Reduction of the soliton interaction and the Gordon–Haus effect by optical phase conjugation

Senfar Wen

Department of Electrical Engineering, Chung-Hua Polytechnic Institute, 30 Tung Shiang, Hsinchu, Taiwan, China

Sien Chi

Institute of Electro-Optical Engineering, National Chiao Tung University, 1001 Ta Hsueh Road, Hsinchu, Taiwan, China

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The reduction of soliton interaction and the Gordon–Haus effect by optical phase conjugation is studied. The criteria for applying the conjugators are considered. It is shown that soliton transmission can be significantly improved by optical phase conjugation.

It has been shown in theory that the data rate of a soliton transmission system can be improved by optical phase conjugation[1–4] (OPC). In lossless fiber without the third-order dispersion, the nonlinear interaction between the solitons can be completely eliminated by OPC. In the presence of power perturbation the soliton interaction can be overcome by application of the conjugator when the pulse shapes of the solitons have not changed significantly. On the other hand, when the soliton is amplified by an optical amplifier to compensate for the fiber loss, the introduced amplified spontaneous emission noise (ASEN) will randomly modulate the carrier frequency of the soliton and cause timing jitter of the soliton. Such an effect is known as the Gordon–Haus effect and can be reduced by OPC. Because the soliton interaction depends on the separation of the solitons, the Gordon–Haus effect affects the soliton interaction. In this Letter we numerically study the simultaneous reduction of the soliton interaction and the Gordon–Haus effect by OPC.

The wave equation that describes soliton propagation in the single-mode fiber can be written as

$$i\frac{\partial\phi}{\partial z}-\frac{1}{2}\beta_2\frac{\partial^2\phi}{\partial\tau^2}+n_2\beta_0|\phi|^2\phi=-\frac{1}{2}i\alpha\phi\,,\qquad(1)$$

where β_2 represents the second-order dispersion, n_2 is the Kerr coefficient, and α is the fiber loss. When $\alpha = 0$, the soliton interaction can be completely eliminated by OPC. We numerically solve Eq. (1) with the fiber loss periodically compensated by an amplifier with the amplifier spacing $L_a = 30$ km. The ASEN power per unit frequency generated by the amplifier is $P_a = n_{\mathrm{sp}}(G-1)h\nu$, where n_{sp} is the spontaneous emission factor, $G = \exp(\alpha L_a)$ is the gain of the amplifier, and $h\nu$ is the photon energy. The soliton wavelength is assumed to be 1.55 μm and the pulse width (FWHM) to be 20 ps. The other coefficients are taken as $\beta_2 = -0.64$ ps^2/km [0.5 ps/(km/nm)], $n_2 = 3.2\times10^{-20}$ m^2/W, $\alpha = 0.2$ dB/km, and $n_{\mathrm{SP}} = 1$. The effective fiber cross section is 35 μm^2. To enhance the soliton interaction, the separation of the neighboring solitons is taken to be 3.5 pulse widths.

First, we consider the soliton interaction without the Gordon–Haus effect. In the lossless case, if there are only two solitons they periodically coalesce, and the first coalescence distance is at $L_i = 3470$ km. Figure 1 shows the evolution of a soliton bit stream (010110111011110) along the periodically amplified fiber. One can see that, after propagation of approximately L_i, the soliton interaction becomes apparent and the interaction depends on the bit pattern. For the case with the bit pattern (0110), the two solitons coalesce near L_i. For a bit pattern with more solitons, the interaction is more complicated. For the case shown in Fig. 1, the conjugator can be applied before approximately 3000 km or at approximately 6940 km, where the solitons do not coalesce or all separate after coalescence. Figure 2 shows the standard deviation σ of the timing jitter of the solitons caused by the interaction. The simulated soliton bit stream consists of 640 bits that are pseudorandom and include 320 zeros and 320 soliton pulses. Note that the initial standard deviation is

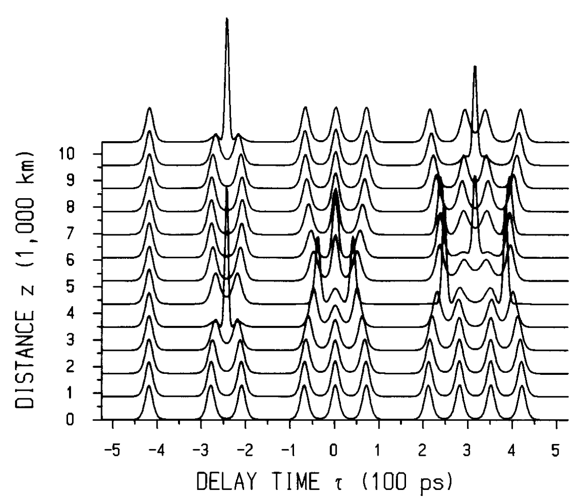

Fig. 1. Power envelope of the soliton bit stream along the fiber without the ASEN.

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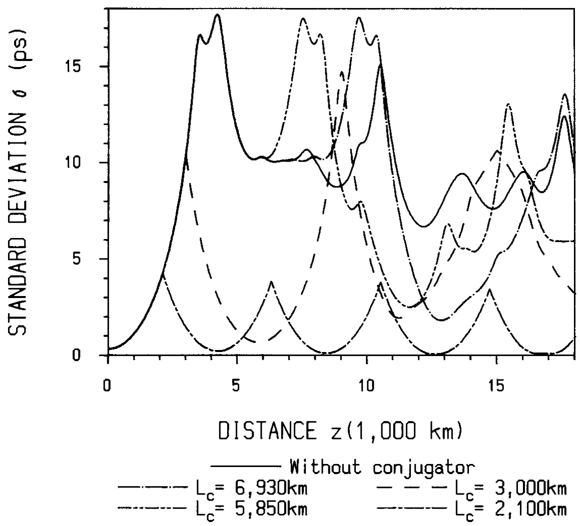

Fig. 2. Standard deviation σ of the timing jitter of the solitons along the fiber without the ASEN. The jth conjugator is appled at $(2j - 1)L_c$.

not zero because of the initial overlap of the solitons. In Fig. 2, as the distance increases, the standard deviation increases until approximately $z = L_i$ where the standard deviation is maximum. After this distance, the solitons separate and the standard deviation decreases; however, the standard deviation is maintained above approximately 6 ps. When the conjugators are applied, if the standard deviation decreases to the initial value the elimination of the soliton interaction is complete. For long-distance transmission, several conjugators are applied. If the first conjugator is applied at $z = L_c$ and the soliton interaction can be reduced, then its complete elimination is at $z = 2L_c$. Therefore the second conjugator is applied at $z = 3L_c$ and the third conjugator is applied at $z = 5L_c$, and so on. One can see that for the cases with $L_c < L_i$ the reduction of the soliton interaction is good, and it is better for shorter L_c. The minimum standard deviation occurs at $z = 2mL_c$, as expected, where m is a positive integer. For the cases with $L_c > L_i$, the reduction of the soliton interaction is not so good as the cases with $L_c < L_i$. The case with $L_c = 6930$ km is better than the case with $L_c = 5850$ km because the separation of the solitons is better at $L_c = 6930$ km. With longer L_c, fewer conjugators are required. However, when the ASEN is considered, the timing jitter is more complicated.[5] We show that it is improper to apply the conjugator after the soliton coalescence that is due to the ASEN.

Including the ASEN, Fig. 3 shows an example of the evolution of the solitons with the same bit stream as in Fig. 1. To show clearly the pulse shapes of the solitons shown in Fig. 3, the ASEN has been filtered out by a Lorentzian transfer function with a 50-GHz bandwidth. One can see that the soliton interaction is quite different from that in the case without the ASEN shown in Fig. 1 because the timing jitter that is due to the ASEN changes the separation between the neighboring solitons. Thus, the conjugator should be applied before the combined effect of the soliton interaction and timing jitter is out of control. Figure 4 shows the standard deviation σ of the timing jitter of the solitons caused by the combination of the soliton interaction and the Gordon–Haus effect for the same 640 pseudorandom bits considered in Fig. 2. When we calculate the timing jitter of the solitons, the Lorentzian transfer function with a 50-GHz bandwidth is used to filter out the ASEN. For comparison, the theoretical curve for the timing jitter without the soliton interaction and OPC is shown. The cases with the conjugators are also shown in Fig. 4, where the conjugators are applied at the same distances as in Fig. 2. It is shown that when the conjugator is applied after L_i the reduction of the timing jitter is poor. When the conjugator is applied before L_i, the reduction of the timing jitter is more effective. For the case with shorter L_c, the reduction is better. Note that the minimum standard deviation does not periodically occur at $z = 2mL_c$, as in the cases shown in Fig. 2.

For further reduction of the timing jitter, the conjugator is applied every L_c to effectively reduce the Gordon–Haus effect. The results are shown in Fig. 5. In Fig. 5, compared with Fig. 4, the timing jitter is significantly reduced for the cases with $L_c < L_i$. For the cases with $L_c > L_i$, the reduction is

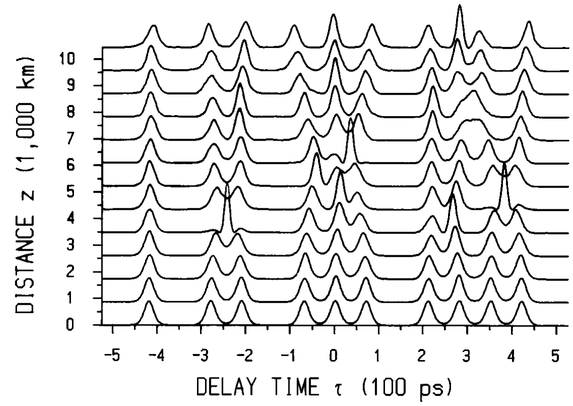

Fig. 3. Power envelope of the soliton bit stream along the fiber with the ASEN. The ASEN has been filtered out by a 50-GHz filter to show the soliton pulse shapes.

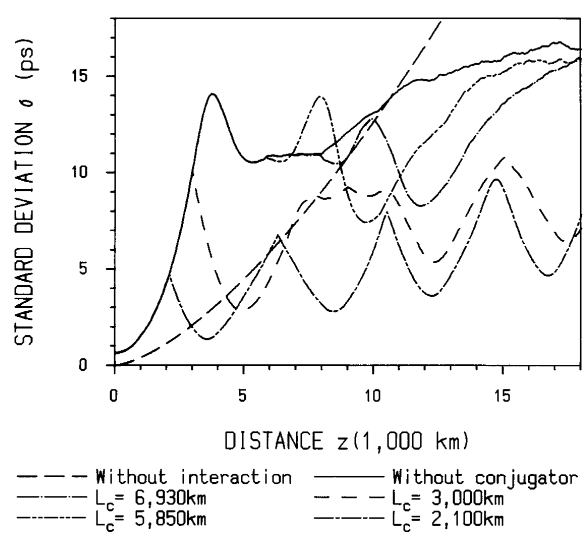

Fig. 4. Standard deviation σ of the timing jitter of the solitons along the fiber with the ASEN. The jth conjugator is appled at $(2j - 1)L_c$.

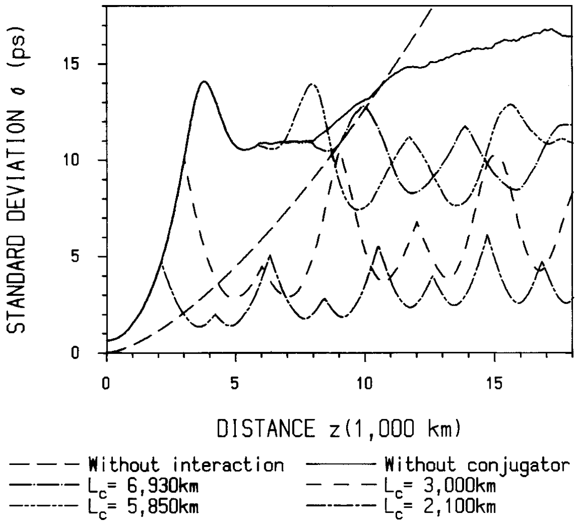

Fig. 5. Standard deviation σ of the timing jitter of the solitons along the fiber with the ASEN. The jth conjugator is applied at jL_c.

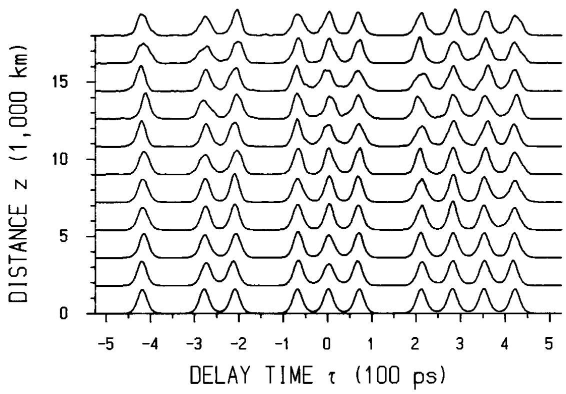

Fig. 6. Power envelope of the soliton bit stream along the fiber with the ASEN and when the conjugator is applied every 2100 km. The ASEN has been filtered out by a 50-GHz filter to show the soliton pulse shapes.

ineffective. Note that there exists a minimum standard deviation between the conjugators. Therefore, the transmission distance should be chosen so that the corresponding standard deviation is minimum. For the considered soliton transmission system, with a 10^{-9} bit error rate, the corresponding standard deviation of the timing jitter is 3.8 ps. For the case with $L_c = 2100$ km shown in Fig. 5, by proper choice of the transmission distance the allowed transmission distance for a bit error rate of 10^{-9} can be greater than 18,000 km. Figure 6 shows an example of the evolution of the soliton bit stream with the ASEN as in Fig. 3, except that the conjugator is applied every 2100 km. One can see that the separations of the solitons are maintained after propagation of 18,000 km.

From the results shown above, the reduction of the timing jitter increases with the number of the conjugators. However, the conjugator is assumed to be ideal. In fact, as there is power loss introduced by the conjugator, we need an additional optical amplifier, and additional ASEN is introduced. Therefore there should be an optimal number of conjugators to reduce both the soliton interaction and the Gordon–Haus effect.

The sliding filter has been used to reduce soliton interaction and Gordon–Haus effect.[6,7] It has been found that, if we place a sliding Fabry–Perot filter after every amplification period without using OPC, the soliton separation cannot be well maintained even without ASEN because the considered soliton separation is small. The solitons may coalesce or repel one another, depending on the bit pattern and filter. For example, for the bit stream shown in Fig. 1 there are solitons that repel each one another after propagating approximately 6900 km with a 190-GHz bandwidth and a +3-GHz/Mm sliding rate where the filter is optimized to maintain the soliton separation without considering ASEN.

In conclusion, the reduction of the soliton interaction and the Gordon–Haus effect by OPC is studied. The conjugator should be applied before soliton coalescence; otherwise the combined effect of the soliton interaction and the Gordon–Haus effect will render the pulse shape and pulse arrival time uncontrollable. It is shown that, by properly applying conjugators, one can significantly improve soliton transmission, with better results than from applying the sliding filter for the example considered.

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