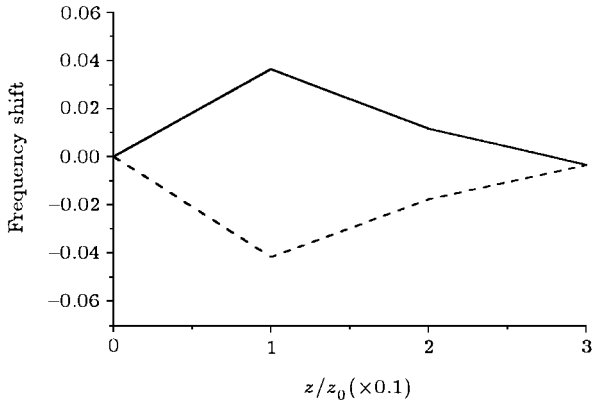


Fig.5. Frequency shift of two polarization solitons versus the distance based on soliton self-trapping.

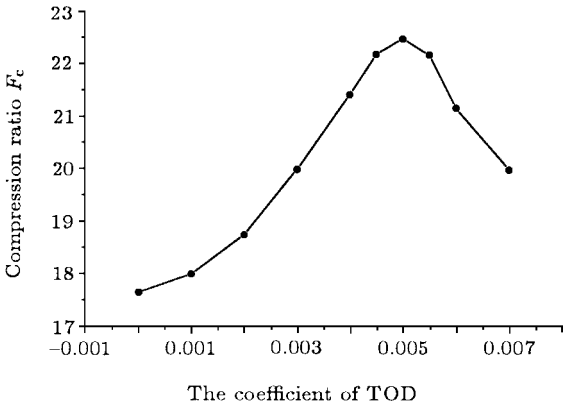


Fig.6. Variation of pulse compression ratio F_c with TOD for z/z_0=0.08.

Our simulation results also show that the polarization soliton along the slow axis has a time delay induced by the effect of TOD (as shown in Fig.1). The larger the TOD value, the longer the time delay. This phenomenon can be explained using the following equation

$$\beta_2 = \frac{\mathrm{d}\beta_1}{\mathrm{d}\omega} = \frac{\mathrm{d}}{\mathrm{d}\omega}\left(\frac{1}{v_g}\right), \tag{5}$$

where v_g is the soliton group velocity. As the polarization soliton propagates along the slow axis, its carrier frequency shifts to the blueshifted frequency band ($\mathrm{d}\omega > 0$). From the above discussion, we know that $\mathrm{d}\beta > 0$, indicating that β_2 increases. Therefore, β_1 increases along with β_2. The group velocity of the soliton along the slow axis reduces, resulting in a time delay of the polarization soliton along the slow axis.

Although the interaction between TOD and XPM is beneficial to pulse compression, our numerical results show that the TOD value affects the pulse compression. There is an optimal value of TOD for obtaining the maximum enhanced compression ratio. Figure 6 shows the variation of pulse compression ratio with TOD. When δ_p=0.005, the maximum compression ratio (~22.5) can be obtained, whereas it is ~16.7 at δ_p=0. When the value of TOD is too large, the pulse compression is suppressed. For example, at δ_p=0.02, the compression ratio F_c is 12.8. This value is smaller than that without TOD. Under this circumstance, TOD is detrimental to the pulse compression.

3.3. The influence of initial chirp on pulse compression

The pulse emitted from a gain-switched distributed feedback laser (DFB) always has a redshifted chirp ($C < 0$). Our results show that the optical pulse with a redshifted chirp is further compressed under the influence of TOD. Curve 3 in Fig.1 is the pulse shape of the polarization soliton propagating over the distance z/z_0=0.08 with a redshifted chirp. The quality of the chirped pulse (curve 3) is better than that of the chirp-free pulse (curve 2). The oscillation construction of the chirped pulse (curve 1) is much smaller than that of the chirp-free pulse (curve 2). The pulse compression ratio for the polarization soliton with a redshifted chirp increases to 25.2 (curve 3 in Fig.2). It is about four times larger than that without a chirp under the same conditions. Further investigation shows that the enhancement of the pulse compression with an initial chirp depends on the properties of the initial chirp. The redshifted chirp is helpful to the pulse compression while the blueshifted chirp is detrimental to the pulse compression. From Fig.2, the maximum compression ratio reaches 25.2 with a redshifted chirp at z/z_0=0.08 (curve 3), while the maximum compression ratio reaches 18.9 with a blueshifted chirp at z/z_0=0.08 (curve 4), which is smaller than that for C=0 (21.5) under the same conditions. However, the quality of the compressed pulse with $C < 0$ is worse than that of the compressed pulse with $C > 0$. The oscillations near the trailing edge of the pulse with $C < 0$ are more obvious (as shown in Fig.7).

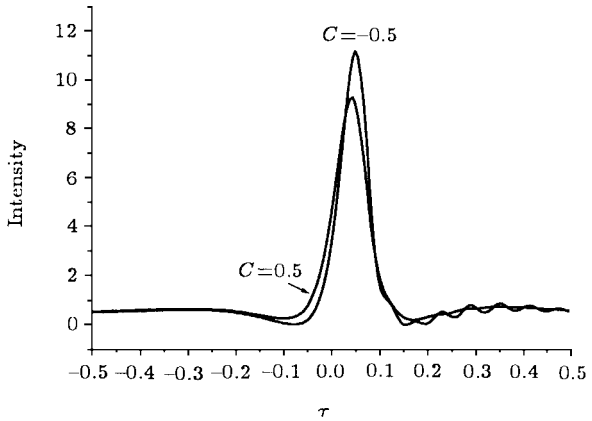


Fig.7. Pulse shape along the slow axis after the maximum compression for the pulses with a redshifted chirp (z/z_0=0.08) and a blueshifted chirp (z/z_0=0.07) under the influence of TOD.

In order to investigate the effect of the redshifted chirp on the enhanced compression, we compare the pulse peak intensities for different redshifted chirp parameters. Figure 8 depicts the variation of pulse peak intensity with different redshifted chirp parameters. The results show that there is also an optimal chirp parameter C=–0.5 to obtain the maximum pulse peak intensity, which corresponds to the maximum pulse compression.

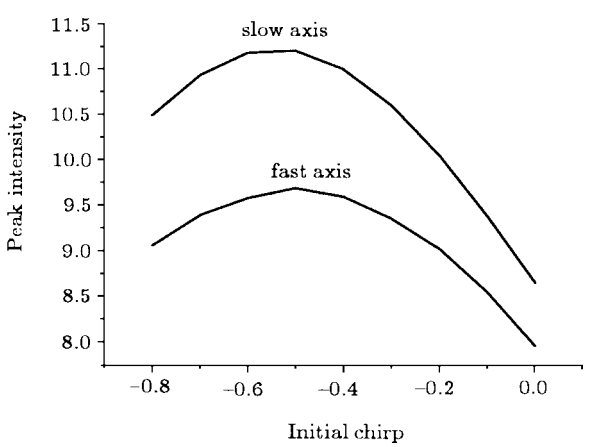


Fig.8. Variation of pulse peak intensity with different initial chirp C after maximum compression. Other parameters are the same as in Fig.1.

3.4 The optimal TOD parameters for N-order solitons

Although we focus on studies of the fifth-order soliton enhanced pulse compression, the enhanced compression behaviour of other higher-order solitons is the same, based on the combined action of TOD and XPM. We find that solitons of different orders require different optimal coefficients of TOD to obtain an optimal pulse compression. The relationship between the optimal coefficient of TOD and soliton number N is depicted in Fig.9. The main results can be stated as follows. (1) The appropriate coefficient of TOD must be selected for a certain order soliton in order to achieve an enhanced pulse compression. For example, when the coefficient of TOD δ is selected to be 0.005 for N=5 (as shown in Fig.6), the optimal compression ratio is achieved. (2) The larger the soliton number N, the smaller the optimal coefficient of TOD. For example, δ is 0.01 for N=3 to obtain the maximum pulse compression at the distance z/z_0=0.16, while it becomes 0.003 for N=7 at z/z_0=0.05. (3) δ is nearly the same for higher-order solitons (N=7–10). We can obtain an enhanced pulse compression for solitons propagating along the slow polarization axis with δ=0.003 for N=7 and 8. (4) The results are the same for the enhanced compression pulse along the fast polarization axis except that the value of the TOD coefficient is negative.

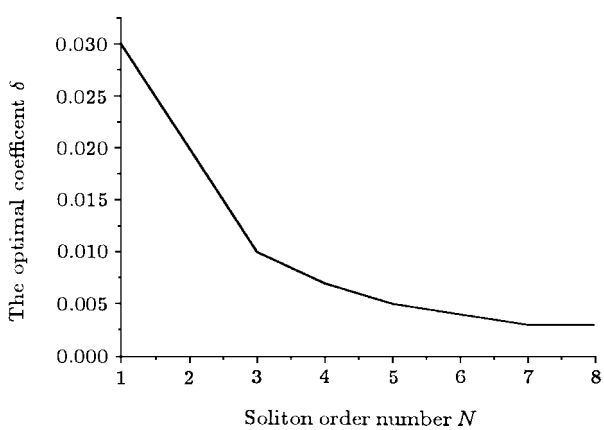


Fig.9. Variation of the optimal coefficient of TOD δ with parameter N for maximum pulse compression.

4. Conclusions

We have shown that the interaction between TOD and XPM effects can enhance the pulse compression in birefringent fibres. The interaction between positive TOD and XPM effects benefits the polarization soliton compression for solitons propagating along the slow axis, while the interaction between negative TOD and XPM effects benefits the polarization soliton compression along the fast axis. There is an optimal value of TOD for obtaining a maximum compression ratio, which is larger than the case without TOD. When the initial chirp is considered, we find that the redshifted chirp benefits the enhanced compression and

the blueshifted chirp is detrimental to the pulse compression. There is also an optimal negative chirp parameter for obtaining maximum pulse compression. The coefficient of TOD must be appropriately selected for solitons of a certain order to obtain maximum pulse compression. The larger the soliton order, the smaller the value of δ. The value of δ is nearly the same for higher-order solitons.

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