1 March 1998

ELSEVIER

OPTICS COMMUNICATIONS

Optics Communications 148 (1998) 27–30

Improving soliton transmission in a dispersion compensated system by pre-chirping and pre-shaping method

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Received 22 July 1997; accepted 28 October 1997

Abstract

Soliton transmission in a dispersion compensated system is numerically studied. The numerical results are consistent with the previous experimental results. The pre-chirping and pre-shaping method is used to reduce the timing jitter and the dispersive wave in a dispersion compensated soliton transmission system. We have found that the pre-chirping and pre-shaping method can stabilize the variation of pulse shape due to the perturbation of the dispersion compensation fiber and the timing jitter can be greatly reduced. © 1998 Elsevier Science B.V.

For long distance optical soliton communication systems, the soliton is periodically amplified by the optical amplifiers which introduce amplified spontaneous emission (ASE) noise to the soliton. The noise leads to the timing jitter and is known as the Gordon–Haus effect [1]. Dispersion management techniques using dispersion compensation fibers (DCFs) are suggested to reduce the ASE noise-induced timing jitter [2,3]. Suzuki et al. have experimentally investigated a dispersion compensated soliton transmission system and found that there was an optimum dispersion compensation rate for the system [3]. However, the DCF introduces positive frequency chirp to the soliton periodically and the soliton pulse shape undergoes significant variations. The frequency chirp in the soliton can be detrimental because it disturbs the exact balance between the group-velocity dispersion (GVD) and SPM effect necessary for the soliton [4]. This local mismatch between the linear and nonlinear effects creates the dispersive wave [5]. The periodic dispersion compensated soliton transmission system of which the input soliton is chirped and properly shaped has been proposed [6–8]. According to Refs. [7,8], the energy required for quasi-soliton formation is less than that required for a local fundamental soliton with the same pulse width.

In this paper, we use the pre-chirping and pre-shaping method to improve soliton transmission in a dispersion compensated system including higher order terms. We first numerically model the soliton transmission in a dispersion compensated system, and the numerical results are found to be consistent with the experimental results by Suzuki et al. [3]. Then we use the pre-chirping and pre-shaping method in the system. We have found, by using this method, that the steady periodic variation of the chirp and the shape of the pulse can be obtained within a short distance and the dispersive wave can be greatly suppressed. In the meantime, we have also found that the timing jitter of the soliton is greatly reduced.

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

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

where $\tau = (t-\beta_1 z)/T_0$ and T_0 is the initial soliton width, β_1 is the reciprocal group velocity, β_2 and β_3 represent the second-order and third-order dispersion of the fiber, respectively, U is the slowly varying normalized field amplitude, n_2 is the Kerr coefficient, C_r is the slope of the Raman gain profile, and α is the fiber loss. The dispersion

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PII S0030-4018(97)00648-2

compensated soliton transmission system considered is shown in Fig. 1. The amplifier spacing is 30 km and the dispersion compensation spacing is 180 km which corresponds to six amplifier spacing. For the transmission fiber, the coefficients in Eq. (1) are taken to be $\beta_2 = -0.255$ ps^2/km, $\beta_3 = 0.14$ ps^3/km, $n_2 = 3.2 \times 10^{-20}$ m^2/W, $C_r = 3.8 \times 10^{-16}$ (ps m)/W, $\alpha = 0.22$ dB/km. For the DCF, the parameters are the same as in the transmission fiber except that $\beta_2 = 80.0$ ps^2/km and $\alpha = 0.5$ dB/km. The transfer function of the Fabry–Perot filter placed after every amplifier is given as

$$H(\Omega) = \frac{1}{1 - \mathrm{i}[(2/B)(\Omega - \Omega_f)]}, \tag{2}$$

where $\Omega = \omega - \omega_0$ and ω_0 is the initial soliton carrier frequency, $\Omega_f = \omega_f - \omega_0$ and ω_f is the center frequency of the filter, and the filter bandwidth B is taken to be 740 GHz. The incident soliton pulse with linear chirp is assumed to be of the form

$$U(z=0,\tau) = \eta_0 \operatorname{sech}(\tau) \exp\left(-\mathrm{i}\tfrac{1}{2} C_0 \tau^2\right), \tag{3}$$

where η_0 is the initial pulse amplitude and C_0 represents the pre-chirping parameter. The pulse at distance z can be written as

$$U(z,\tau) = |U(z,\tau)| \exp[\mathrm{i}\phi(z,\tau)], \tag{4}$$

where $\phi(z, \tau)$ is the time dependent phase of the pulse. The chirping parameter $C(z, \tau)$ can be obtained by

$$C(z,\tau) = -\partial^2\phi(z,\tau)/\partial\tau^2. \tag{5}$$

We numerically simulate a single soliton propagation in a dispersion compensated transmission system with different dispersion compensation rates which range from 80% to 100%. The parameters of the input pulse are chosen to be $\eta_0 = 1.39$, $T_{\mathrm{FWHM}} \cong 1.763 T_0 = 7$ ps, the initial soliton separation is 50 ps (20 Gbits/s), and $C_0 = 0$, i.e., without initial chirp. Fig. 2(a) and Fig. 2(b) show the chirping parameter at $\tau = 0$ and the pulsewidth of the soliton, respectively, as the soliton propagates along the fiber in the dispersion compensated system with 100% dispersion compensation rate. The oscillation of the chirping parameter reaches a steady state after 4 Mm transmission. The detailed variations of the chirping parameter and pulsewidth are shown in Fig. 3(a) and Fig. 3(b), respectively, where

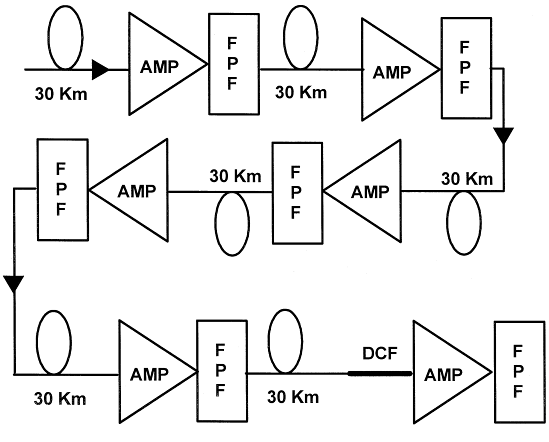

Fig. 1. Schematic diagram of the dispersion compensated soliton transmission system.

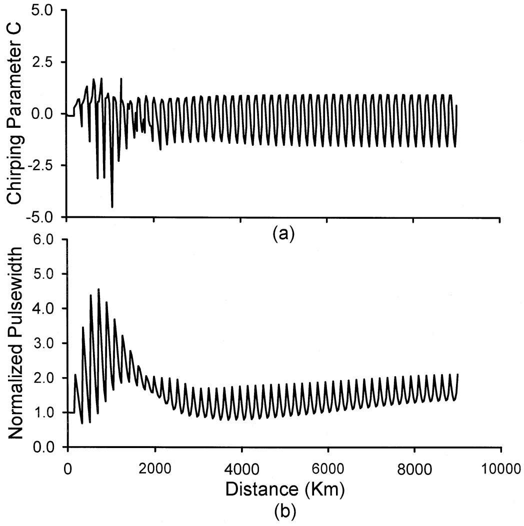

Fig. 2. (a) The chirping parameter C at $\tau = 0$ and (b) the normalized pulsewidth of the soliton in the dispersion compensated soliton transmission system.

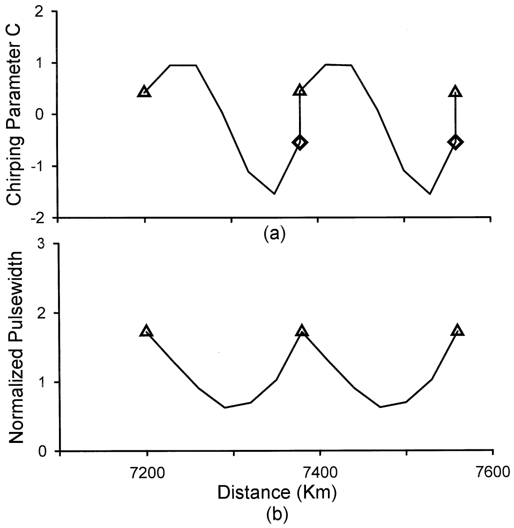

Fig. 3. The detailed variations of (a) the chirping parameter C at $\tau = 0$ and (b) the normalized pulsewidth of the soliton in the dispersion compensated soliton transmission system when stable oscillation has been obtained. (◇) and (△) represent the chirping parameter or pulsewidth of the soliton at the position right before the DCF and right after the optical amplifier, respectively.

the steady state oscillation of the chirping parameter has been reached. In Fig. 3(a), (◇) and (△) represent the chirping parameter of the soliton when $\tau = 0$ at the position right before the DCF and right after the optical amplifier, which is negative and positive, respectively. In Fig. 3(b), (△) represents the pulsewidth of the soliton at the position right after the optical amplifier. Therefore, if we launch a soliton whose initial chirp and pulsewidth match the chirp and pulsewidth as (△) shown in Fig. 3, then the oscillation of the chirp and pulsewidth should reach a steady state more rapidly. We can choose this new steady state as the input and repeat the process until the oscillation reaches steady state within a short distance. Using this pre-chirping and pre-shaping method, i.e., choosing the input parameters of the soliton to be $\eta_0 = 1.05$, $T_{\mathrm{FWHM}} = 12.376$ ps, the initial soliton separation is 50 ps (20 Gbits/s), and $C_0 = 0.59$ for 100% dispersion compensation rate, we obtain the chirping parameter and the pulsewidth of the soliton as shown in Fig. 4. Since the pulse shape right after the DCF is not the exact sech function, the initial trifling non-steady state oscillation is unavoidable. Comparing Figs. 2 and Figs. 4, we can see that the oscillations of the chirping parameter and the pulsewidth are more stable when the pre-shaping and pre-chirping method is used.

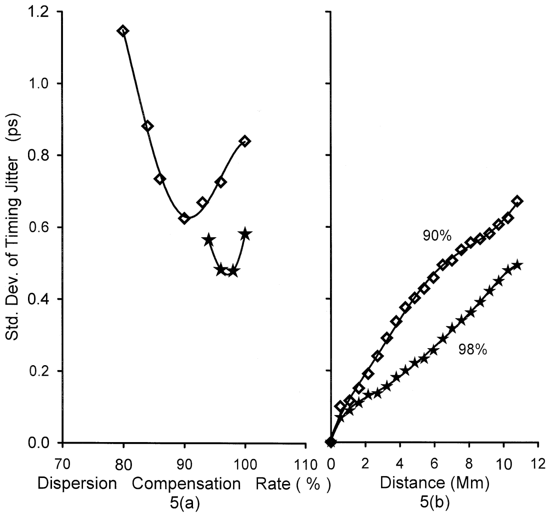

Fig. 5. The standard deviation of the timing jitters of solitons (a) at $z = 10260$ km for different dispersion compensation rates and (b) in the dispersion compensated transmission system for the optimum dispersion compensation rate. (★) and (◇) represent the timing jitters of solitons for the input solitons with and without pre-chirping and pre-shaping, respectively.

When the soliton is periodically amplified by the optical amplifiers, every amplifier introduces ASE noise to the soliton. The ASE noise randomly modulates the soliton carrier frequency and causes the timing jitter of the soliton. Since the soliton interaction depends on the separation of the solitons, the ASE noise-induced timing jitter influences the soliton interaction and vice versa. The ASE noise power per unit frequency generated by an amplifier is $P_{\mathrm{a}} = n_{\mathrm{sp}}(G-1)h\nu$, where $n_{\mathrm{sp}} = 1.2$ is the spontaneous emission factor, $G = \exp(\alpha L_{\mathrm{a}})$ is the gain of the amplifier, L_{a} is the amplifier spacing and $h\nu$ is the photon energy. Fig. 5 shows the standard deviation of the timing jitters of the solitons in the dispersion compensated transmission system, which is caused by the combination of the soliton interactions and ASE noise-induced timing jitters for the 512 pseudo-random bits. In Ref. [3], Suzuki et al. have experimentally investigated a dispersion compensated soliton transmission system with different compensation rates which range from 80% to 100%, the best performance of the system was obtained with 90% dispersion compensation rate. In Fig. 5(a), (★) and (◇) represent the timing jitters of solitons at $z = 10260$ km versus dispersion compensation rate for input solitons with and without pre-chirping and pre-shaping, respectively. When the solitons are not pre-chirped and pre-shaped, the minimum timing jitter occurs at 90% dispersion compensation rate, which coincides with Suzuki et al.'s experiment. When the solitons are pre-chirped and pre-shaped, the minimum timing jitter occurs at 98% dispersion compensation rate, since the dispersive wave caused by the DCF can be reduced by using the pre-chirping and pre-shaping method. Fig. 5(b) shows that the timing jitters of solitons increase with propagation distance when the dispersion compensation rates are optimized for the input solitons with and without pre-chirping and pre-shaping.

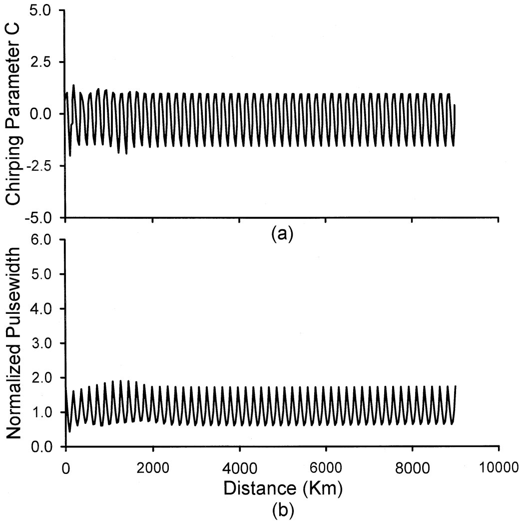

Fig. 4. (a) The chirping parameter C at $\tau = 0$ and (b) the normalized pulsewidth of the soliton in the dispersion compensated soliton transmission system using the pre-chirping and pre-shaping method.

In conclusion, we have numerically studied a dispersion compensated soliton transmission system. The numerical results are shown to be consistent with previous experimental results. We have studied that the pre-chirping and pre-shaping method can effectively reduce the dispersive wave and timing jitter in the dispersion compensated soliton transmission system.

Acknowledgements

This research was supported by the National Science Council of the Republic of China under contract NSC-86-2811-E-009-002R.

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