Reduction of soliton interactions by sliding-frequency second-order Butterworth filters

Jeng-Cherng Dung and Sien Chi

Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu, Taiwan 30050, China

Senfar Wen

Department of Electrical Engineering, Chung-Hua Polytechnic Institute, Hsinchu, Taiwan 30050, China

Received October 16, 1995

The reduction of the soliton interaction by use of optical sliding-frequency second-order Butterworth filters is studied numerically. It is found that the second-order Butterworth filters can reduce the soliton interaction more effectively than Fabry–Perot filters or third-order Butterworth filters because the second-order Butterworth filter induces larger frequency chirping on the soliton, compressing it as it propagates in the fiber after the filter.

In a long-distance soliton communication system that uses optical amplifiers to compensate for the fiber loss the limit to the bit-rate–distance product is set by the soliton–soliton interaction and the noise-induced timing jitter. A large separation between neighboring solitons is required to avoid the nonlinear interaction between them, thus reducing the bit rate.[1] On the other hand, the introduced amplified spontaneous emission noise (ASEN) will randomly modulate the carrier frequency of the soliton, causing timing jitter of the soliton.[2] This is known as the Gordon–Haus effect. To reduce the soliton interaction and timing jitter, an optical bandpass filter is inserted after every optical amplifier.[3–5] The bandpass filter causes the center frequency of the soliton spectrum to experience more gain than the other parts, and thus the bandwidth-limited amplification can stabilize the carrier frequency and group velocity of the soliton. Furthermore, it is found that, if the center frequency of the filter is slowly sliding with the distance along the fiber, the reductions of the soliton interaction and timing jitter are better than those achieved with a filter of fixed center frequency.[6,7] Such a filter is called a sliding-frequency filter. Usually a Fabry–Perot filter (FPF) is used as the bandpass filter,[6–8] but recently an optical second-order Butterworth filter (BWF) was used in a soliton communication system.[9] In this Letter we compare the reductions of the soliton interactions by using three different sliding-frequency filters: the FPF, which can be considered a first-order BWF; the second-order BWF; and the third-order BWF. It is found that the sliding-frequency second-order BWF can reduce the soliton interaction more effectively than the sliding-frequency FPF or the sliding-frequency third-order BWF because it induces larger frequency chirping on the soliton, compressing it as it propagates in the fiber after the filter. Even when we consider the soliton interaction and the noise-induced timing jitter simultaneously, the bit-rate–distance product can be greatly increased by use of the sliding-frequency second-order BWF.

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

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

where β_2 and β_3 represent the second- and third-order dispersions, respectively; n_2 is the Kerr coefficient; c_r is the coefficient of the self-frequency shift; and α is the fiber loss. The coefficients in Eq. (1) are taken to be $\beta_2 = -0.638$ ps^2/km [0.5 ps/(km nm)], $\beta_3 = 0.075$ ps^3/km, $n_2 = 3.2 \times 10^{-20}$ m^2/W, $c_r = 3.8 \times 10^{-16}$ (ps m)/W, and $\alpha = 0.22$ dB/km. The effective fiber cross section is 35 μm^2. The amplifier spacing is $L_a = 30$ km, and the considered soliton pulse width is $T_W = 20$ ps. The transfer function of the optical BWF placed after every amplifier is taken to be

$$H(\Omega - \Omega_f) = \frac{1}{1 + i\left[\dfrac{2}{B}\,(\Omega - \Omega_f)\right]^m}\,. \quad (2)$$

Here m is the order of the BWF; $\Omega = \omega - \omega_0$, where ω_0 is the original soliton carrier frequency; B is the filter bandwidth; and Ω_f is the center frequency of the filter. For the sliding-frequency filter, Ω_f varies along the fiber. [Note that the transfer function of the FPF can be written as Eq. (2) with $m = 1$]. In our study the filter bandwidth is taken to be $B/2\pi = 150$ GHz.

To show the soliton interactions, we consider the transmission of the soliton bit stream (00101101110111100) and take a 3.5-pulse-width separation between the neighboring solitons to enhance the interaction. The corresponding bit rate is 14.3 Gbits/s. It has been shown that, with respect to the reduction of the soliton interaction and timing

0146-9592/96/050339-03$6.00/0

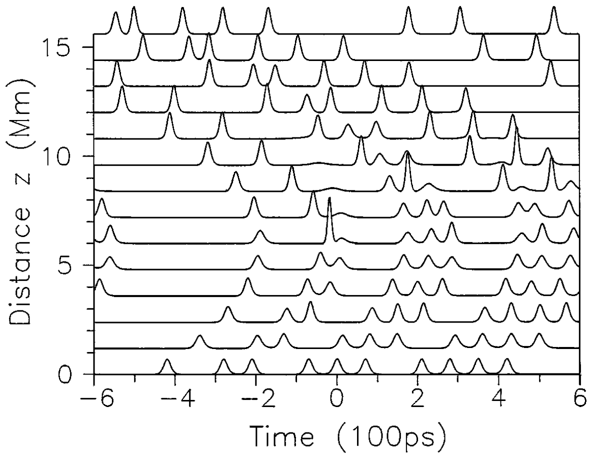

Fig. 1. Power evolution of a soliton bit stream along the fiber with the sliding-frequency FPF. The filter bandwidth is 150 GHz, and the up-sliding rate is 4 GHz/Mm.

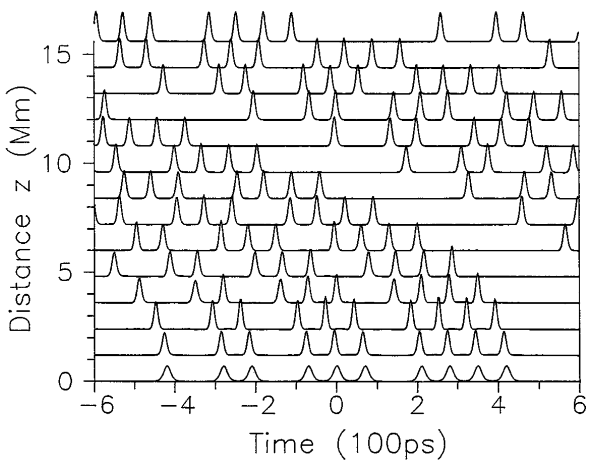

Fig. 2. Power evolution of a soliton bit stream along the fiber with the sliding-frequency second-order BWF for the same filter bandwidth and sliding rate as in Fig. 1.

jitter, the up-sliding-frequency filter is better than the down-sliding-frequency filter for the FPF because of the third-order dispersion of the FPF.[10,11] Here we use the up-sliding filter with a sliding rate of 4 GHz/Mm to reduce the soliton interaction. Figures 1 and 2 show the evolutions of the soliton bit stream along the fiber for the sliding-frequency FPF and the sliding-frequency second-order BWF, respectively. One can see that the soliton interaction depends on the bit pattern. In Fig. 1, for the case of the FPF, the two solitons with the bit pattern (0110) coalesce at ~6.0 Mm, and the solitons with other bit patterns interact after this coalescence distance. For the case of the second-order BWF shown in Fig. 2 we see that the separations of the soliton are well maintained even after 15.6 Mm of transmission. Therefore the soliton interaction can be significantly reduced with the sliding-frequency second-order BWF. Without the filters the coalescence distance is only ~3.1 Mm, but by using the sliding-frequency FPF we can reduce the soliton interaction by the bandwidth-limited amplification.[1] Comparing Figs. 1 and 2, one can see that, by using the sliding-frequency second-order BWF, we compress the pulse width of the soliton in addition to the bandwidth-limited amplification. The pulse compression is due to the frequency chirping of the soliton that is induced by the second-order BWF. Figure 3 shows the frequency chirping of a single soliton at 2.1 Mm just after the FPF and the second- and third-order BWF's. One can see that the frequency chirping of the soliton after the second-order BWF is larger than that after the FPF or the third-order BWF. Furthermore, with the second-order BWF the frequency chirping is almost linear near the soliton peak power. Since the chirping is blue shifted the soliton is compressed in the negative-dispersion regime. With the FPF the soliton is only slightly compressed. The third-order BWF cannot reduce the soliton interaction effectively because the phase of the third-order BWF is flat at the center of the filter. The coalescence distance for the soliton pair is ~3.4 Mm for the third-order BWF. Therefore, with respect to reducing the soliton interaction, the sliding-frequency second-order BWF is better than the sliding-frequency FPF or the sliding-frequency third-order BWF.

In a real system, every amplifier introduces ASEN to the soliton when the soliton is periodically amplified by the optical amplifiers, and the ASEN in turn causes the timing jitter of the soliton. When optical filters are used, the extra gain must be employed to offset the loss that the solitons experience from passage through the filters. In Fig. 4, using the same filter bandwidth for both filters, we show the extra gains required to overcome the loss imposed on the solitons by the sliding-frequency second-order BWF and the sliding-frequency FPF. We find that the extra gains introduced by the FPF are larger than those introduced by the second-order BWF. This difference is of practical significance because the extra gains imply that the ASEN induced by the FPF will be larger than that induced by the second-order BWF, when the filter bandwidth is the same for both. Similar results have been obtained for fixed-frequency filters.[12] Thus using the second-order BWF requires less amplifier gain than using the FPF and is preferable.

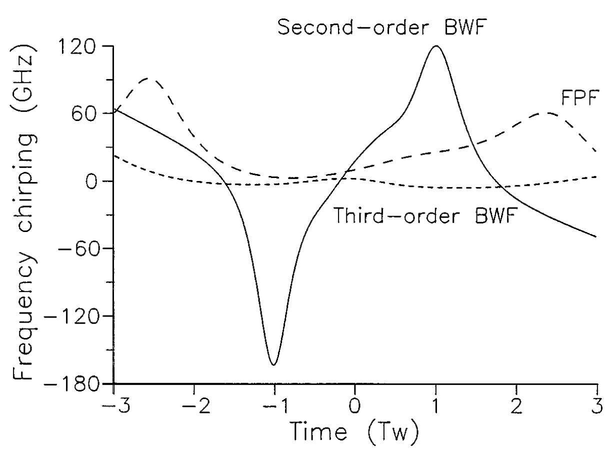

Fig. 3. Frequency chirpings of the soliton pulse at 2.1 Mm just after the filter for the sliding-frequency FPF, the second-order BWF, and the third-order BWF. Tw = 20 ps is the pulse width.

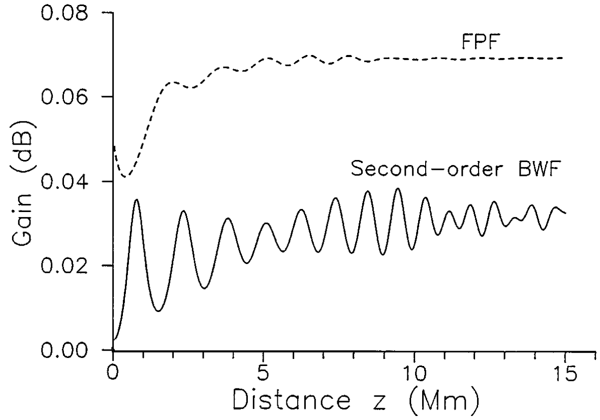

Fig. 4. Extra gain versus distance to compensate for the filter loss for the sliding-frequency second-order BWF and the FPF.

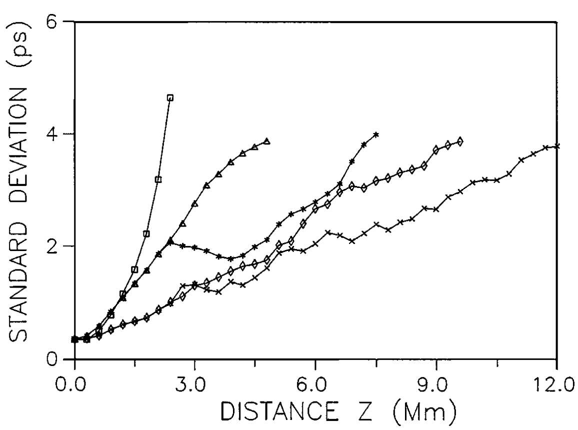

Fig. 5. Evolutions of the standard deviation of the timing jitter of the solitons for the up-sliding FPF(Δ), the second-order BWF(◇), and the third-order BWF(□) and for the zigzag-sliding FPF(∗) and the second-order BWF (×).

Since the soliton interaction depends on the separation of the solitons, the Gordon–Haus effect influences the soliton interaction and complicates the problem. The ASEN power per unit frequency generated by an amplifier is $P_a = n_{\mathrm{sp}}(G - 1)h\nu$, where $n_{\mathrm{sp}} = 1.2$ is the spontaneous emission factor, $G = \exp(\alpha L_a)$ is the gain of the amplifier, and $h\nu$ is the photon energy. For a soliton transmission system with a 20-ps pulse width and a 3.5-pulse-width separation (14.3 Gbits/s), a 10^{-9} bit-error rate corresponds to a 3.8-ps standard deviation of the timing jitter. For the up-sliding-frequency and zigzag-sliding-frequency filters with a sliding rate of 4 GHz/Mm and a zigzag period of 9 Mm, we show in Fig. 5 the standard deviation of the timing jitter of the solitons caused by the combination of the soliton interaction and the Gordon–Haus effect. The simulated soliton bit stream consists of 512 bits that are pseudorandom and includes 256 zeros and 256 soliton pulses. Note that the initial standard deviation is not zero because of the initial overlap of the solitons. The allowed transmission distances for a 10^{-9} bit-error rate are 4.7, 9.6, and 2.2 Mm for the up-sliding-frequency FPF, the second-order BWF, and the third-order BWF, respectively. The allowed transmission distances for a 10^{-9} bit-error rate are 7.2 and 12.0 Mm for the zigzag-sliding-frequency FPF and BWF, respectively.

In conclusion, we have numerically studied the reduction of the soliton interaction and the noise-induced timing jitter by a sliding-frequency FPF, a second-order BWF, and a third-order BWF. It is shown that the sliding-frequency second-order BWF is better than the sliding-frequency FPF or the third-order BWF because it induces larger frequency chirping on the soliton. The soliton is then compressed as it propagates in the fiber (with negative dispersion), and the soliton interaction is more effectively reduced.

This research was partially supported by the National Science Council of the Republic of China under contract NSC 85-2215-E-009-0014.

References

1. P. L. Chu and C. Desem, Electron. Lett. **19,** 956 (1983).
2. J. P. Gordon and H. A. Haus, Opt. Lett. **11,** 665 (1986).
3. Y. Kodama and A. Hasegawa, Opt. Lett. **17,** 31 (1992).
4. Y. Kodama and S. Wabnitz, Electron. Lett. **27,** 1931 (1991).
5. A. Mecozzi, J. D. Moores, H. A. Haus, and Y. Lai, Opt. Lett. **16,** 1841 (1991).
6. L. F. Mollenauer, J. P. Gordon, and S. G. Evangelides, Opt. Lett. **17,** 1575 (1992).
7. Y. Kodama and S. Wabnitz, Opt. Lett. **18,** 1311 (1993).
8. L. F. Mollenauer, E. Lichtman, M. J. Neubelt, and G. T. Harvey, Electron. Lett. **29,** 910 (1993).
9. M. Suzuki, N. Edagawa, H. Taga, H. Tanada, S. Yamamoto, and S. Akiba, Electron. Lett. **30,** 1083 (1994).
10. J. C. Dung, S. Chi, and S. Wen, Opt. Lett. **20,** 1862 (1995).
11. E. A. Golovchenko, A. N. Pilipetskii, C. R. Menyuk, J. P. Gordon, and L. F. Mollenauer, Opt. Lett. **20,** 539 (1995).
12. A. Mecozzi, Opt. Lett. **20,** 1859 (1995).