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Adjusting the detection window to improve the soliton communication system

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Abstract

The improvements of the Q factors of 10-Gb/s soliton systems detected by adjusting detection window are studied. We have found that the optimal width of the detection window depends on the noise-induced timing jitter, noise-induced soliton energy fluctuation, amplifier noise, dispersive wave, and soliton pulse width.

Keywords: Solitons; Optical communication; Nonlinear optics

The performances of soliton transmission systems were evaluated by considering the noise-induced timing jitter [1], the fluctuation of soliton amplitude [2,3], and the fluctuation of soliton energy. The most commonly used method of measuring the system performance in an optical transmission system is the decision circuit method of measuring Q factor [4]. The Q factor can be calculated by integrating its power over a bit slot [5], which is called the integration and dump method. The integration of soliton power over a bit slot is not an optimal design because soliton energy lies within a duration much smaller than a bit slot. It has been reported that the in-line optical gate in time domain could reduce amplified spontaneous emission (ASE) noise [6]. The optical gate can be realized by a sinusoidal driven electroabsorption modulator and the gate function is nearly square shaped [6–8]. Considering such an optical gate is placed before the photodiode of the receiver, only the soliton power within the gate time is able to arrive at the photodiode. Then the received signal is integrated over a bit duration in the receiver. Therefore, the optical gate together with the receiver circuit function as an integrator which integrates the soliton power over a duration of the gate time. We call the gate time as detection window. When the detection window is less than a bit slot, a fraction of noise energy can be excluded without the expense of signal energy. On the other hand, with too small a detection window like sampling the signal's amplitude at bit centrum, the system performance may suffer from the noise-induced timing jitter. The dependence of the system performance on detection window has not

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been considered in literatures. In this letter we will study the improvements of the Q factors of a soliton systems by adjusting the detection window.

The modified nonlinear Schrödinger equation describing the soliton propagation in a fiber is numerically solved. We take the carrier wavelength $\lambda = 1.55$ μm, the second-order fiber dispersion $\beta_2 = -0.25$ ps^2/km, the third-order fiber dispersion $\beta_3 = 0.14$ ps^3/km, the Kerr coefficient $n_2 = 2.7 \times 10^{-20}$ m^2/W, the effective fiber area $A_{\mathrm{eff}} = 50$ μm^2, and the fiber loss $\alpha = 0.2$ dB/km. The soliton system of 10-Gb/s bit rate is considered and its bit slot $T_{\mathrm{b}} = 100$ ps. The soliton pulse width T_{s}(FWHM) and the transmission distance L_{t} are varied. The soliton is amplified every 50 km and the spontaneous emission factor n_{sp} of an optical amplifier is assumed to be 1.2. An in-line Fabry–Perot filter is inserted after every amplifier to reduce the ASE noise and noise-induced timing jitter, where the filter bandwidth is optimized. A second-order Butterworth electric filter with a narrower bandwidth $\Delta\nu_{\mathrm{f}}$ in the receiver is used to further reduce noise [9,10]. The accumulated ASE noise is detrimental for optical amplified long links [2], and the shot noise and thermal noise in the receiver are negligible. For the cases shown in this paper, $\Delta\nu_{\mathrm{f}}$ is also optimized. The bit energy is obtained by integrating the amplitude of the filtered signal over a bit slot in which its centrum coincides with the bit centrum. The gate function of the detection window is modeled by a fifth-order super-Gaussian function

$$G(T) = \exp\left[-\frac{1}{2}\left(\frac{T}{T_{\mathrm{d}}}\right)^{2m}\right], \tag{1}$$

where T_{d} is the detection window and $m = 5$. The system performance can be evaluated by bit error rate (BER) which is given by [11]

$$\mathrm{BER} = \frac{1}{4}\left[\mathrm{erfc}\left(\frac{\overline{E}_1 - E_{\mathrm{D}}}{\delta E_1\sqrt{2}}\right) + \mathrm{erfc}\left(\frac{E_{\mathrm{D}} - \overline{E}_0}{\delta E_0\sqrt{2}}\right)\right], \tag{2}$$

where $\mathrm{erfc}(x) = 2/\sqrt{\pi}\int_x^{\infty} \mathrm{e}^{-y^2}\mathrm{d}y$ is the complementary error function. In Eq. (2), E_{D} is the decision threshold; $\overline{E}_1$ and $\overline{E}_0$ are the average integrated energies of 1 and 0 bits, respectively; δE_1 and δE_0 are the standard deviations of energies of 1 and 0 bits, respectively. The Q factor of the soliton system can be evaluated by BER, which is $Q = \sqrt{2}\,\mathrm{erfc}^{-1}(2\,\mathrm{BER})$. For $\mathrm{BER} = 10^{-9}$, $Q = 6$. For a given detection window T_{d}, the decision threshold E_{D} is optimized for the minimum BER or the maximum Q. We use 1024 sample bits of equal probable 1 and 0 bits to calculate the Q factor.

Fig. 1 shows an output of two neighboring 1 and 0 bits for the case of transmission distance $L_{\mathrm{t}} = 10\,000$ km and soliton pulse width $T_{\mathrm{s}} = 10$ ps. In Fig. 1, the initial pulse shape and the output pulse shape without ASE noise are shown for comparison. One can see that, in the absence of ASE noise, soliton broadens and the displacement of the soliton is due to the third-order fiber dispersion and filters. In the presence of ASE noise, soliton further broadens and the displacement of the soliton is due to noise-induced timing jitter in addition to the third-order fiber dispersion and filters. In the presence of ASE noise, the beating and the nonlinear interaction between ASE noise and soliton lead to the distortion of output pulse shape, especially on the pedestal of the soliton, and the fluctuation of integrated energy. There is significant dispersive wave radiated from the soliton owing to the nonlinear interaction. One can see that the output soliton energy with ASE noise

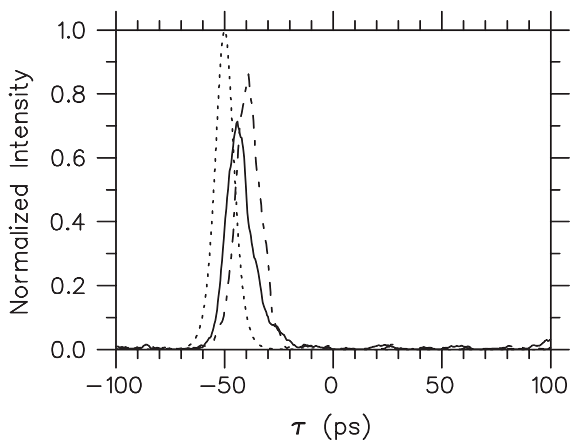

Fig. 1. An output pulse shape of two neighboring 1 and 0 bits at 10 000 km for the case of soliton pulse width $T_{\mathrm{s}} = 10$ ps. The initial pulse shape is shown by dotted line. The output pulse shapes with and without noise are shown by solid and dashed-dotted lines, respectively.

is less than that without ASE noise. The noise-induced soliton energy fluctuation and timing jitter are the main origins of the BER of 1 bits. Because the power of dispersive wave is low and the nonlinear interaction between ASE noise and dispersive wave is weak, the beating between ASE noise and dispersive wave is the main origin of the BER of 0 bits and is also an origin of the BER of 1 bits when detection window T_d is large.

Fig. 2(a) shows the average integrated soliton energy $\overline{E}_1$ versus detection window T_d at 10 000 km

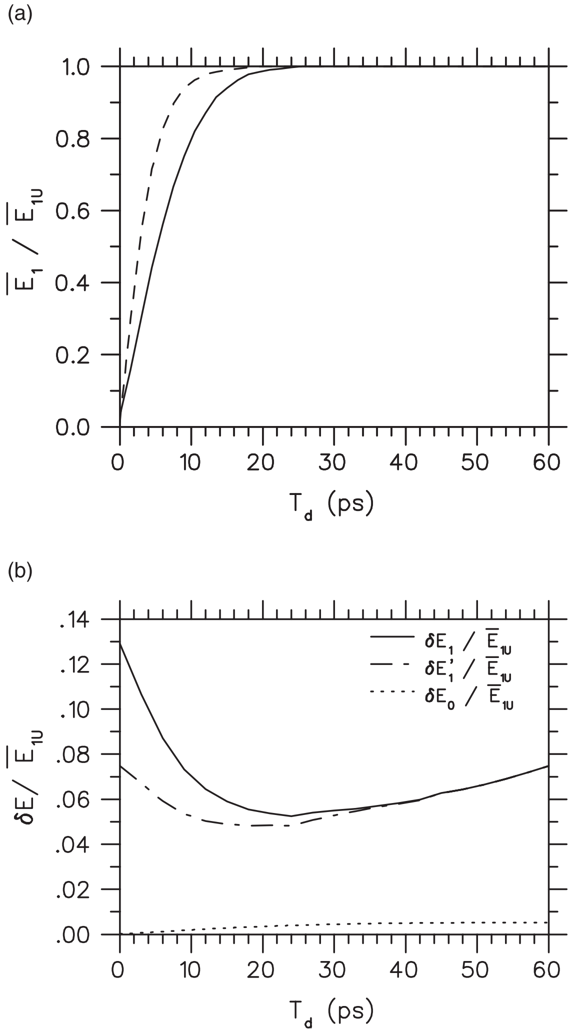

Fig. 2. (a) The average integrated soliton energy $\overline{E}_1$; (b) the standard deviation of integrated energies δE_1, $\delta E'_1$ and δE_0.

for the case of $T_s = 10$ ps. The data shown in the figure is normalized by the average energy within a bit slot $\overline{E}_{1U}$, i.e., $\overline{E}_{1U} = \overline{E}_1(T_d = T_b)$. The dashed line represents the case that the center of the detection window is at the soliton peak in order to exclude the effect of timing jitter. Solid line represents the case that the center of the detection window is at bit centrum and the effect of timing jitter is included. We can see that, when T_d is small, the average integrated soliton energy $\overline{E}_1$ including the timing jitter is less than that without the timing jitter. When T_d is larger than about 25 ps, the effect of timing jitter on the average soliton energy can almost be neglected. Fig. 2(b) shows δE_1 and δE_0 versus T_d for the same case shown in Fig. 2(a). One can see that δE_0 slowly increases with T_d. δE_1 rapidly decreases as T_d increases when T_d is less than about 20 ps mainly because of noise-induced timing jitter. This shows that the effect of timing jitter is more tolerable with larger detection window. The noise-induced soliton energy fluctuation also contributes to δE_1, which can be observed by comparing δE_1 to $\delta E'_1$ shown in the figure by dashed-dotted line. $\delta E'_1$ is the standard deviation of integrated energies of 1 bits calculated by taking the center of the detection window at the soliton peak in order to exclude the effect of timing jitter. When T_d is larger than 25 ps, δE_1 increases with T_d that is due to the ASE noise and dispersive wave.

For the integration and dump method, the optimal T_d relates to soliton pulse width. Fig. 3 shows the increase of average root-mean-square (rms) pulse width T_r normalized by initial rms pulse width T_{ri} along the fiber for the case of 10-ps soliton. In Fig. 3 both cases with and without amplifier noise are shown. As is explained previously, ASE noise enhances soliton broadening. We optimize T_d along the transmission distances and the results are shown in Fig. 4, where the corresponding Q are also shown. One can see that the optimal T_d increases with pulse width. A larger pulse width requires a wider detection window in order to reduce the degradation of Q that is due to noise-induced timing jitter and soliton energy fluctuation.

Fig. 5 shows Q versus T_d for $L_t = 10 000$ km and $T_s = 10$, 15, and 20 ps. The optimal $T_d = 35$,

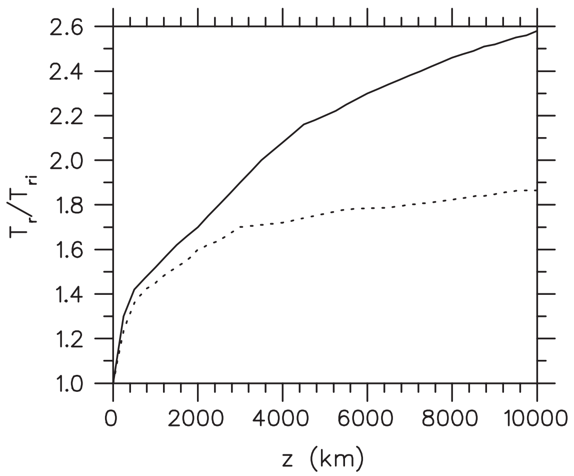

Fig. 3. Average rms pulse width T_r normalized by initial value T_{ri} along the fiber for the case of 10-ps soliton. The cases with and without amplifier noise are shown by solid and dashed lines, respectively.

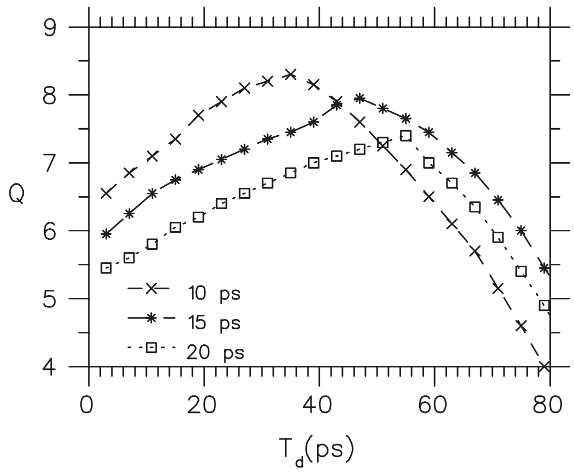

Fig. 5. Q factor versus detection window T_d for 10-Gb/s bit rate and 10 000-km transmission distance. The cases of the soliton pulse width $T_s = 10$, 15, and 20 ps are shown.

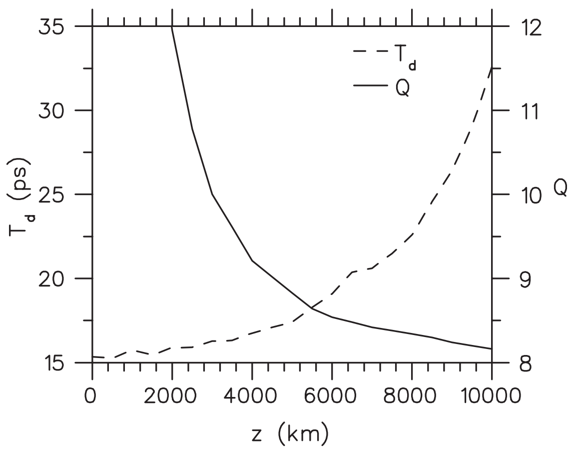

Fig. 4. Optimal detection window T_d and the corresponding Q factor for different transmission distances for the case of 10-ps soliton.

47, and 55 ps for $T_s = 10$, 15, and 20 ps, respectively. For the considered cases, the optimal T_ds are about three times of the initial pulse widths. One can see that the optimal T_f for the maximum Q factor increases with initial soliton pulse width. For a small detection window, Q factor is mainly deteriorated by 1 bits that is due to noise-induced timing jitter and soliton energy fluctuation. When T_d is much less than the pulse width, the detection method in fact becomes the sampling method in which the Q factor is calculated by sampling the signal's amplitude at bit centrum. The result shows that the sampling method is not the best detection method to obtain the maximum Q factor. For a larger detection window ($T_d > 22$ ps in the case of $T_s = 10$ ps), Q is mainly degraded by 0 bits because 0 bits contain significant dispersive waves which can be clearly observed in Fig. 1. Again, from the results shown in Fig. 5, the Q measured by sampling method are smaller than the maximum Q measured by the integration and dump method. With the integration and dump method, the maximum Q is higher for shorter initial pulse width because the signal-to-noise ratio is higher for the soliton of shorter pulse width.

In conclusion, the improvements of the Q factors of 10-Gb/s soliton systems detected by adjusting detection window are studied. The optimal detection window depends on the noise-induced timing jitter, noise-induced soliton energy fluctuation, ASE noise, dispersive wave, and soliton pulse width. The contribution of BER from 1 bits is slightly larger than 0 bits with the optimal detection window. It is found that the optimal detection window by the integration and dump method is about three times of the initial soliton pulse width for the considered cases.

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