Improving soliton transmission by optical phase conjugation

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ABSTRCAT

The optical phase conjugation is numerically shown to reduce the soliton interaction and the timing jitter of the soliton caused by the Gordon—Haus effect. With the conjugator, both the bit rate and the transmission distance of the soliton communication system can be improved. The criteria for applying the conjugators are discussed.

1. INTRODUCTION

The optical phase conjugation (OPC) has been proposed to compensate for the chromatic dispersion to improve the bit rate of the optical transmission system.[1] Recently, the OPC is demonstrated to improve the bit rate of the transmission of the 1.55 μm signal in the standard fiber with the loss compensated by the erbium—doped fiber amplifiers.[2-3] This technique in fact can also be applied to improve the performance of the soliton transmission system.[4-5] Large separation between neighboring solitons is required to avoid the nonlinear interaction between them. On the other hand, the transmission distance is limited by the timing jitter of the soliton caused by the amplified spontaneous emission noise (ASEN) introduced by the optical amplifier, which randomly modulates the carrier frequency of the soliton. This is known as the Gordon—Haus effect.[6] In this paper, we will numerically show that they can be reduced by the OPC and discuss the criteria for applying the conjugators.

2. REDUCTION OF THE SOLITON INTERACTION

The soliton propagation in the single mode fiber follows the wave equation

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

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. From the Eq.(1), when $\beta_3=\alpha=0$, it can be proved that the effects of the second—order dispersion, self—phase modulation, and SFS can be completely recovered by the OPC.[7-8] Therefore, in the lossless fiber without the third—order dispersion, the soliton interaction can be undone by the OPC even in the presence of the SFS. In the followings, the soliton wavelength is assumed to be 1.55 μm. The coefficients in the Eq.(1) are taken as $\beta_2=-0.64$ ps^2/km (D= 0.5 ps/km/nm), $\beta_3=0.074$ ps^3/km, $n_2=3.2\times10^{-20}$m^2/W, $c_r=3.85\times10^{-16}$ps m/W, and $\alpha=$ 0.2 dB/km. The effective fiber cross section $A_{eff}=35\ \mu$m^2.

Fig.1 shows the evolution of the soliton pair along the fiber, which is periodically amplified with a period of 30 km to compensate for the fiber loss. The pulse width of the soliton is 20 ps and there is 3.5 pulse width separation between them. In the lossless case, the coalescence distance is 3470 km. In the Fig.1, the two solitons coalesce at about the same distance. From the Ref.5, it is shown that, to undo the interaction well, the conjugator should be applied before there are significant changes of the pulse shapes. Figs.2(a)—(d) show the evolutions of the soliton pair with the conjugator applied at 3300km, 3150km, 3000km, and 2700km,

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respectively. One can see that, as the conjugator is applied further away from the coalescence distance, the undoing of the soliton interaction is better. In the Fig.2(a), the conjugator is applied near the coalescence distance and the interaction can not be undone. In the Fig.2(d), the conjugator is applied at the distance where the pulse shapes slightly change and the undoing is almost complete. In the Figs.2(b) and (c), the conjugators are applied at the distances where there are significant pulse shape changes and the undoings are not so well as the case shown in the Fig.2(d).

The OPC can also be applied after the coalescence of the solitons to reduce the number of the conjugators used in the system. In the Ref.4, the conjugator is applied at the middle of the 10400 km transmission system. In that case, the coalescence has been occurred before applying the conjugator. However, this is valid only when the timing jitter of the soliton caused by the Gordon—Haus effect is small. Otherwise the combined effect of the soliton interaction and the Gordon—Haus effect will make the pulse shape and pulse arrival time out of control.

3. REDUCTION OF THE GORDON—HAUS EFFECT

When the soliton is amplified by an optical amplifier, the ASEN is added to the system. It has been shown that, due to the randomly modulated carrier frequency of the soliton by the ASEN, the variance of the carrier frequency of the soliton caused by the amplifier is[9]

$$<\Omega^2>_0 = \frac{2\pi n_2 n_{sp} h c (G-1)^2}{3\tau_0 \lambda^2 |\beta_2| A_{eff} G \alpha L_a}, \tag{2}$$

where n_{sp} is the spontaneous emission factor of the amplifier; h is the Planck's constant; c is the velocity of light; L_a is the amplifier spacing; $G=\exp(\alpha L_a)$ is the gain of the amplifier; $\tau_0= \tau_s/1.763$ and τ_s is the pulse width of the soliton; λ is the soliton wavelength. When the soliton propagates z distance and is periodically amplified by $N=z/L_a$ amplifiers, the total variance of the timing jitter contributed from the N amplifiers is

$$<\delta t^2> = \beta_2{}^2 <\Omega^2>_0 \sum_{j=1}^{N} [z-jL_a]^2. \tag{3}$$

After propagating L distance with $M= L/L_a$ amplifiers, a conjugator is applied and both the frequencies of the soliton and the ASEN are inverted. For further propagating ΔL distance, where $\Delta L= \Delta M L_a$, the total variance of the timing jitter of the soliton at $z= L+\Delta L$ becomes

$$<\delta t^2>=\beta_2{}^2<\Omega^2>_0\{ \sum_{j=1}^{M} [L-jL_a-\Delta L]^2 + \sum_{j=1}^{\Delta M} [\Delta L-jL_a]^2 \}, \tag{4}$$

where the terms with first and second summations represent the variances caused by the amplifiers which are used before and after the conjugator, respectively. If the conjugator is applied at the middle of the system, $\Delta L=L$ and $\Delta M=M$. In this case, Eq.(4) reduces to the case shown in the Ref.4 and it is easy to show that the variance can be reduced to 1/4 of the value obtained without using the conjugator or the standard deviation is reduced to 1/2 of the value obtained without using the conjugator.

In the following, a numerical example is taken to show the reduction of the timing jitter by the OPC by assuming $n_{sp}=1$ and the numerical parameters given above. Fig. 3 shows the standard deviation σ of the timing jitter calculated from the Eqs.(3) and (4) along the fiber for 9000 km transmission distance and the conjugator is applied at 4500 km. In the Fig.3, the case without the conjugator is also shown for comparison. To confirm the results, we numerically solve the transmissions of 256 solitons in the presence of the ASEN and obtain the standard deviation of the timing jitter. Here, the third—order dispersion, the SFS, and the soliton interaction are neglected to satisify the assumptions made when the Eq.(2) is derived. The results are also shown in the Fig.3 and agree with the results calculated from the Eqs.(3) and (4). From the Eq.(4), at 9000 km, σ= 5.2 ps when the conjugator is applied and σ= 10.3 ps when no conjugator is applied. For the results obtained by the numerical simulations, at 9000 km, σ= 5.7 ps when the conjugator is applied and σ= 10.7 ps when no conjugator is applied. One can see that the standard deviation at 9000 km for the case with the conjugator is reduced to a half to compare with the case without the conjugator as is expected because the conjugator is applied at the middle, i.e. at 4500km. It is noticed that the minimum standard deviation is σ = 2.1 ps at 6360 km from the Eq.(4). Therefore, the optimal position to apply the conjugator is not at the middle of the system. From the Eq.(4), it is easy to show that, for a total transmission distance of L_t, the optimal distance to reduce the Gordon—Haus effect is at $0.707L_t$ and the standard deviation is reduced to 0.35 of the value obtained without using the conjugator.

The results shown in this section are valid under the conditions: (1) the soliton interaction is absent, and (2) the additional ASEN caused by the conjugator can be neglected. When the soliton interaction can not be ignored, as is shown in the last section, the conjugator should be applied away from the coalescence distance and several conjugators may be used in the long—haul system. As the number of the conjugators increases, the more reduction of the Gordon—Haus effect. However, as the loss of a conjugator is large,[10] the gain of the amplifier following the conjugator and the ASEN power introduced by the amplifier are large. Therefore, in reality, there should exist an optimal number of the conjugators to reduce both the soliton interaction and the Gordon—Haus effect.

4. CONCLUSIONS

The reductions of the soliton interaction and the Gordon—Haus effect by the OPC are shown. With the conjugator, both the bit rate and the transmission distance of the soliton communication system can be improved. The conjugator should be applied before there are significant changes of the pulse shapes to undo the interaction well and to avoid the combined effect of the soliton interaction and the Gordon—Haus effect. The optimal position to apply the conjugator to reduce the Gordon—Haus effect is found. To design the system, the soliton interaction, the Gordon—Haus effect, and the ASEN caused by the conjugators should be considered.

5. REFERENCES

1. A. Yariv, D. Fekete, and D. M. Pepper," Compensation for channel dispersion by nonlinear optical phase conjugation," Opt. Lett., vol. 4, pp. 52—54, 1979.

2. S. Watanabe, T. Naito, and T. Chikama," Compensation of chromatic dispersion in a single—mode fiber by optical phase conjugation," IEEE Photon. Technol. Lett., vol. 5, pp. 92—95, 1993.

3. M. C. Tatham, G. Sherlock, and L. D. Westbrook," Compensation fibre chromatic dispersion by optical phase conjugation in a semiconductor laser amplifier," Electron. Lett., vol. 29, pp. 1851—1852, 1993.

4. W. Forysiak, and N. J. Doran," Conjugate solitons in amplified optical fibre transmission systems," Electron. Lett., vol. 30, pp. 154—155, 1994.

5. S. Wen and S. Chi," Undoing of soliton interaction by optical phase conjugation," to appear in Electron. Lett.

6. J. P. Gordon and H. A. Haus," Random walk of coherently amplified solitons in optical fiber transmission," Opt. Lett., vol. 11, pp. 665—667, 1986.

7. R. A. Fisher, B. R. Suydam, and D. Yevick," Optical phase conjugation for time—domain undoing of dispersive self—phase—modulation effects," Opt. Lett., vol. 8, pp. 611—613, 1983.

8. S. Chi and S. Wen," Recovery of soliton self—frequency shift by optical phase conjugation," submitted to Opt. Lett.

9. D. Marcuse," An alternative derivative of the Gordon—Haus effect," IEEE J. Lightwave Technol., vol. 10, pp. 273—278, 1992.

10. S. Wen, S. Chi, and T.—C. Chang," Effect of cross—phase modulation on optical phase conjugation in dispersion—shifted fiber," to appear in Opt. Lett.

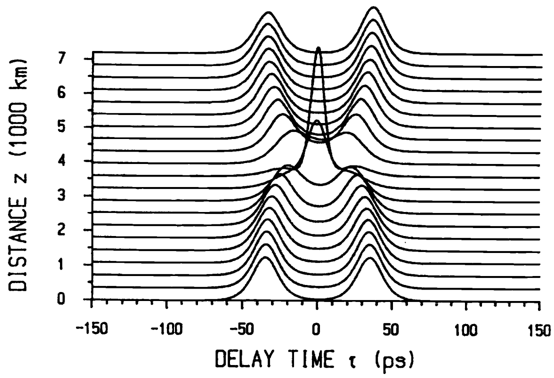

Figure 1: Power envelope of the soliton pair along the fiber.

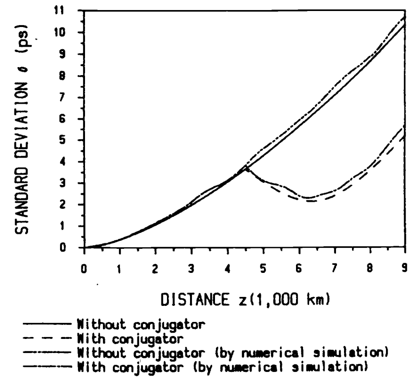

Figure 3: Standard deviation σ of the timing jitter of the soliton along the fiber. A conjugator is applied at 4500km.

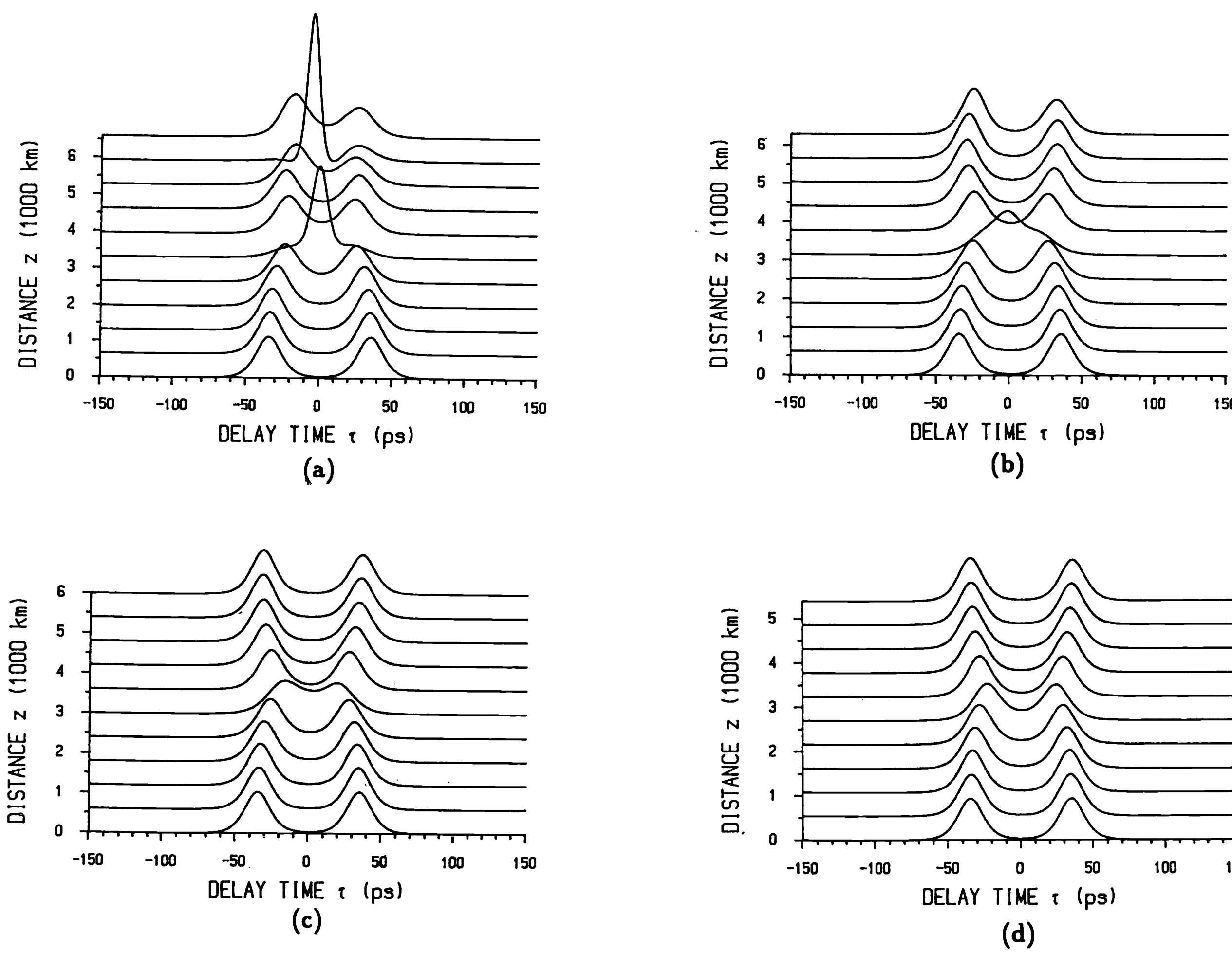

Figure 2: Power envelopes of the soliton pair along the fiber with a conjugator applied at (a) 3300km, (b) 3150km, (c) 3000 km, and (d) 2700km, respectively.