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INFLUENCE OF EVEN ORDER DISPERSION ON SOLITON TRANSMISSION QUALITY WITH COHERENT INTERFERENCE

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Abstract—The transmission speed of optical networks strongly depends on the impact of higher order dispersion. In the presence of coherent interference which can't be kept under control by optical filtering, the impact of higher order dispersion becomes more serious. In this paper we give general expressions that describe pulse deformation due to even higher order dispersion in a single-mode fiber. The impulsive responses for even order dispersion in the presence of coherent interference are characterized by symmetrical waveforms with long trailing skirts. Individual and joint influence of second and fourth order dispersion on the transmission quality is studied. Pulse shape and eye diagram are obtained.

1. INTRODUCTION

Intramodal or chromatic dispersion may occur in all types of the optical fiber and origins from the finite spectral linewidth of the optical source [1–13]. It causes broadening of each transmitted mode (LP_{01} in single-mode fiber), i.e., induces effect known as intersymbol interference (ISI). Therefore, chromatic dispersion is one of the main factors that limit the transmission length and transmission speed in optical telecommunication systems that use single-mode fiber.

The strong harmful influence of second order dispersion is well known in literature [1]. This was reason for investigating new methods and new technologies that could reduce and undo degrading influence of second order of dispersion. Some of them are: dispersion shifted fiber (DSF), dispersion flattened fiber (DFF), dispersion compensating fiber (DCF), dispersion-managed optical fiber, temporal optical conjugation (TOC), etc. In the optical transmission system with bit rate higher than hundreds of Mb/s, influence of fourth order dispersion on pulse propagation must not be neglected [2–4]. In some cases it is necessary to investigate the joint influence of both above mentioned order of dispersion on transmission quality of signal.

Incoherent (outband crosstalk) and coherent interferences (inband crosstalk and reflected signal) are another limiting factor in optical telecommunication systems [5]. Incoherent interference can in most cases be kept under control with optical filtering at the receiver. Coherent interference [6–8] is more problematic than incoherent interference because it can not be controlled on this way and its influence on pulse propagation along the optical fiber under chromatic dispersion (second or fourth order) is investigated in this paper.

Until now, we used numerical "split-step" Fourier method for solving nonlinear Schrödinger equation under the influence of coherent interference on pulse propagation [9, 10]. For the linear single mode fiber we are allowed to use analytical expressions. In this paper we consider the worst case of interference influence on sech pulse propagation along the linear single mode fiber.

2. THEORY

Ultrashort pulses from lasers often have a temporal shape that can be described with Sech function [2, 3]. Such optical pulse is given by:

$$s(t) = \sqrt{P_0}\,\mathrm{Sech}\left(\frac{t}{T_0}\right)\cdot e^{j\omega_o t} \tag{1}$$

where ω_0 is optical carrier frequency, P_0 is optical pulse peak power and T_0 is pulse width.

Coherent interference is at the same frequency as useful signal but it can be time and phase shifted in regard to useful signal. Such model of coherent interference can be written as:

$$s_i(t) = \sqrt{P_i}\,\mathrm{Sech}\left(\frac{t}{T_0} - b'\right)\cdot e^{j(\omega_o t+\varphi)} \tag{2}$$

where P_i is interference peak power and b ($b = b'T_0$) is time shift of interference. The value of time shift (propagation delay) depends on the nature of coherent interference (inband crosstalk or multipath reflection) [6–8, 12–15]. The phase shift φ varies in random way due to temperature variation and wavelength variation in the range of $(0-\pi)$ [13]. The envelope and phase of resulting signal $s_r(t)$ are:

$$|s_r(t)| = \sqrt{\left(\sqrt{P_0}\mathrm{Sech}\left(\frac{t}{T_0}\right)\right)^2 + 2\sqrt{P_0}\mathrm{Sech}\left(\frac{t}{T_0}\right)\sqrt{P_i}\mathrm{Sech}\left(\frac{t}{T_0}-b'\right)\cos\varphi + \left(\sqrt{P_i}\mathrm{Sech}\left(\frac{t}{T_0}-b'\right)\right)^2} \tag{3}$$

$$\psi(t) = \mathrm{arctg}\frac{\sqrt{P_i}\mathrm{Sech}\left(\frac{t}{T_0}-b'\right)\sin\varphi}{\sqrt{P_0}\mathrm{Sech}\left(\frac{t}{T_0}\right) + \sqrt{P_i}\mathrm{Sech}\left(\frac{t}{T_0}-b'\right)\cos\varphi} \tag{4}$$

A general expression of fiber response $r(t, L)$ for an arbitrary input pulse is [1]:

$$r(t, L) = \frac{1}{2\pi}e^{-\alpha L}e^{j(\omega_0 t-\beta_0 L)}\int_{-\infty}^{\infty}F(\omega)e^{j\left(\omega t-\omega\beta_1 L-\frac{1}{2!}\beta_2 L\omega^2-\frac{1}{3!}\beta_3 L\omega^3-\ldots\right)}d\omega \tag{5}$$

$F(\omega)$ is Fourier transform of input pulse. According to the interference phase shift value, coherent interference can be constructive or destructive. If we consider the worst case, i.e., the destructive coherent interference and assume that it appears at the beginning of the optical fiber (e.g., double reflection [8, 13, 14] or inband crosstalk resulting of WDM components used for routing and switching along the optical network [6]), the receiver pulse shape under the influence of second or fourth order dispersion is:

$$\begin{aligned} r_{2,4}(t, L) &= \frac{\sqrt{P_0}T_0}{2}e^{-\alpha L}e^{j(\omega_0 t-\beta_0 L+\theta(t))}\sqrt{I_1^2(t)+I_2^2(t)} \\ \theta(\tau) &= \mathrm{arctg}\frac{I_2(\tau)}{I_1(\tau)} \end{aligned} \tag{6}$$

with

$$I_1(t) = \int_{-\infty}^{\infty} \mathrm{Sech}\left(\frac{\pi T_0 \omega}{2}\right) \left[\left(1 - \sqrt{\frac{P_i}{P_0}} \cos\left(b' T_0 \omega\right)\right) \cos\left(\omega t - b_2 \omega^2 - b_4 \omega^4\right) \right.$$
$$\left. - \sqrt{\frac{P_i}{P_0}} \sin\left(b' T_0 \omega\right) \sin\left(\omega t - b_2 \omega^2 - b_4 \omega^4\right) \right] d\omega \quad (7)$$

$$I_2(t) = \int_{-\infty}^{\infty} \mathrm{Sech}\left(\frac{\pi T_0 \omega}{2}\right) \left[\left(1 - \sqrt{\frac{P_i}{P_0}} \cos\left(b' T_0 \omega\right)\right) \sin\left(\omega t - b_2 \omega^2 - b_4 \omega^4\right) \right.$$
$$\left. + \sqrt{\frac{P_i}{P_0}} \sin\left(b' T_0 \omega\right) \cos\left(\omega t - b_2 \omega^2 - b_4 \omega^4\right) \right] d\omega \quad (8)$$

where

$$b_2 = \left(\frac{\beta_2 L}{2!}\right)$$
$$b_4 = \left(\frac{\beta_4 L}{4!}\right) \quad (9)$$

If we consider only the influence of second, i.e., fourth order dispersion, in Equations (6)–(9) we should substitute $b_4 = 0$, i.e., $b_2 = 0$ respectively.

3. THE INFLUENCE OF SECOND AND FOURTH ORDER DISPERSION ON PULSE PROPAGATION — NUMERICAL RESULTS

Binary data sequences with values 0 and 1 are transmitted along the optical fiber. For no overlapping of light pulses down on an optical fiber link the digital bit rate (B) must be less than the reciprocal of the broadened (through certain order of dispersion) pulse duration. In the following figures (Figs. 1, 2 and 3) we consider such cases. Depending on the value of interference time shift, coherent interference can be left ($b < 0$) or right ($b > 0$) shifted in regard to center of data in binary sequences. In all figures in the paper fiber length is expressed via dispersion length which is for n-th order dispersion given by:

$$L_D = \frac{(T_0')^n}{|\beta_n|} \quad (10)$$

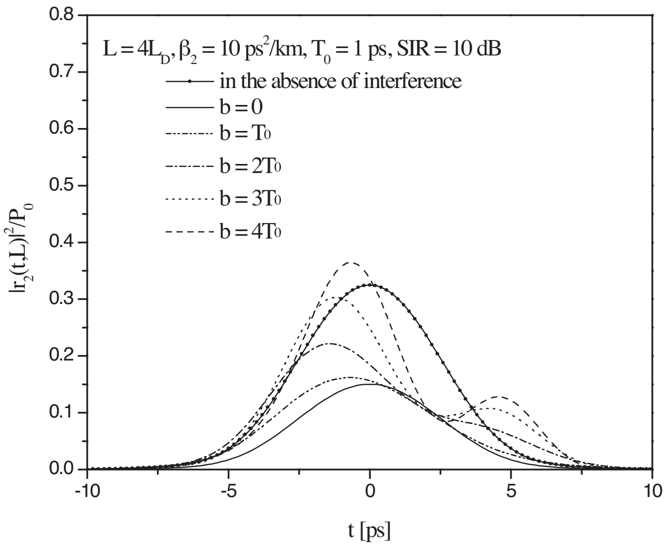


Figure 1. Pulse shape at the end of the optical fiber ($L = 4L_D$) under second order dispersion for SIR = 10 dB and different time shifts $b > 0$.

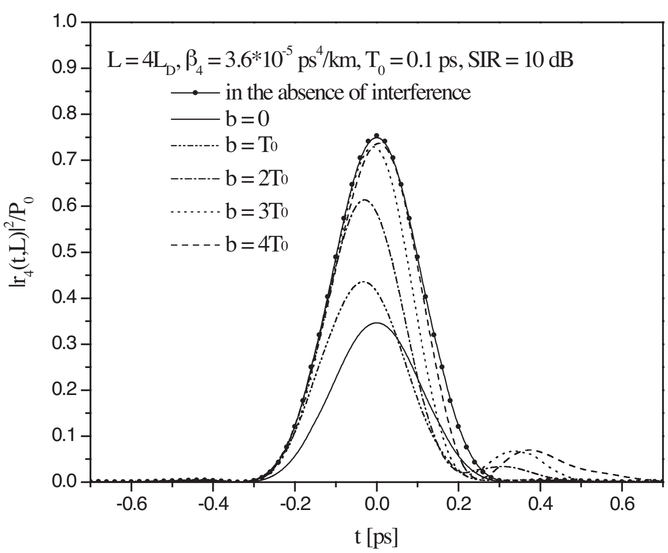


Figure 2. Pulse shape at the end of the optical fiber ($L = 4L_D$) under fourth order dispersion for SIR = 10 dB and different time shifts $b > 0$.

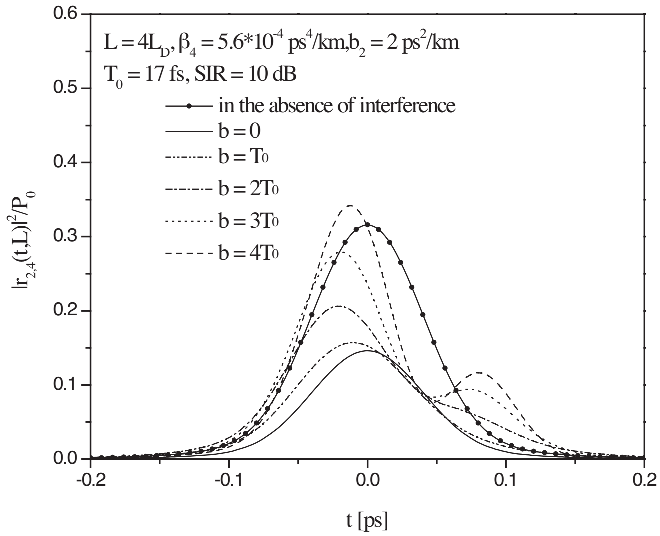


Figure 3. Pulse shape at the end of the optical fiber ($L = 4L_D$) under second and fourth order dispersion for SIR = 10 dB and different time shifts $b > 0$.

Second order dispersion induces symmetrical broadening of pulse and there is no need to investigate influence of both $b > 0$ and $b < 0$. Fig. 1 shows the strong influence of interference even for $b > T_0$. Great time shift of interference induces the asymmetrical pulse deformation and occurrence of trailing skirts. Long trailing skirts may give rise to intersymbol interference (ISI) and thus limit the transmission length. Because of both the noisy nature of the input to clock-recovery circuit and noise produced by optical amplifiers, timing jitter can also be produced. Then previously mentioned asymmetrical pulse deformation may be dangerous. The worst case in detection process happens for $b = 0$. This situation is very often in switching systems [5, 7]. The eye diagram for the worst case is depicted on Fig. 4.

If we employ one of the methods that compensate for degrading influence of second and third order dispersion, fourth order dispersion will have the great influence on pulse shape. Fourth order dispersion distorts the pulse shape symmetrically around zero and result responses have also long trailing skirts just like for the second order dispersion. Because of symmetrical deformation of pulse induced by fourth order dispersion (oscillation on the trailing edge) the biggest error in the detection process will appear for zero interference time shift. Great absolute values of time shift increase ISI if B is enough big to induce

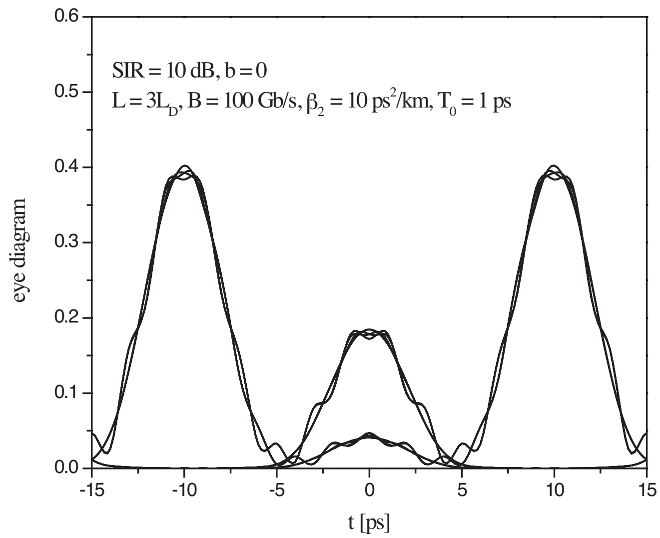


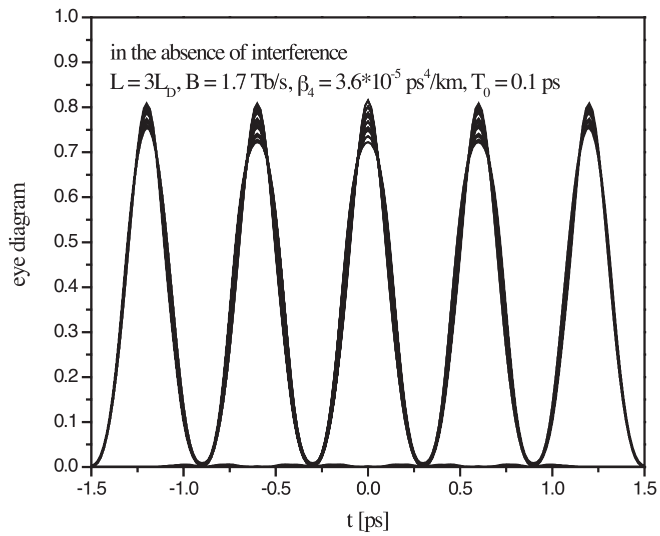
Figure 4. Eye diagram for individual influence of second order dispersion in the presence of worst case interference.

sizeable overlapping of pulses. Fig. 5 shows eye diagram for both in absence of interference and in the presence of the most destructive (harmful) interference.

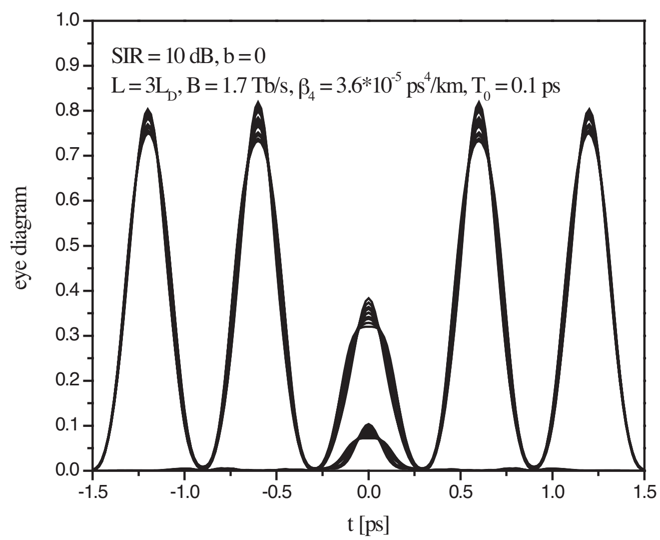
Figures 3 and 6 show joint influence of the second and fourth order dispersion. Sech pulse at the receiver (Fig. 3) is broadened by second and fourth order dispersion interplay and it has a long trailing edge as a result of interference. Results presented on Fig. 3 testify no time shifted interference is the most dangerous for pulse propagation along the fiber. Eye diagram for this case is shown on Fig. 6.

4. CONCLUSION

Chromatic dispersion is the phenomenon in the optical telecommunication system whose influence on pulse propagation should not be neglected. In this paper we derived analytical expressions that describe pulse shape in the presence of coherent interference along the fiber under individual or joint influence second and fourth order dispersion. Coherent interference is considered, since it is the most significant limitation to the performance of optical systems, among the various crosstalk and reflected signal contributions.



(a)



(b)

Figure 5. Eye diagram for individual influence of fourth order dispersion ($L = 3L_D$): (a) in absence of interference; (b) in the presence of worst case interference.

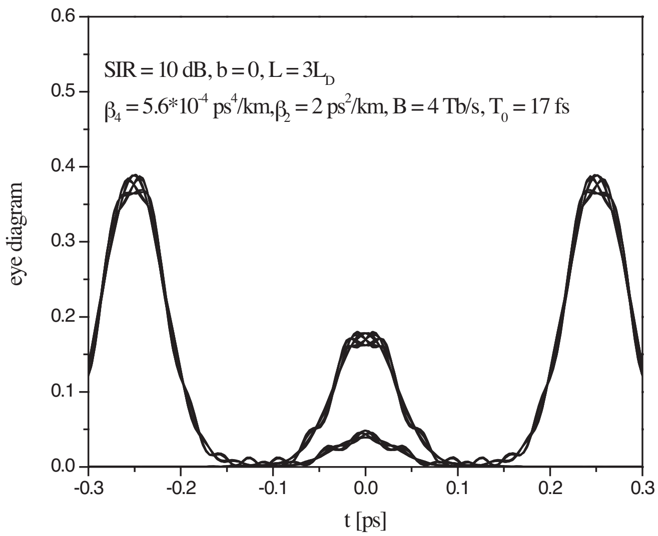


Figure 6. Eye diagram for joint influence of second and fourth order dispersion ($L = 3L_D$ in the presence of worst case interference.

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