

Improving the undoing of soliton interaction with optical phase conjugation by phase alternation between neighboring solitons

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Abstract

The undoing of the soliton interaction with the optical phase conjugation by the phase alternation between neighboring solitons is numerically studied. When the phase alternation is larger than 90°, the undoing of the soliton interaction is good even when the conjugation is applied at the distance where the solitons interact seriously.

Owing to the successful demonstration of the dispersion compensation in the fiber by the optical phase conjugation (OPC), the application of the OPC to the soliton transmission system is investigated [1,2]. In theory the combined effects of the second-order dispersion β_2 , the self-phase modulation (SPM) and the self-frequency shift (SFS) can be undone by the OPC in the lossless case [3–5]. Therefore the soliton effects in the lossless fiber without the third-order dispersion β_3 can also be undone by the OPC. In the presence of the third-order dispersion and the fiber loss which is compensated by the optical amplifiers, it is found that the undoing of the soliton interaction is good when the conjugator is applied before significant changes of the pulse shapes [2]. The soliton interaction can be reduced by introducing phase alternation between the neighboring solitons [6,7]. In this paper, we consider the undoing of the soliton interaction by the OPC in such a system. It is found that the undoing can be improved with the phase alternation between the neighboring solitons.

The soliton propagation in the single-mode fiber can be described by the modified nonlinear Schrödinger equation

$$i \frac{\partial U}{\partial z} - \frac{1}{2} \beta_2 \frac{\partial^2 U}{\partial \tau^2} - i \frac{1}{6} \beta_3 \frac{\partial^3 U}{\partial \tau^3} + n_2 \beta_0 |U|^2 U - c_r \frac{\partial |U|^2}{\partial \tau} U = - \frac{1}{2} i \alpha U, \quad (1)$$

where β_2 and β_3 represent the second-order and third-order dispersions, respectively; n_2 is the Kerr coefficient; c_r is the coefficient of the self-frequency shift (SFS); α is the fiber loss. The soliton wavelength is assumed to be 1.55 μm and the coefficients in Eq. (1) are taken as $\beta_2 = -0.57 \text{ ps}^2/\text{km}$ (0.45 $\text{ps}^2/\text{km}/\text{nm}$), $\beta_3 = 0.075 \text{ ps}^3/\text{km}$, $n_2 = 3.2 \times 10^{-20} \text{ m}^2/\text{W}$, $c_r = 3.8 \times 10^{-16} \text{ ps} \cdot \text{m}/\text{W}$, and $\alpha = 0.22 \text{ dB}/\text{km}$. The effective fiber cross section is 35 μm^2 . From Eq. (1), when $\alpha = \beta_3 = 0$, it can be proved that the soliton effects governed by Eq. (1) can be undone by the midsystem OPC [4,5]. Therefore, the OPC can be applied any-

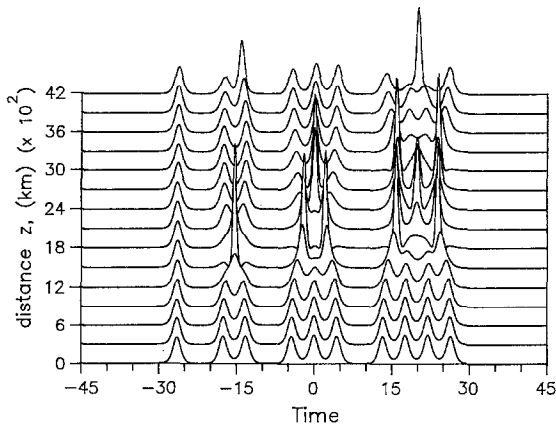


Fig. 1. Power evolution of soliton bit stream along the fiber without using the OPC and phase alternation.

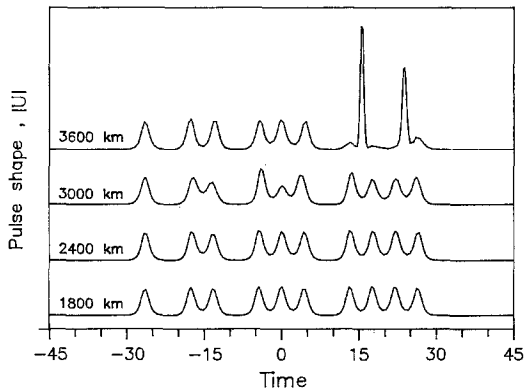


Fig. 2. The pulse shapes of the soliton at 1800, 2400, 3000, and 3600 km, when the conjugators are applied at 900, 1200, 1500, and 1800 km, respectively.

where to undo the soliton interaction. For the real case where $\alpha \neq 0$ and $\beta_3 \neq 0$, the fiber loss is periodically compensated by the lumped amplifiers and the amplification period is assumed to be 30 km. The considered soliton pulse width is 20 ps and its soliton period is about 350 km. Since the soliton period is much longer than the amplification period, the soliton transmission is stable which is necessary for the undoing of the soliton interaction by the OPC [2].

To show the soliton interaction, we consider the soliton bit stream (0010110111011100) and take 2.5 pulse width separation between the neighboring solitons to enhance the interaction. Fig. 1 shows the evolution of the soliton bit stream along the fiber without using the OPC and phase alternation. One can see that

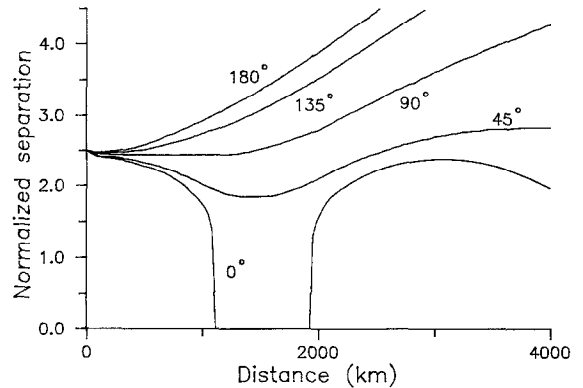


Fig. 3. Normalized separation between solitons along the fiber for initial phase differences 0° , 45° , 90° , 135° , and 180° , respectively.

the solitons with the bit patterns (0110) coalesce at about 1500 km and the solitons with the other bit patterns interact after this coalescence distance. If we apply the conjugator well before the coalescence distance where the solitons do not yet significantly interact, the interaction can be almost completely undone. Fig. 2 shows the pulse shapes of the solitons at the distances 1800, 2400, 3000, and 3600 km in which the conjugators are applied at 900, 1200, 1500, and 1800 km, respectively. It is seen that the undoing of the soliton interaction becomes worse as the conjugator is applied near the coalescence distance. For the case with the conjugator applied at 900 km, the pulse shapes are almost identical to the input pulse shapes. When the conjugator is applied at 1500 or 1800 km, where the solitons interact seriously, the soliton interaction cannot be undone. As the numerical results obtained by assuming $\beta_3 = 0$ are similar to that shown in Fig. 2, the fact that the soliton interaction cannot be undone by the OPC is mainly due to the periodic amplification. In the presence of the periodic amplification, the nonlinear effect cannot be undone well due to the power perturbation. When the solitons seriously interact, the nonlinear effect is enhanced and the undoing of the soliton interaction is worse. In the following, we will show that this deficiency can be overcome by introducing the phase alternation between neighboring solitons.

The interaction force between the solitons depends on their relative phase [6]. Fig. 3 shows the soliton separation of the bit stream (0000110000) along the fiber for several phase differences between the two solitons. One can see that when the phase difference is

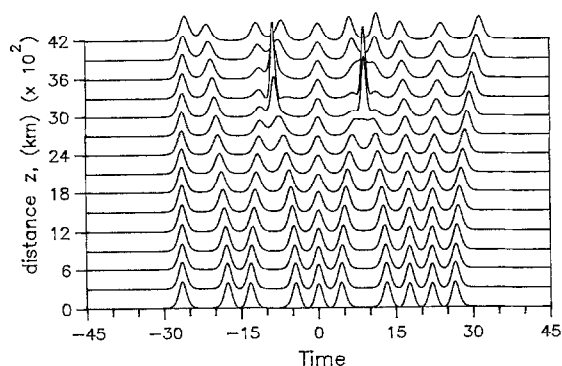


Fig. 4. Power evolution of soliton bit stream as in Fig. 1, except that the phase difference between the neighboring solitons is 180° .

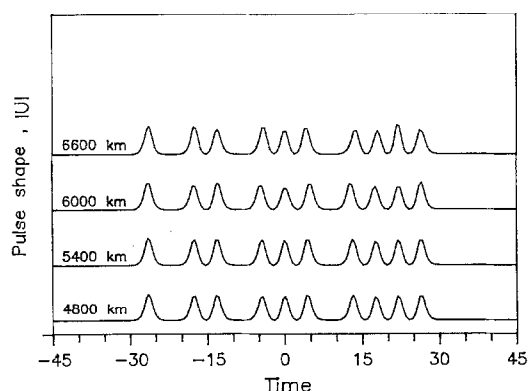


Fig. 5. The undoing of the soliton interaction with phase alternations 180° . The pulse shapes of the soliton are at 4800, 5400, 6000, and 6600 km, when the conjugators are applied at 2400, 2700, 3000, and 3300 km, respectively. The undoing is good even when the conjugator is applied at 3000 or 3300 km where the solitons interact seriously.

larger than 90° , the soliton separation increases monotonously [7]. This means that the interaction force between the two solitons becomes repulsive and the repulsive force is the strongest when the phase difference is 180° . When the phase difference is less than 90° , the interaction force is initially attractive and there exists the minimum separation between the two solitons during the propagation [7]. When the phase difference is less than about 45° , the two solitons coalesce. From Fig. 3, the phase difference larger than 90° leads to the repulsive force. For the more complex soliton bit stream, for example (the bit stream shown in Fig. 1), the repulsive force may delay the soliton coalescence. Fig. 4 shows the evolution of the soliton bit stream as in Fig. 1, except that there is a 180° phase alternation

between the neighboring time slots in the bit stream. One can see that the soliton coalescence is delayed and the first coalescence occurs at about 3300 km. For the case shown in Fig. 4, Fig. 5 shows the pulse shapes of the solitons at the distances 4800, 5400, 6000, and 6600 km in which the conjugators are applied at 2400, 2700, 3000, and 3300 km, respectively. One can see that the undoing is also better as the conjugator is applied away from the distance where the solitons coalesce. It is noticed that, to compare with the cases without the phase alternation, the undoing of the soliton interaction is still good even when the conjugator is applied at 3000 or 3300 km where the solitons interact seriously. For the other phase alternations, the undoing can also

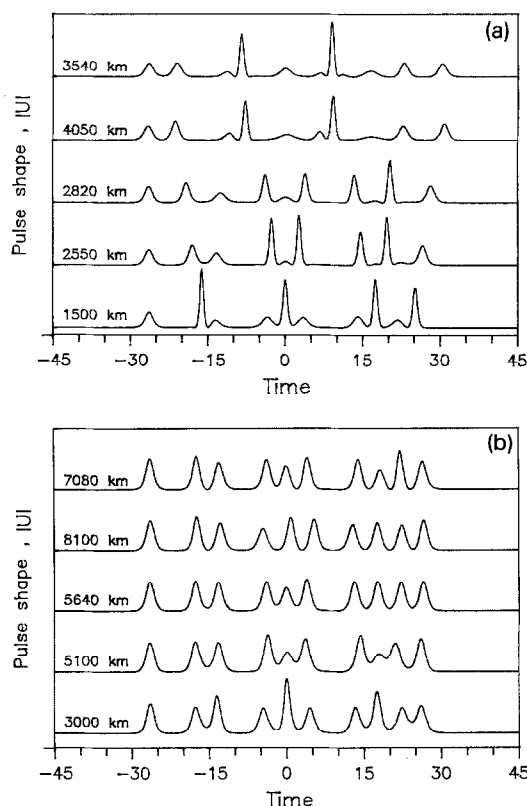


Fig. 6. The undoing of the soliton interaction with phase alternations 22.5° , 45° , 90° , 135° , and 157.5° . (a) The soliton pulse shapes with phase alternations 22.5° , 45° , 90° , 135° , and 157.5° at the distances 1500, 2550, 2820, 4050, and 3540 km, respectively, where the solitons collapse. (b) The pulse shapes at the distance 3000, 5100, 5640, 8100, and 7080 km, with phase alternations 22.5° , 45° , 90° , 135° , and 157.5° , respectively, with the conjugators applied at the distances shown in (a).

be improved when the phase alternation is larger than 90° . Figs. 6a and b show the undoing of the soliton interaction for the other phase alternations. Fig. 6a shows the pulse shapes at the distance where the solitons coalesce for several phase alternations. For cases with the phase alternations 22.5° , 45° , 90° , 135° , and 157.5° , the distances are 1500, 2550, 2820, 4050, and 3540 km, respectively. With the conjugators applied at the distances shown in Fig. 6a, Fig. 6b shows the pulse shapes at the distances 3000, 5100, 5640, 8100, and 7080 km for cases with the phase alternations 22.5° , 45° , 90° , 135° , and 157.5° , respectively. From Fig. 6b, one can see that the soliton pulse shapes recover better for larger phase alternation. When the phase alternation is less than 90° , the undoing is not good. When the phase alternation is larger than 90° , the undoing is good; however, not so good as in the case with the 180° phase alternation shown in Fig. 5, because the soliton interaction is stronger for smaller phase alternation. Therefore, the best phase alternation for the undoing is 180° . But as the coalescence distance for the 180° phase alternation is shorter than that for the 135° phase alternation, it may not be a best choice for the system applications.

The longest coalescence distance is the case with the 135° phase alternation.

In conclusion, the undoing of the soliton interaction with the OPC by the phase alternation between the neighboring solitons is numerically studied. It is found that the undoing is improved with the phase alternation larger than 90° . When the phase alternation is larger than 90° , the undoing of soliton interaction is good even when the conjugator is applied at the distance where the solitons interact seriously.

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