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Multiple soliton interactions in a polarization–division multiplexing system

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Abstract

We numerically study multiple soliton interactions in a polarization–division multiplexing transmission system. It is found that, unlike the transmission system of solitons with the same polarization, the two soliton interaction is not the strongest compared to the interaction of more than two solitons. Therefore, the maximum transmission distance limited by the interaction of solitons cannot be inferred by the collision distance of two solitons in a polarization–division multiplexing system and the interactions of more solitons must be considered. © 1998 Elsevier Science B.V.

1. Introduction

The interaction of solitons is an important limitation of the bit rate–distance product in a soliton transmission system. The experiments demonstrated that the interaction between orthogonally polarized solitons is weaker than that of parallel polarized solitons [1,2]. Therefore, a way to reduce the soliton interactions and increase transmission capacity is to make the adjacent soliton orthogonally polarized, which is called the polarization–division multiplexing (PDM) technique [1–6]. Moreover, whenever two orthogonal polarized solitons at the input of a fiber transmission link may maintain a high degree of polarization throughout the whole link, even though the presence of random variations of fiber birefringence and polarization dispersion [1]. In fact, it is considered that the typical length scale where birefringence and polarization dispersion fluctuations occur is much shorter that the soliton period, so that the fluctuating local birefringence vector may be averaged over all polarization states [7,8]. The soliton interaction in a PDM system has been analyzed by the perturbation method [3–5]. On the other hand, to reduce the soliton–soliton interaction and noise-induced timing jitter in parallel polarized soliton transmission system, an the optical bandpass filter with frequency sliding is inserted after every optical amplifier [9–11]. In recent experimental and theoretical works, it has been found that the interaction between PDM solitons is also notably reduced by a sliding-frequency filter (SFF) [2,5].

In a parallel polarized soliton transmission system, the distance of soliton coalescence which is based on the interaction between two solitons is a good indication of the maximum transmission distance since two soliton interaction is stronger than more than two soliton interactions which have longer coalescence distance [12]. So far, for a PDM soliton transmission system, only two soliton interaction has been analyzed theoretically [3–5], where the maximum transmission distance of a PDM soliton system is considered by the coalescence distance of two solitons.

In this paper, we numerically analyze the interactions among multiple solitons in a PDM system. It is found that the interaction between two solitons is no longer the main limitation factor for a PDM transmission system. In the considered cases, the distance of coalescence of two solitons is shortest for four soliton interaction. If we use the SFF in the PDM system, the soliton interaction becomes

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weaker. In this case the two soliton interaction is weaker than more than two solitons. Therefore, the maximum transmission distance cannot be inferred by the coalescence distance of two solitons, and we must consider the interactions of more than two solitons.

2. Theory

The PDM soliton propagation in a random birefringent fiber can be described by the coupled averaged propagation equations (CAPE) [7,8]

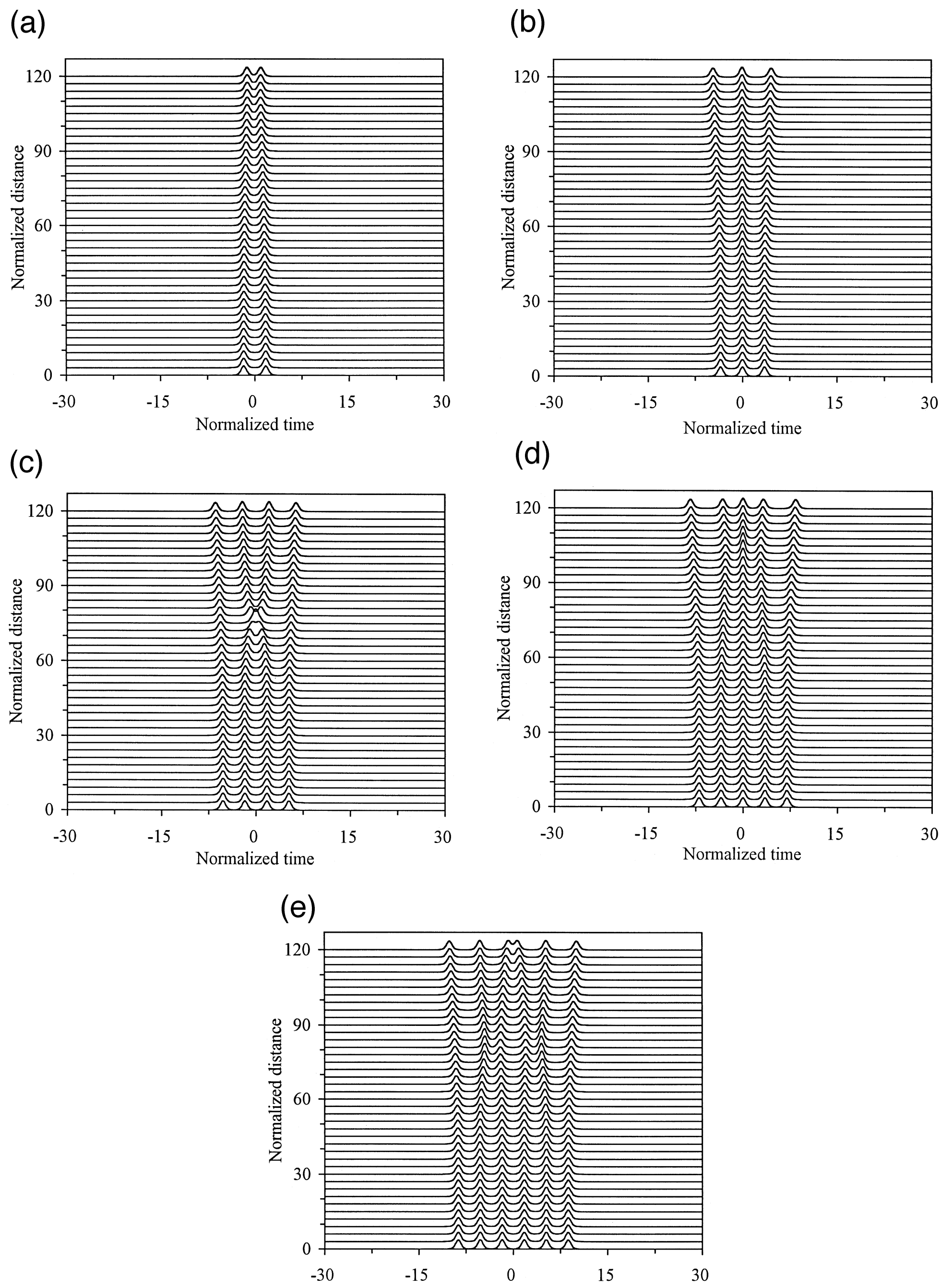

Fig. 1. Mutual interactions of multiple solitons in a PDM transmission system: (a) two soliton interaction, (b) three soliton interaction, (c) four soliton interaction, (d) five soliton interaction, and (e) six soliton interaction.

$$\mathrm{i}\frac{\partial u}{\partial Z}+\frac{1}{2}\frac{\partial^2 u}{\partial T^2}+\left(|u|^2+|v|^2\right)u=\mathrm{i}\gamma u, \tag{1a}$$

$$\mathrm{i}\frac{\partial v}{\partial Z}+\frac{1}{2}\frac{\partial^2 v}{\partial T^2}+\left(|u|^2+|v|^2\right)v=\mathrm{i}\gamma v, \tag{1b}$$

where $u=\sqrt{9/8}\,U$, $v=\sqrt{9/8}\,V$. U and V are the two polarization components of the electric field envelope normalized by the electric field scale Q, Z and T are normalized by the dispersion length L_D, and time scale T_0, respectively. Q, L_D and T_0 are related by

$$Q=\left[\frac{\lambda|\beta_2|A_{\mathrm{eff}}}{2\pi n_2 T_0^2}\right]^{1/2}, \quad L_D=\frac{T_0^2}{|\beta_2|},$$

where λ is the wavelength, β_2 is the group-velocity dispersion parameter, A_{eff} is the effective fiber cross section, and n_2 is the Kerr coefficient, $T_0=T_W/1.763$ and T_W is the full pulsewidth at half magnitude. $\gamma=\alpha L_D$ where α is the fiber loss. For a PDM soliton system, the polarizations of the neighboring solitons are orthogonal. On the other hand, the parallel polarized soliton propagation in a single mode fiber can be described by Eq. (1a) without v component.

The transfer function of the optical filter placed after every amplifier is taken as

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

where $\Omega=\omega-\omega_0$ and ω_0 is the original soliton carrier frequency, Ω_f is the center frequency of the filter, and B is the filter bandwidth. For the SFF, in dimensionless units, $\Omega_f=\alpha_0 Z$ where α_0 is the sliding rate.

3. Numerical solutions and discussion

We use the split-step Fourier method to solve Eqs. (1). The fiber loss is periodically compensated by the lumped amplifiers and the amplification period is assumed to be $0.25L_D$. The normalized filter bandwidth is taken to be $B=9$. To show multiple soliton interactions, we take a 3.5 pulse width separation between neighboring solitons to enhance the interaction. In the following discussion, the distance is normalized by L_D and the time is normalized by T_W. We have numerically simulated the propagation of multiple solitons in a parallel polarized soliton transmission system, the behaviors are similar to those shown in Ref. [12]. The two solitons coalesce at about $17L_D$, whereas, the other multiple solitons interact after this coalescence distance. Thus, the interaction between two solitons is the main limitation in a parallel polarized soliton transmission system. In Fig. 1, we show the mutual interactions of multiple solitons in a PDM soliton transmission system. Figs. 1a–1e show the power envelope $|u|^2+|v|^2$ of two solitons, three solitons, four solitons, five solitons, and six solitons, respectively. In Fig. 1a, two solitons attract each other and collide at about $112L_D$. For a larger number of solitons, the two outside solitons are repulsed at about $37L_D$. It is seen from Figs. 1 that in the case of four solitons the two pulses in the center coalesce at a distance of $75L_D$, and for the other cases the center solitons collide after this coalescence distance. The average standard deviations of the timing jitter of the solitons only caused by the soliton interactions are shown in Fig. 2. The average standard deviations of the timing jitter are calculated by the following process. We assume that there are N pulses and their initial positions are written to be P_{01}, P_{02}, ..., P_{0N}. First, we find the pulse positions P_{i1}, P_{i2}, ..., P_{iN} at some propagation distance, they are written too. Then we obtain $\Delta P_{ij}=P_{ij}-P_{0j}$ where $j=1,\dots,N$. Finally, we can obtain the average standard deviations of the timing jitter, $\overline{\Delta P_{ij}}=\sqrt{\Sigma\left[\Delta P_{ij}-\left(\Sigma\Delta P_{ij}\right)/N\right]^2/N}$. It is seen that in the case of two solitons the standard deviation gradually increases until the collision distance, and in the cases of larger number of solitons initially the pulses maintain their relative positions, then the standard deviations greatly increase after the distance $50L_D$. The standard deviation of the four solitons is larger than that of the other cases after the distance $59L_D$ and is found to be maximum at about $75L_D$ where the center solitons coalesce. Therefore, the maximum transmission distance can not be inferred by the collision of two solitons in a PDM soliton transmission system.

In Fig. 3, we show the mutual interactions of multiple solitons in a PDM soliton transmission system with up-sliding-frequency filters. Here, we use a up-sliding-

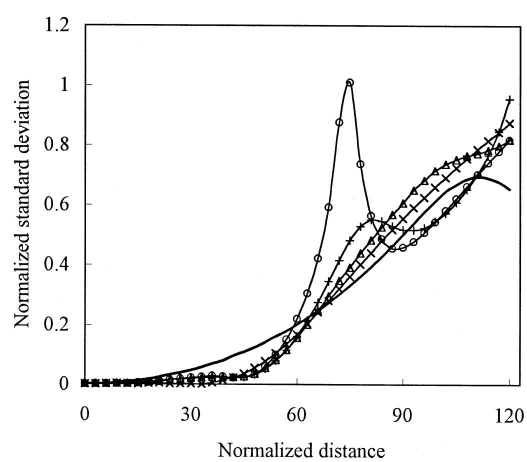

Fig. 2. Evolutions of the standard deviations of the timing jitters of the solitons for different soliton interaction. (————) Two soliton interaction, (– ∗ –) three soliton interaction, (– ∘ –) four soliton interaction, (– △ –) five soliton interaction, and (– + –) six soliton interaction.

frequency filter with a normalized sliding rate of 0.03 to reduce the soliton interaction [9]. It can be seen from Fig. 3 that the solitons maintain well up to $180 L_D$ for the two solitons case, but for the other cases the solitons collide before that distance. In the considered cases, the coalescence distance of five solitons is the shortest, about $160 L_D$. Fig. 4 shows the standard deviations of the solitons considered in Fig. 3. One can be see that the standard deviation of the two solitons is smaller than that of more than two solitons. Therefore, the allowed transmission distance for a PDM transmission system should be much shorter than the distance expected from the interaction of two solitons in a communication system.

For a numerical example in terms of real units, we take

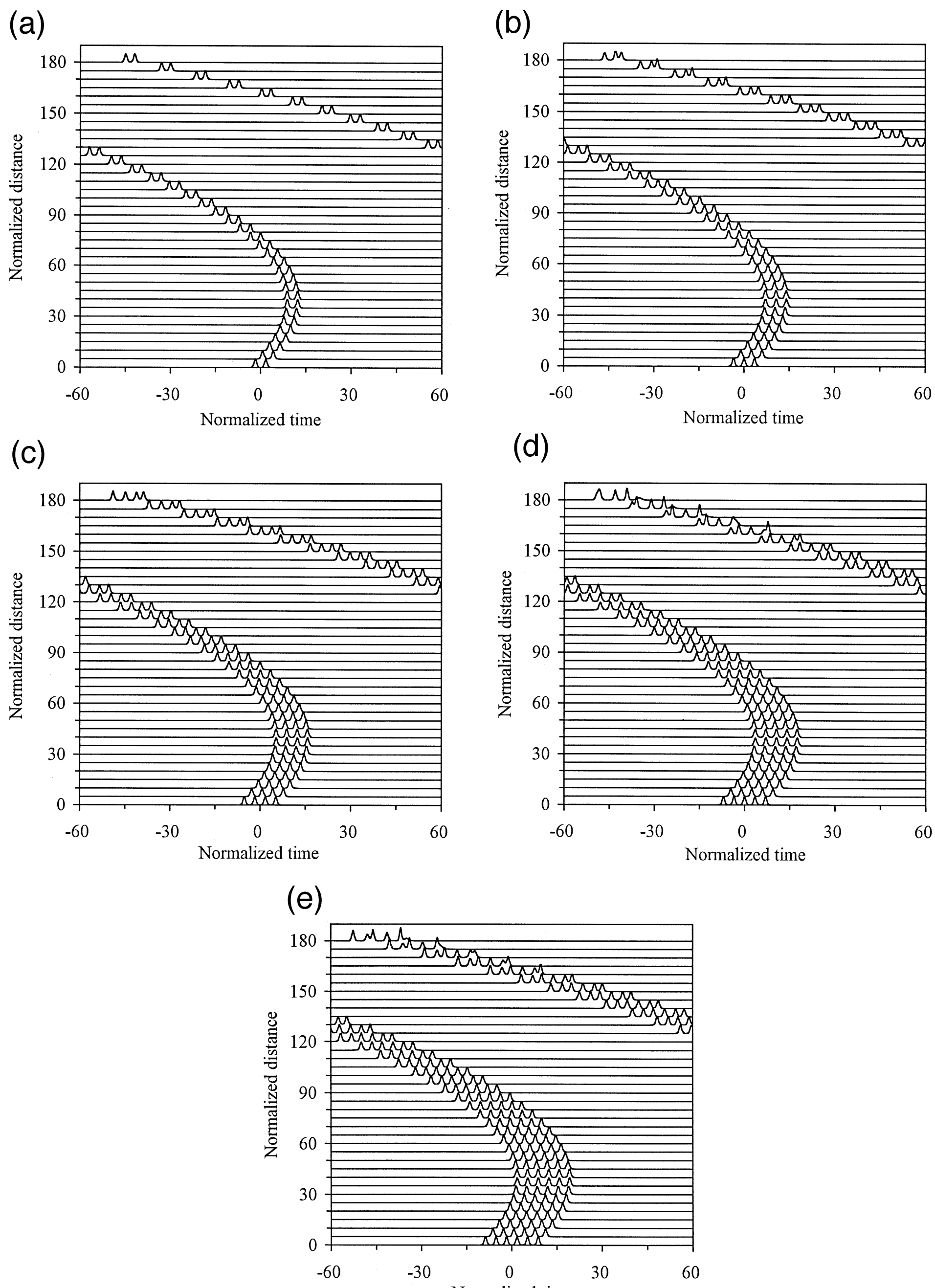

Fig. 3. Same as in Fig. 1, with up-sliding-frequency filters.

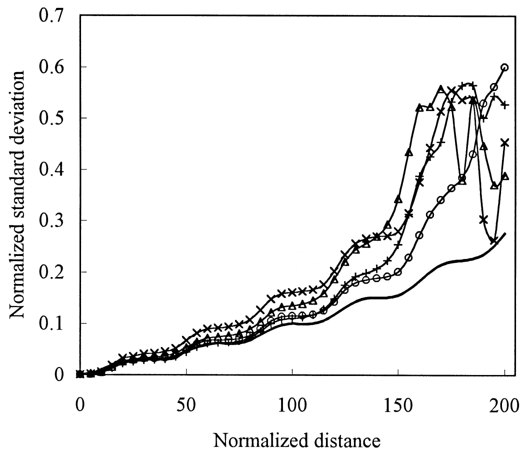

Fig. 4. Same as in Fig. 2, with up-sliding-frequency filters.

$T_W = 12$ ps and $\beta_2 = -0.382$ ps^2/km ($D = 0.3$ ps/km/nm). When sliding-frequency filters are not used, the isolated two adjacent solitons collide at about 13.5 Mm, and in the case of four solitons the two central pulses coalesce at a distance of about 9 Mm. When up-sliding-frequency filters are used, the shortest coalescence distance found in the case of four solitons is about 19.4 Mm.

4. Conclusion

In conclusion, we numerically study the interactions of multiple solitons in a PDM transmission system. It is found that, unlike the parallel polarized soliton transmission system, the two soliton interaction is not the strongest compared to the interaction of more than two solitons. In fact, when sliding-frequency-filters are used in a PDM system, the two soliton interaction has the least standard deviation of timing jitters. Therefore, the maximum transmission distance limited by the interaction of solitons can not be inferred by the collision distance of two solitons in a PDM system, and the interactions of more solitons must be considered.

Acknowledgements

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