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Effects of the initial chirp and fibre loss on the soliton mechanism of picosecond pulse compression in optical fibres

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***Abstract*. The effect of the initial chirp and fibre loss on the efficiency of soliton-effect picosecond pulse compression are analysed by simulating numerically the transmission of picosecond pulse in fibres by the split-step Fourier method. Analysis of changes in the compression factor, the optimum fibre length, and the compression efficiency showed that the initial chirp and fibre loss affect the compression of a picosecond pulse in opposite ways. A further study revealed that an additional properly created initial chirp provides good pulse compression.**

Keywords: *soliton, optical fibre.*

1. Introduction

The practical use of pulse-compression techniques in nonlinear fibre optics is of tremendous technological value [1, 2]. Optical pulses at wavelengths exceeding 1300 nm generally experience both self-phase modulation (SPM) and anomalous group-velocity dispersion (GVD) during their propagation in silica fibres. Such a fibre can act as a compressor. By an appropriate choice of the fibre length, the input pulses can be compressed. Such a compressor is referred to as the soliton-effect compressor to emphasise the role of solitons [3]. Compared to the fibre-grating compression and all-fibre compression, the soliton-effect compression techniques are used widely due to their compactness, convenience, and good compression effect. The soliton-effect compression has been studied taking into account the fibre loss in Refs [4, 5] and the effect of the initial chirp was considered in Ref. [6]. In this paper, the effects of both fibre loss and initial chirp on soliton-effect picosecond pulse compression are studied in optical fibres.

In a real soliton-based communication system, the effect of fibre loss on the compression of pulses can be neglected if the wavelength of the input pulse is about of 1500 nm. On the other hand, the optical pulses generated by direct current modulation are chirped, and the initial chirp should be considered. In this paper, the propagation of picosecond pulses in fibres is simulated numerically by the split-step Fourier method in four cases. By comparing the effect of fibre loss with that of initial chirp on the soliton-effect compression, we have analysed in detail the physical mechanism of these effects. Finally, a new method is presented which can improve the compression effect in the presence of fibre losses.

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2. Theoretical model and numerical method

The propagation of optical picosecond pulses in single-mode fibres in the presence of losses is described by the nonlinear Schrödinger equation:

$$\mathrm{i}\frac{\partial U}{\partial \xi} = -\frac{1}{2}\frac{\partial^2 U}{\partial \tau^2} - N^2|U|^2U - i\Gamma U, \qquad (1)$$

$$U = \frac{A}{\sqrt{P_0}},\ \xi = \frac{z}{L_\mathrm{d}},\ \tau = \frac{T}{T_0},\ N^2 = \frac{\gamma P_0 T_0^2}{|\beta_2|},\ \Gamma = \frac{\alpha T_0^2}{|2\beta_2|}, \qquad (2)$$

where U is the normalised amplitude of the pulse envelope; P_0 is the peak power of the input pulse; ξ and τ are the normalised distance and time, respectivily; L_d is the dispersion length; T_0 is the half-width of pulse (at the 1/e-intensity level); β_2 is the GVD parameter; γ is the nonlinear parameter responsible for SPM; α accounts for the fibre loss. The first and second terms in the right-hand side of (1) describe GVD and SPM, respectively.

When ξ, τ, N, Γ are dimensionless quantities, it is convenient to solve Eqn (1) numerically. Among many numerical methods, the split-step Fourier (SSF) method is widely used, which is much faster than other finite-difference calculation schemes [7, 8]. This is caused by the use of the fast Fourier transform (FFT) algorithm. Let us describe briefly the SSF method.

To explain the concept of the SSF method, we write Eqn (1) formally in the form

$$\frac{\partial U}{\partial \xi} = \left(\hat{D} + \hat{N}\right)U, \qquad (3)$$

where $\hat{D}$ is a differential operator that accounts for dispersion and absorption in a linear medium and $\hat{N}$ is a nonlinear operator that describes the effect of fibre nonlinearities on the pulse propagation. These operators are given by

$$\hat{D} = \frac{\mathrm{i}}{2}\frac{\partial^2}{\partial \tau^2} - \Gamma, \quad \hat{N} = iN^2|U|^2. \qquad (4)$$

Generally, dispersion and nonlinearty act together along the length of the fibre. The SSF method gives an approximate solution by assuming that upon propagation of the optical field over a small distance $\Delta\xi$, the dispersive and nonlinear effects can be treated independently. More specifically, the propagation from ξ to $\xi+\Delta\xi$ is described in two steps. In the first step, the nonlinearity acts alone, and $\hat{D}=0$ in Eqn (3). In the second step, dispersion acts alone, and $\hat{N}=0$ in Eqn (3). Mathematically, this is written as

$$U(\xi+\Delta\xi,\tau)\approx\exp\big(\Delta\xi\hat{D}\big)\exp\big(\Delta\xi\hat{N}\big)U(\xi,\tau). \tag{5}$$

The action of the exponential operator $\exp(h\hat{D})$ can be written in the Fourier representation as

$$\exp\big(\Delta\xi\hat{D}\big)B(\xi,\tau)=\big\{F^{-1}\exp[\Delta\xi D(\mathrm{i}\omega)]F\big\}B(\xi,\tau), \tag{6}$$

where F is the Fourier-transform operator. The function $D(\mathrm{i}\omega)$ is obtained from operator (4) by replacing the differential operator $\partial/\partial\tau$ by $\mathrm{i}\omega$; and ω is the frequency in the Fourier representation. In this case, $D(\mathrm{i}\omega)=-\mathrm{i}\omega^2/2-\Gamma$.

If the step sizes in ξ and T are selected carefully to maintain the required accuracy, the SSF method can provide a detailed and accurate description of the propagation of picosecond pulse in fibres.

3. Numerical results and discussion

We assume that input pulse has a hyperbolic secant shape, and its amplitude has the form:

$$U(0,\tau)=N\mathrm{sech}(\tau)\exp\big(-\mathrm{i}C\tau^2/2\big), \tag{7}$$

where N is the soliton order and C is the chirp parameter. We also calculated the compression of pulses of other types, for example, Gaussian pulses.

We assumed in calculations that, the width of an input pulse is $T_{\mathrm{FWHM}}=30$ ps. For hyperbolic secant shape, T_0 and T_{FWHM} are related by

$$T_{\mathrm{FWHM}}=2\ln\big(1+\sqrt{2}\big)\,T_0\approx1.76\,T_0. \tag{8}$$

In this case, $T_0=17$ ps. We will use the typical fibre parameters $\beta_2=-4.6$ ps^2 km^{-1}, $\gamma=1.3$ W^{-1} km^{-1} and $\alpha=0.092$ km^{-1}, which correspond to the input beam with a wavelength about of 1320 nm propagating in a single-mode fibre. The fibre loss parameter calculated from (2) is $\Gamma=2.9$. In the program, we sampled 8192 points in time for the input pulse and selected the cut-off points at ±8. In addition, the step over the spatial axis was taken equal to 1/2000 of the dispersion length.

The propagation of solitons was simulated numerically in single-mode fibre for four cases to obtain the effects of initial chirp and fibre loss separately and the combined effects of them on soliton-effect compression. Generally, the fibre output is selected at the fibre length where pulse is compressed into a narrowest one. The maxima of the curves shown in Fig. 1 are the first maxima of the compression and quality factors, and the corresponding fibre length. Here, the length that corresponds to the maximum of the compression factor is an optimum fibre length denoted by z_{opt}.

To characterise the performance of a soliton-effect compressor, it is useful to define two parameters as

$$F_{\mathrm{c}}=\frac{T_{\mathrm{FWHM}}}{T_{\mathrm{comp}}},\quad Q_{\mathrm{c}}=\frac{\int_{-T_{\mathrm{FWHM}}}^{T_{\mathrm{FWHM}}}|U(\xi,\tau)|^2d\tau}{\int_{-T_{\mathrm{FWHM}}}^{T_{\mathrm{FWHM}}}|U(0,\tau)|^2d\tau}, \tag{9}$$

where T_{comp} is the FWHM of the compressed pulses and F_{c} is the compression factor. The parameter Q_{c} is the quality factor that measures the quality of the compressed pulse.

The results of numerical solution of Eqn (1) with the initial pulse $U(0,\tau)=N\mathrm{sech}(\tau)\exp(-\mathrm{i}C\tau^2/2)$ are shown in Figs 1a–d for different values of C and Γ and different soliton orders $N=2.5$ and 10.

Figs 1a–d show that an optimum value of the fibre length exists for which both F_{c} and Q_{c} are maximum, which is a common feature of such compressors. This is consistent with numerical calculation of the pulse compression in fibre-grating compressors [3]. Comparison of Fig. 1a and Fig. 1b reveals that the initial chirp induces the increase in F_{c} and Q_{c} and the decrease in z_{opt}. In Fig. 1c, F_{c} and Q_{c} decrease clearly, and the maxima of Q_{c} for second-order and fifth-order soliton disappear in the presence of fibre losses. Furthermore, fibre losses increase the optimum fibre length z_{opt} for fifth-order and tenth-order solitons. Finally, comparing Fig. 1d with other three plots, we see that the values of compression parameters of solitons in Fig. 1d lie between the values of compression coefficients shown in Fig. 1b and Fig. 1c. This means that the initial chirp and fibre losses affect the compression of bicosecond pulses in the opposite ways. Note that the optimum length for the second-order solitons in Fig. 1d is larger than z_{opt} in Fig. 1c, whereas for solitons of the fifth and tenth orders, the opposite situation takes place.

By enhancing the fibre loss parameter Γ, the higher-order soliton-effect compression is simulated numerically. The result shows that the opposite change mentioned above also occurs for higher-order solitons ($N\geqslant2$) when the fibre loss is large enough. This can be explained by the fact that a critical value Γ_{cr} of fibre loss exists for a given amount of pulse energy (corresponding to the soliton order). If fibre losses exceed Γ_{cr}, the optimum length increases with the chirp. In the above examples, the fibre loss $\Gamma=2.9$ exceeds Γ_{cr} for the second-order soliton.

The soliton-effect compressor makes use higher-order solitons supported by the fibre as a result of an interplay between SPM and anomalous GVD. In the anomalous-dispersion regime of the fibre, the SPM-induced chirp is positive while the dispersion-induced chirp is negative. For values of $N\gg1$, Eqn (1) suggests that the effects of SPM should dominate over those of GVD, at least during the initial stages of pulse evolution. Thus the net chirp is positive and leads to the pulse compression. This means that the main effect of SPM is to decrease the broadening rate imposed on the pulse by the GVD alone. During the pulse propagation, the initial positive chirp enhances the SPM-induced chirp while fibre losses reduce the effect of SPM. This interprets the contrary effects of initial chirp and fibre loss on soliton-effect compression.

To obtain higher compression factor F_{c} and quality factor Q_{c}, we can enhance the initial chirp of pulses for a given amount of fibre loss Γ. Fig. 2 shows that F_{c} and Q_{c} increase significantly. This increase is larger for pulses with a higher soliton order. Furthermore, unlike Fig. 1c and d, the maxima of Q_{c} for second-order and fifth-order solitons appear in Fig. 2 because the initial chirp compensates for the effect of fibre loss on the pulse compression. As a result, we can obtain ideal compressed pulses at the outputs of

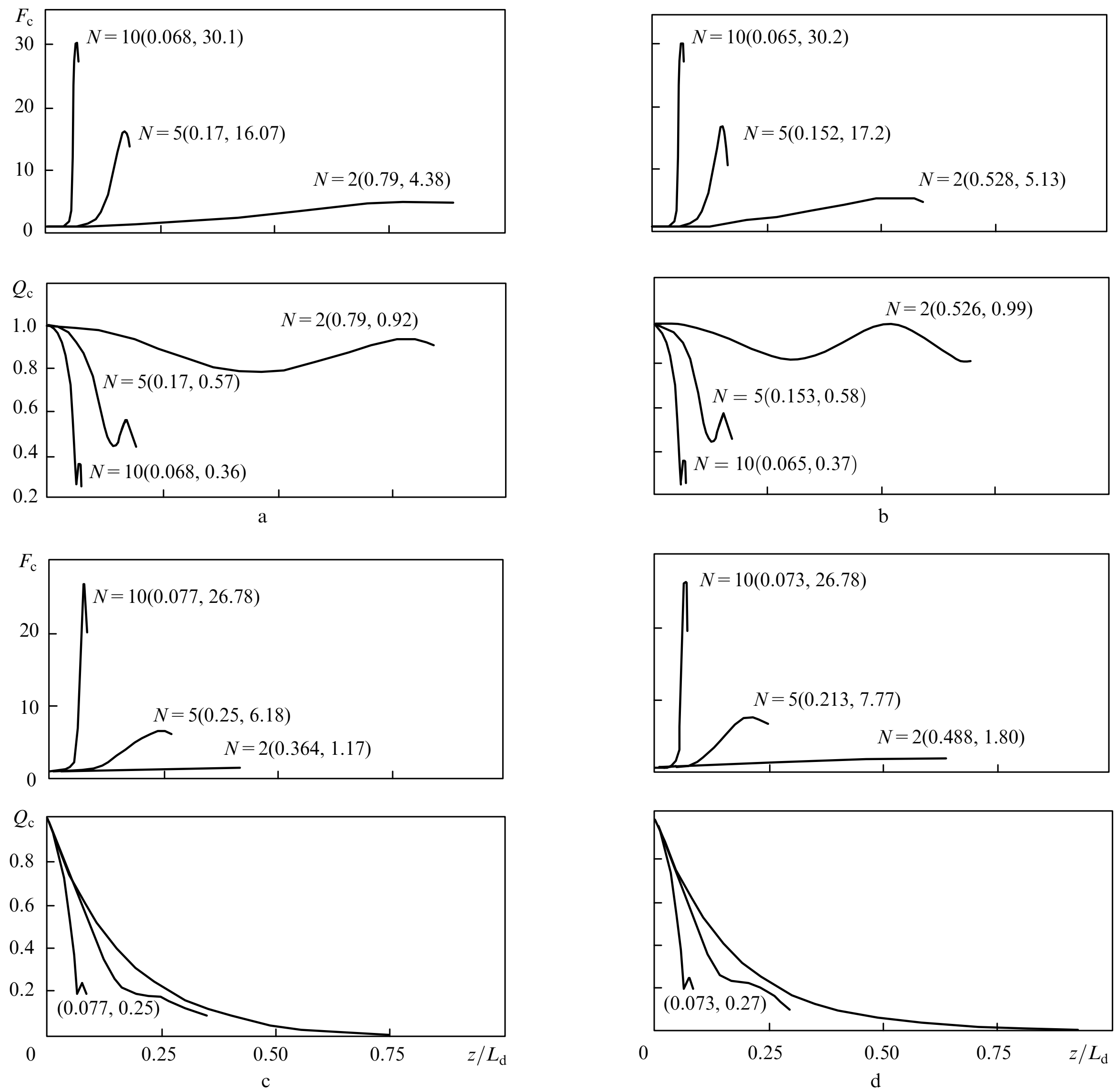

Figure 1. Calculated properties of the compressed pulse in single-mode fibre as functions of the distance z/L_d: (a) $C = 0, \Gamma = 0$; (b) $C = 1.0, \Gamma = 0$; (c) $C = 0, \Gamma = 2.9$; (d) $C = 1.0, \Gamma = 2.9$.

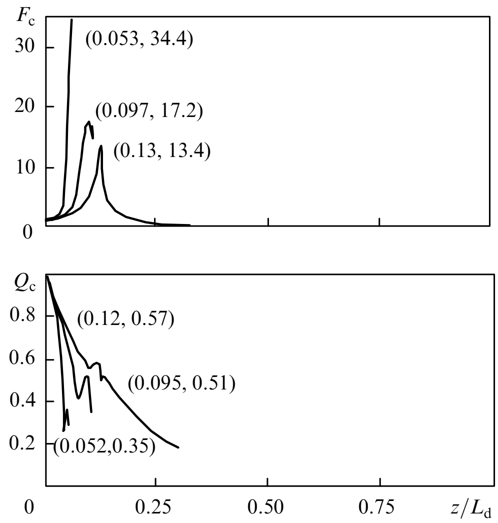

Figure 2. Calculated properties of the compressed pulse in single mode fibres as functions of the distance z/L_d: $C = 8.0, \Gamma = 2.9$.

fibres by this method. However, an important point is that the advantage is achieved only at the expense of reduced optimum fibre length. Therefore, the choice of the initial chirp should be appropriate. Finally, Fig. 3 shows the evolution of the second-order soliton for (a) $C = 1.0, \Gamma = 2.9$ and (b) $C = 8.0, \Gamma = 2.9$.

4. Conclusions

We showed, first, that the compression factor F_c and the quality factor Q_c achieve their maxima simultaneously for the optimum value of the fibre length. Second, the initial chirp increases F_c and Q_c and decreases z_{opt} whereas fibre loss produces the opposite effect. We have also found that a critical value Γ_{cr} of fibre loss exists for a given amount of pulse energy (corresponding to the soliton order). If fibre loss exceeds Γ_{cr}, the effects of initial chirp and fibre loss on soliton-effect compression change contrarily compared to those on higher-order soliton. Finally, a method is provided to obtain higher compression factor F_c and quality factor Q_c, and good compression effect is achieved.

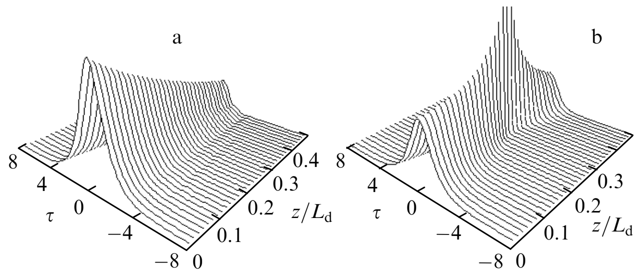

Figure 3. Evoluation of the second-order soliton in single-mode fibres for (a) $C = 1.0, \Gamma = 2.9$; (b) $C = 8.0, \Gamma = 2.9$.

References

1. Knox W H, Fork R L, Downer M C, et al. *Appl. Phys. Lett.* **46** 1120 (1985)
2. Blow K J, Doran N J, Nelson B P *Opt. Lett.* **10** 393 (1985)
3. Agrawal G P *Nonlinear Fiber Optics* (Boston, Academic Press Inc., 1989)
4. Mollenauer L F, Stolen R H, Gordon J P *Opt. Lett.* **8** 289 (1983)
5. Dianov E M, Nikonova Z S, Prokhorov A M, et al. *Sov. Tech. Phys. Lett.* **12** 311 (1986)
6. Cao Wenhua, Liao Changjun, et al. *Acta Opt. Sinica* **13** 1003 (1993)
7. Feit M D, Fleck J *Appl. Opt.* **18** 2843 (1979)
8. Potasek M J, Agrawal G P, Pinault S C *J. Opt. Soc. Amer. B : Opt. Phys.* **3** 205 (1986)