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1998 J. Opt. 29 278

(http://iopscience.iop.org/0150-536X/29/4/006)

J. Opt. **29** (1998) 278–281. Printed in the UK PII: S0150-536X(98)93172-0

Modelling of a polarization-division multiplexing soliton transmission system

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Received 31 December 1997, accepted 6 April 1998

Abstract. We have simulated numerically a polarization-division multiplexing soliton transmission system by using propagation equations with and without the third-order dispersion and Raman shift terms, respectively. It is found that the Raman shift terms can reduce the soliton interactions and hence the allowed transmission distance increases.

Keywords: Soliton transmission, polarization-division multiplexing

Modèle de transmission soliton par multiplexage à division de la polarisation

Résumé. Nous avons simulé numériquement un système de transmission soliton par multiplexage à division de la polarisation en utilisant des équations de propagation avec et sans terme dispersifs du troisième ordre ou terme de décalage Raman.

Nous montrons que les termes d'effet Raman peuvent réduire les interactions entre solitons et donc augmenter la distance de transmission.

Mots clés: Transmission soliton, multiplexage à division de polarisation

1. Introduction

In optical soliton communication systems using optical amplifiers to compensate for fibre loss, the transmission bit-rate–distance product is limited by the soliton interaction [1] and the timing jitter arising from noise introduced by the optical amplifiers [2], from the acoustic interaction among the solitons [3] and from the polarization dispersion [4]. A method to reduce the soliton interaction is provided by polarization-division multiplexing (PDM), for which the adjacent solitons are orthogonally polarized [5–9]. It was demonstrated that the interaction of orthogonally polarized solitons was weaker than that of parallelly polarized solitons [5]. An analytical description of the orthogonally polarized soliton interaction was found using the perturbation method, which neglected the effects of third-order dispersion and Raman shift [6–8]. The modified coupled averaged propagation equations which describe the soliton propagation including the effects of the third-order dispersion and Raman shift in a PDM transmission system have been derived [8]. In recent theoretical and experimental works, it was found that the interaction of the orthogonally polarized solitons could also be reduced by a sliding-frequency filter (SFF) as the interaction of the parallelly polarized solitons [9, 10].

In this paper, we will study numerically the interactions of the orthogonally polarized solitons and the allowed transmission distance in a PDM system by using propagation equations with and without the third-order dispersion and Raman shift terms, respectively. We will also show that the soliton interactions are reduced and the allowed transmission distance increases when the Raman shift terms are included, and the third-order dispersion term has negligible effect. Therefore, for ultra-high capacity of the PDM soliton transmission system, the Raman shift terms must be included. On the other hand, we will show that these terms have little effect on the soliton interactions and the allowed transmission distance in the parallelly polarized soliton system.

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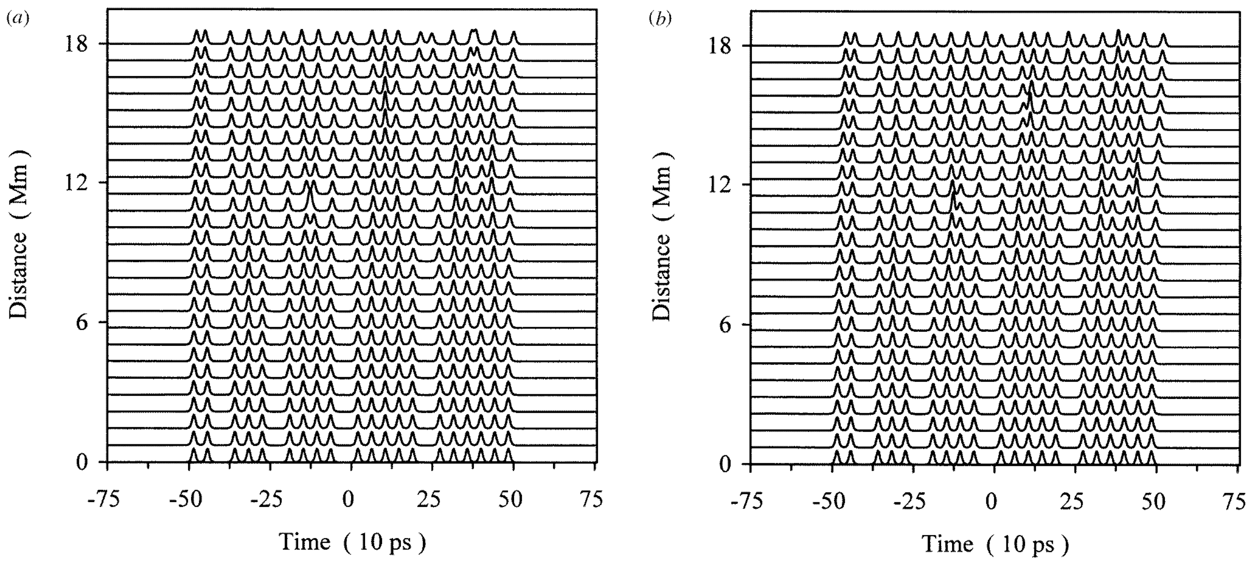

Figure 1. Power evolution of a soliton bitstream along the fibre in a PDM soliton transmission system without the SFF: (*a*) when the third-order dispersion and Raman shift terms are not included and (*b*) when the third-order dispersion and Raman shift terms are included.

2. The modified propagation equations

Soliton propagation in single-mode fibre with random birefringence can be described by the modified coupled averaged propagation equations [8]

$$\begin{aligned} &\mathrm{i}\frac{\partial u}{\partial z} + \frac{1}{2}\frac{\partial^2 u}{\partial T^2} - \mathrm{i}\frac{C_3}{6}\frac{\partial^3 u}{\partial T^3} + \left(|u|^2 + |v|^2\right)u \\ &\quad - \tau_{\mathrm{R}} u \frac{\partial}{\partial T}|u|^2 - \frac{1}{2}\tau_{\mathrm{R}} u \frac{\partial}{\partial T}|v|^2 \\ &\quad - \frac{1}{2}\tau_{\mathrm{R}} v \frac{\partial}{\partial T}(v^* u) = \mathrm{i}\gamma u \qquad (1a) \end{aligned}$$

$$\begin{aligned} &\mathrm{i}\frac{\partial v}{\partial z} + \frac{1}{2}\frac{\partial^2 v}{\partial T^2} - \mathrm{i}\frac{C_3}{6}\frac{\partial^3 v}{\partial T^3} + \left(|u|^2 + |v|^2\right)v \\ &\quad - \tau_{\mathrm{R}} v \frac{\partial}{\partial T}|v|^2 - \frac{1}{2}\tau_{\mathrm{R}} v \frac{\partial}{\partial T}|u|^2 \\ &\quad - \frac{1}{2}\tau_{\mathrm{R}} u \frac{\partial}{\partial T}(u^* v) = \mathrm{i}\gamma v \qquad (1b) \end{aligned}$$

where u and v are 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

$$Q = \left[\frac{9}{8}\frac{\lambda|\beta_2|A_{\mathrm{eff}}}{2\pi n_2 T_0^2}\right]^{1/2} \qquad L_{\mathrm{D}} = \frac{T_0^2}{|\beta_2|}$$

where λ is the wavelength, β_2 is the second-order dispersion, A_{eff} is the effective fibre cross section area and n_2 is the Kerr coefficient. $T_0 = T_{\mathrm{W}}/1.763$, where T_{W} is the initial full pulse width at half magnitude. The coefficients in equations (1) are

$$C_3 = \frac{\beta_3 L_{\mathrm{D}}}{T_0^3} \qquad \tau_{\mathrm{R}} = \frac{T_{\mathrm{R}}}{T_0} \qquad \gamma = \alpha L_{\mathrm{D}}$$

where β_3 is the third-order dispersion, α is the fibre loss, T_{R} is the slope of the Raman gain profile at the carrier frequency. The last three terms on the left-hand side of equations (1) describe the averaged Raman effect, in which the first term is the self-frequency shift term, and the other two are the cross-frequency shift terms. The parallelly polarized soliton propagation in a single-mode fibre can be described by equation (1*a*) without a v component or equation (1*b*) without a u component. The transfer function of the optical filter placed after every amplifier is taken as

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

where $\Omega = \omega - \omega_0$ and ω_0 is the input soliton carrier frequency, Ω_f is the centre frequency of the filter and B is the filter bandwidth.

3. Numerical results

The typical fibre parameters for solving equations (1) are: soliton wavelength $\lambda = 1.55$ μm, $\beta_2 = -0.32$ ps^2 km^{-1} ($D = 0.25$ ps km^{-1} nm^{-1}), $\beta_3 = 0.1$ ps^3 km^{-1}, $\alpha = 0.21$ dB km^{-1}, $n_2 = 2.3 \times 10^{-20}$ m^2 W^{-1}, $T_{\mathrm{R}} = 3$ fs and $A_{\mathrm{eff}} = 50$ μm^2. The fibre loss is periodically compensated by the optical amplifiers with 30 km spacing. We consider the soliton pulsewidth $T_{\mathrm{W}} = 12$ ps. To show the multiple soliton interactions, we consider the soliton trains with pattern ⟨00110111011110111110111111100⟩ and take a 3.5 pulse width separation between the neighbouring solitons. The corresponding bit rate is 23.8 Gbits s^{-1}. To reduce the soliton interaction and timing jitter, we insert the up-sliding filter after every optical amplifier. For the maximum transmission distance, the bandwidths of the filters and the sliding rate are taken to be 190 GHz and 4 GHz Mm^{-1} in a PDM soliton transmission system, and 225 GHz and 8 GHz Mm^{-1} in a parallelly polarized soliton transmission system, respectively.

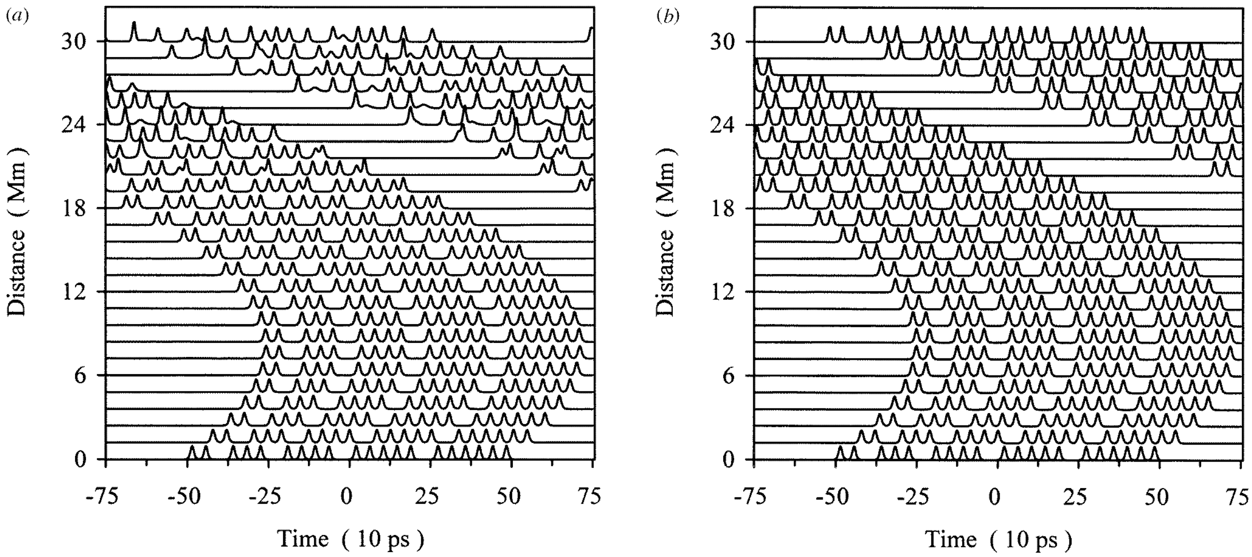

Figure 2. Power evolution of a soliton bitstream along the fibre in a PDM soliton transmission system with the SFF: (*a*) when the third-order dispersion and Raman shift terms are not included and (*b*) when the third-order dispersion and Raman shift terms are included.

Figures 1(*a*) and (*b*) show the power evolution $|u|^2 + |v|^2$ of a soliton bitstream in a PDM soliton transmission system when the third-order dispersion and Raman shift terms are not and are included, respectively. It is seen in figure 1(*a*) that the two central solitons in bit patterns (011110) coalesce at a distance of 11 Mm. In figure 1(*b*), the same solitons get close at 11 Mm but do not coalesce. Therefore, the interactions of PDM solitons are weaker when the third-order dispersion and Raman shift terms are considered. Figure 2 shows the same evolution as in figure 1 except that a SFF is placed after each amplifier. We can see from figure 2(*a*) that the solitons in the bit patterns (011110) and (0111110) coalesce around 21 Mm. In figure 2(*b*), it is seen that the separations of the solitons are well maintained even up to a distance of 30 Mm. As the numerical results obtained with $\beta_3 = 0$ are almost identical to those shown in figures 1(*b*) and 2(*b*), the reduction of the soliton interaction is mainly due to the Raman shift terms. Therefore, when the SFF is used, the interactions of PDM solitons are greatly reduced, and the interactions are much weaker when the Raman shift terms are considered.

In a soliton communication system using optical amplifiers to compensate for the fibre loss, noise will be introduced. The noise randomly modulates the soliton carrier frequency and causes the timing jitter of the system. The noise-induced timing jitter will influence the soliton interaction and complicate the problem. In addition, the acoustic interaction among the solitons and the polarization dispersion also induce timing jitters. Thus, the total standard deviation of timing jitter can be written as [9]

$$\sigma = \left(\sigma_c^2 + \sigma_a^2 + \sigma_p^2\right)^{1/2} \qquad (3)$$

where $\sigma_c, \sigma_a, \sigma_p$ represent the standard deviation in picoseconds of the combined soliton interaction and noise-induced jitter, the acoustic-interaction-induced jitter and the polarization-dispersion-induced jitter, respectively. σ_a can be estimated by [3]

$$\sigma_a = 140 A_{eff}^{-3/4} \frac{D^2}{T_W} \gamma^{-1} z \left(\frac{R}{1-r} - \frac{9.33}{A_{eff}^{1/2}}\right)^{1/2} \qquad (4)$$

where D is the group-delay dispersion in ps km^{-1} nm^{-1}, T_W is the FWHM pulsewidth in ps, A_{eff} is the effective fibre cross section in μm^2, r is the intensity reflection coefficient of sound from the cladding–coating boundary, R is the bit rate in Gbits s^{-1}, z is total path in Mm and γ^{-1} is the damping length in Mm. In addition, σ_p can be estimated by [4]

$$\sigma_p = \left[\frac{\pi}{16} \frac{(G-1) n_{sp} h\nu}{W_{sol}} \frac{D_p^2 z^2}{L_{amp}}\right]^{1/2} \qquad (5)$$

where G is the amplifier power gain, n_{sp} is the spontaneous emission factor of an amplifier, W_{sol} is the soliton pulse energy at an amplifier output, D_p is the fibre polarization dispersion parameter and L_{amp} is amplifier spacing. In our system the other parameters are taken as $r = 0.25$, $R = 23.8$ Gbits s^{-1}, $\gamma^{-1} = 0.37$ Mm, $G = 4$, $n_{sp} = 1.2$, $h\nu / W_{sol} = 2 \times 10^{-6}$ and $D_p = 0.1$ ps km$^{-1/2}$, we obtain $\sigma_a = 0.8$ ps and $\sigma_p = 0.23$ ps at $z = 10$ Mm.

We calculate the standard deviation by simulating the transmission of 512 pseudorandom bits. Figure 3 shows the evolutions of the standard deviation of the timing jitters of solitons in a PDM soliton system and a parallelly polarized soliton system when the third-order dispersion and Raman shift terms are and are not considered, respectively. It is seen that the difference caused by these terms is very little for the parallelly polarized soliton system and is substantial for the PDM soliton system. In our case, the allowed 10^{-9} bit error rate corresponds to a 2.3 ps standard deviation of the timing jitter. The allowed transmission distance for the PDM soliton system is 12.8 Mm and 11 Mm when the

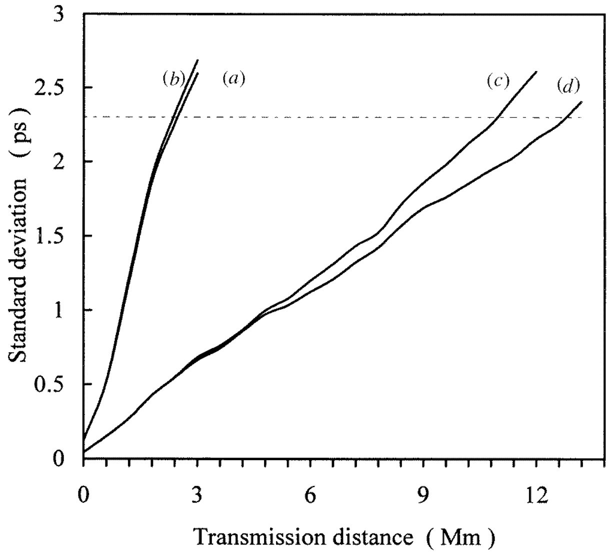

Figure 3. Evolutions of the standard deviation of the timing jitter of solitons. Curves (*a*) and (*b*) are the evolutions when the third-order dispersion and Raman shift terms are not and are included in a parallelly polarized soliton transmission system, respectively. Curves (*c*) and (*d*) are the evolutions when the third-order dispersion and Raman shift terms are not and are included in a PDM soliton transmission system, respectively.

third-order dispersion and Raman shift terms are and are not considered, respectively. Furthermore, it is found that the allowed transmission distance is almost identical with and without the third-order dispersion. Therefore, for the increment of the allowed transmission distance the effect of the Raman shift terms is mainly due to the Raman-shift terms. On the other hand, the allowed transmission distance for the parallelly polarized solitons system is only around 2.4 Mm.

4. Conclusion

In conclusion, we have simulated numerically the interactions of the orthogonally polarized solitons and the allowed transmission distance in a PDM transmission system by using propagation equations with and without the third-order dispersion and Raman shift terms, respectively. It is found that the soliton interactions are reduced and the allowed transmission distance increases when the Raman shift terms are included, and the third-order dispersion term has a negligible effect. Therefore, for ultra-high capacity PDM soliton transmission systems, the Raman shift terms must be included. We have also simulated the parallelly polarized soliton system with the same system parameters, and it is found that the allowed transmission distance is much shorter than the PDM system.

Acknowledgment

This work is partially supported by National Science Council, Republic of China, under contract no NSC 86-2811-E009-002R.

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