Compensation for the self-steepening effects in optical fiber communication system using midway optical phase conjugation

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Effects of self-steepening (SS) of chirped Gaussian pulses on optical fiber communication system using midway optical phase conjugation (OPC) are analyzed. Dynamic evolution of the ultrashort pulses is simulated numerically. It is found that OPC cannot compensate for pulse waveform distortion due to SS. The initial chirp of pulses and dispersion can counteract SS and improve the compensation performance for the distortion.

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Optical phase conjugation (OPC) is a promising optical technology that can compensate for dispersion and nonlinearity effects simultaneously in pulse propagation through a single-mode fiber (SMF)[1−4]. In the reported researches, optical pulses widths were ≥1 ps, and only group-velocity dispersion (GVD) and self-phase modulation (SPM) were considered. For the propagation of ultrashort pulses whose widths are less than 100 fs, the first derivative of the slowly varying part of nonlinearity must be added, which leads to self-steepening (SS) of the pulse edge[5−7]. The SS arises from an intensity-dependent group velocity delay. It generates a shock-front with intense edge, and produces a temporal pulse distortion and a spectral asymmetry. In general, the SS has to be taken into account in the system whose data rate is beyond 160 Gb/s and power is larger than 14 dBm. In this paper, we simulate numerically the propagation of chirped Gaussian pulses in the optical fiber communication system using midway OPC, and investigate the effects of the SS on the compensation for pulse waveform distortion. The relationships between the SS and the chirped pulses are also discussed.

The schematic of the optical fiber communication system using midway OPC is shown in Fig. 1. If the SS term is considered, pulse propagation in the system is governed by a generalized nonlinear Schrödinger equation[5]. In the normalized coordinates, the equation takes the form

$$\frac{\partial U}{\partial z} = -i\frac{\mathrm{sgn}\,(\beta_2)}{2}\frac{\partial^2 U}{\partial \tau^2} + iN^2\left|U\right|^2 U - N^2 s\frac{\partial(\left|U\right|^2 U)}{\partial \tau}, \quad (1)$$

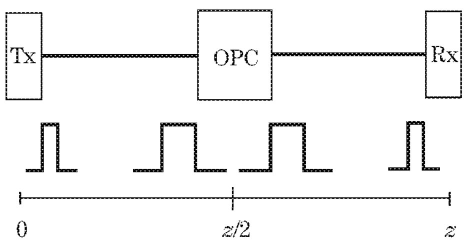

Fig. 1. Schematic of compensation for dispersive and nonlinear distortion with midway OPC.

where U, z, τ are the normalized amplitude, distance, and time scale respectively, β_2 is the GVD coefficient, $N^2 = L_{\mathrm{D}}/L_{\mathrm{NL}}$. L_{D} and L_{NL} are the dispersion length and nonlinear length respectively. N^2 provides the scale over which the dispersive or nonlinear effects become important for pulse evolution along a fiber. $s = \frac{2}{\omega_0 T_0}$ is the SS coefficient, ω_0 is the angular frequency, and T_0 is the pulse width.

The complex-conjugated form of Eq. (1) can be written as

$$\frac{\partial U^*}{\partial z} = i\frac{\mathrm{sgn}\,(\beta_2)}{2}\frac{\partial^2 U^*}{\partial \tau^2} - iN^2\left|U^*\right|^2 U^* - N^2 s\frac{\partial(\left|U^*\right|^2 U^*)}{\partial \tau}. \quad (2)$$

The three terms on the right-hand side of Eqs. (1) and (2) correspond to the GVD, SPM, and SS respectively. Because the SS term is real part, its sign is not changed after conjugated. When the SS term is ignored and $s = 0$, the relationship between Eqs. (1) and (2) is mutual-conjugated. The distorted pulses due to GVD and SPM in the first fiber $(0 - z/2)$ can be compensated perfectly after the propagation through the second fiber $(z/2 - z)$. When the SS term is added, it can be found that the compensation for the distortion due to the SS is different with the values of GVD and SPM in the system[5].

The normalized chirped Gaussian pulse amplitude can be written as

$$U(0,\tau) = \exp\left[-\frac{(1+iC)}{2}\tau^2\right], \quad (3)$$

where C is chirp coefficient.

The root-mean-square (RMS) width of the pulses is used as a measurement of pulse broadening. Broadening factor (BF) is defined as the final-to-initial RMS-width ratio.

According to Refs. [5] and [6], we choose $\mathrm{sgn}(\beta_2) = -1$ and $z = 4L_{\mathrm{D}}$ in the anomalous dispersion regime. For $\lambda = 1550$ nm and $T_0 = 50$ fs, $s = 0.03$.

Depending on the values of the GVD and SPM, the compensation for the distortion due to the SS can be classified in the following four categories.

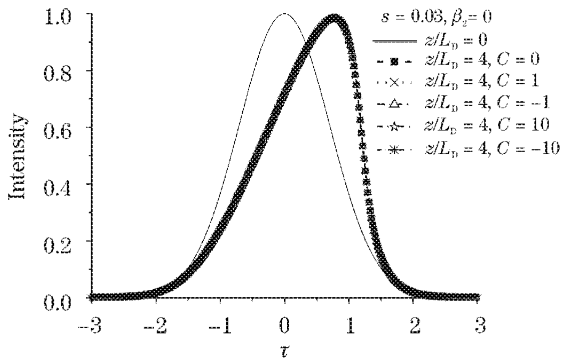

Fig. 2. Variations of pulse shapes at z/L_D=4.

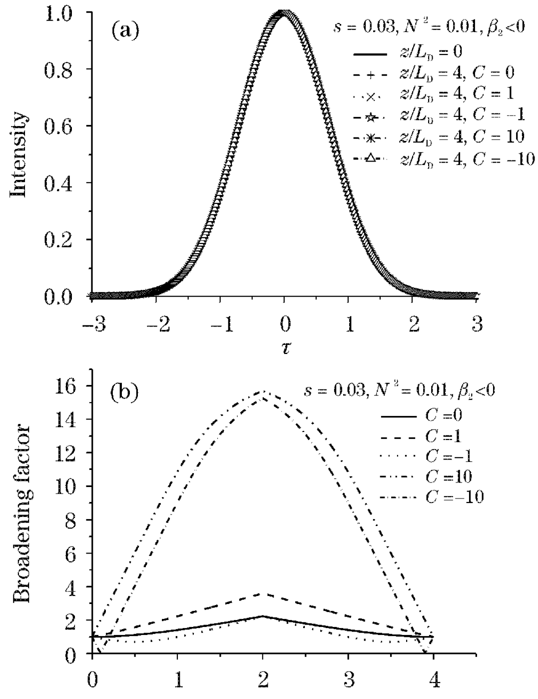

Fig. 3. Variations of (a) pulse shapes at z/L_D = 4 and (b) pulse broadening factor with distance along the fiber.

1) $\beta_2 = 0$, the GVD is ignored, only the SPM and SS are considered.

It is shown in Fig. 2 that the distortion due to the SS is not completely compensated by OPC in the absence of dispersion. As the pulse propagates, its peak shifts toward the trailing edge and becomes asymmetric and steep. Because the SS is intensity-dependent, the chirps do not influence the evolution results. The results are the same for different C values in the system.

The SS of the pulse edge increases spectral width and makes dispersion important. Hence the dispersion term in Eqs. (1) and (2) becomes non-negligible.

2) $\beta_2 < 0$, and $N^2 \ll 1$, where the GVD is more significant than the SPM.

As shown in Fig. 3, the pulse shape and spectrum are considerably affected by GVD. The dispersion dissipates the shock, counteracts the nonlinear SS and reestablishes a dynamical balance. It makes the pulses less, even no asymmetry. The distortion due to GVD, SPM and SS can be compensated by OPC as shown in Fig. 3.

The results are also the same for different C values because of the dependence of intensity. But it is shown in Fig. 3(b) that the processes are different. If $\beta_2 C < 0$, a chirped Gaussian pulse broadens monotonically with z. When $\beta_2 C > 0$, it goes through an initial narrowing stage. And it also goes through the final narrowing stage, which corresponds to the initial narrowing stage. The narrowing distance depends on the C value. For example, when $C > 0$, the BF increases and the narrowing distance shortens with the increase of C value.

It is found in Fig. 3 that for $\beta_2 C > 0$, the conjugator can be placed at a suitable position after midpoint, thus the endpoint will be in the final narrowing stage. It is useful to improve the compensation performance for the distortion due to the GVD, SPM and SS.

3) $\beta_2 < 0$, and $N^2 = 1$, where both the GVD and SPM are important.

When SPM and GVD play an equally important role, the effects of SPM and GVD counteract each other and the effect of SS increases. The pulse shapes are asymmetrized and distorted again. But the distortions are smaller than those in absence of the GVD. As shown in Fig. 4, the distortion due to the SS still cannot be compensated by OPC.

It is demonstrated in Fig. 4 that chirps influence the results and processes of the pulse propagation. As shown in Table 1, the peaks change with the C values. The chirps can counteract with the effects of SS and reduce the shifts of peaks.

The increase of the nonlinear effects shortens the initial and final narrowing distances. When $C = -1$, the narrowing distance is $1.996L_D$ for $N^2 = 0.1$, while it is only $1.54L_D$ for $N^2 = 1$.

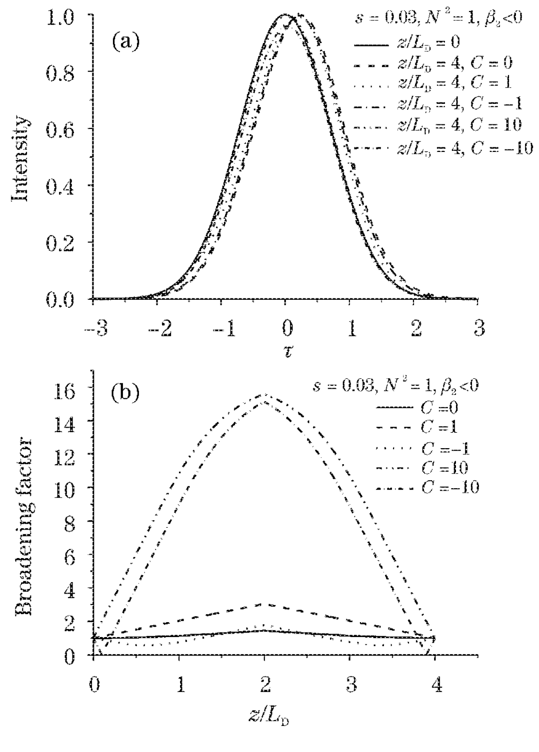

Fig. 4. Variations of (a) pulse shapes at z/L_D = 4 and (b) pulse broadening factor with distance along the fiber.

Table 1. Shift of Peaks with Different C Value

Chirp	0	1	−1	10	−10
Peak Value	0.998	1.003	0.993	0.999	0.958
τ	0.224	0.186	0.205	0.029	0.029

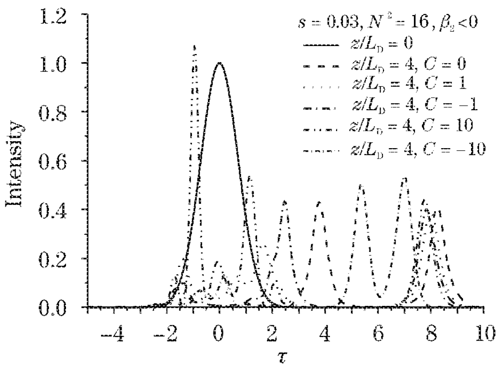

Fig. 5. Variations of pulse shapes at z/L_D=4.

4) $\beta_2 < 0$, and $N^2 \gg 1$, where SPM dominates over GVD.

The increases of power enhance the effects of SS and SPM. This accelerates the shift of the pulse peak, and accompanies with oscillatory structures and sidelobes (Fig. 5). The chirps are not useful for the compensation for the distortion.

In conclusion, this letter has discussed the effects of SS of ultrashort chirped Gaussian pulses on optical fiber communication system using midway OPC. In the absence of the dispersion, OPC cannot compensate for the distortion due to the SS. The results are the same for different chirps. When GVD is added, it can counteract the nonlinear SS, eliminate asymmetry of pulses. Therefore OPC can compensate for the distortions due to GVD, SPM, and SS. For $\beta_2 C > 0$, it leads to the initial and final narrowing stages, which is useful for optimizing the system design and improving compensation performance for the distortion.

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