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The Common Influence of Time Shift and Appearing Place of Interference on Signal Propagation along Optical Fiber

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Introduction

Chromatic dispersion results from refractive index and mode propagation constant frequency dependence appearing into both linear and nonlinear optical fiber. Chromatic dispersion leads to pulse deformity, i.e. pulse broadening when it propagates along an optical fiber. Dispersion coefficient, parameter β_2, shows the magnitude of the dispersion and defines dispersive regime of an optical fiber. When $\beta_2>0$, an optical fiber works under the normal dispersive regime. However, when $\beta_2<0$, we say that an optical fiber is exposed to anomalous dispersion [1].

Refractive index depends on the intensity of pulse that propagates along optical fiber and that dependence causes the appearance of nonlinear effects, so-called Kerr's nonlinearity, in optical fiber. If signal propagates along optical telecommunication system at high data rate and at long distance, the influence of nonlinear effects should be taken into consideration because signal intensity is big enough not to allow for the disregard of the intensity dependence of refractive index. These effects can decrease the influence of dispersive effects under anomalous dispersive regime of optical fiber, which is shown in this paper by determining pulse shape along optical fiber, solving Schrödinger equation by symmetrical split-step Fourier method [1].

Interference, one kind of disturbance that appears in optical telecommunication system [2]-[3], can be inband or outband, i.e. it can be of the same or of different frequency in relation to a useful signal. Since inband interference cannot be eliminated by optical filtering in a receiver, it is considered the more important of the two and is, therefore, discussed in the paper.

Nonlinear Schrödinger equation

Pulse propagation along a nonlinear-dispersive optical fiber can be described by the equation [1]:

$$\frac{\partial A}{\partial z}+\beta_1\frac{\partial A}{\partial t}+\frac{i}{2}\beta_2\frac{\partial^2 A}{\partial t^2}+\frac{\alpha}{2}A=i\gamma|A|^2A, \qquad (1)$$

where A is slowly varying amplitude of pulse, α is optical losses, $\beta_1=\left.\frac{\partial\beta}{\partial\omega}\right|_{\omega=\omega_0}=\frac{1}{v_g}, \beta_2=\left.\frac{\partial^2\beta}{\partial\omega^2}\right|_{\omega=\omega_0}$, β is a mode-propagation constant, v_g is group velocity and γ is a nonlinearity coefficient that is defined as:

$$\gamma=2\pi n_2/(\lambda A_{eff}), \qquad (2)$$

n_2 is a nonlinear index coefficient, λ is the wavelength of a signal and A_{eff} is an effective core area. If we introduce the following normalization:

$$\tau=\frac{T}{T_0}=\frac{t-\beta_1 z}{T_0},\ U=\frac{A}{\sqrt{P_0}}; \qquad (3)$$

where T_0 is half-width, i.e. the time when the signal power declines to $1/e$ of its top value, P_0 is the peak power of a useful signal, we can introduce the following changes [1]:

$$L_D=\frac{T_0^2}{|\beta_2|},\ L_{NL}=(\gamma P_0)^{-1}; \qquad (4)$$

where L_D is dispersive length and L_{NL} is nonlinear length, then (1) becomes:

$$\frac{\partial U}{\partial z}=-i\frac{\operatorname{sgn}(\beta_2)}{2L_D}\frac{\partial^2 U}{\partial\tau^2}+\frac{i}{L_{NL}}|U|^2U. \qquad (5)$$

Optical losses are neglected in (5), i.e. $\alpha=0$, because they are very small for $\lambda=1.55$ μm [1]. Equation (5) is a well-known nonlinear Schrödinger equation. Despite the fact that there are many methods to solve this equation, symmetrical split-step Fourier method is used in this paper because of the fact that it is a very fast and very accurate method [1].

The parameter that defines working regime of an optical fiber is:

$$N^2 = L_D / L_{NL} = \gamma P_0 \, T_0^2 \big/ |\beta_2| . \qquad (6)$$

When $N^2 << 1$, dispersive effects dominate an optical fiber. In case of $N^2 \approx 1$, dispersive and nonlinear effects establish a mutual balance [1].

Signal propagation along optical fiber in the presence of interferences

A signal that has got Gaussian envelope is very often found as a useful signal in optical telecommunication systems and it can be written as [1], [4]-[5]:

$$U(0,\tau) = a \exp(-\tau^2/2) , \qquad (7)$$

where the value of parameter a depends on the transmitted information (1 or 0). A useful signal at the beginning of optical fiber is:

$$s(0,\tau) = U(0,\tau) \cos \omega_r \tau , \qquad (8)$$

$\omega_r = \omega T_0$ is a normalized frequency. Inband interference is of the same frequency as a useful signal and we assume that it also has a Gaussian form [6]. Interference is time and phase shift in relation to a useful signal. Interference at the place of appearance is:

$$\begin{cases} s_i(z_i,\tau) = U_i(z_i,\tau)\cos(\omega_r \tau + \varphi), \\ U_i(z_i,\tau) = a_i \exp(-(\tau - b)^2/2); \end{cases} \qquad (9)$$

where b and φ are the time and phase shift, respectively. z_i is the place along an optical fiber where interference appears. The value of parameter a_i depends on the magnitude of the interference. The envelope and phase of the resulting signal on the place where interference appears [4]-[5]:

$$U_r(z_i,\tau) = \sqrt{U^2(z_i,\tau) + 2U(z_i,\tau)U_i(z_i,\tau)\cos\varphi + U_i^2(z_i,\tau)} , (10)$$

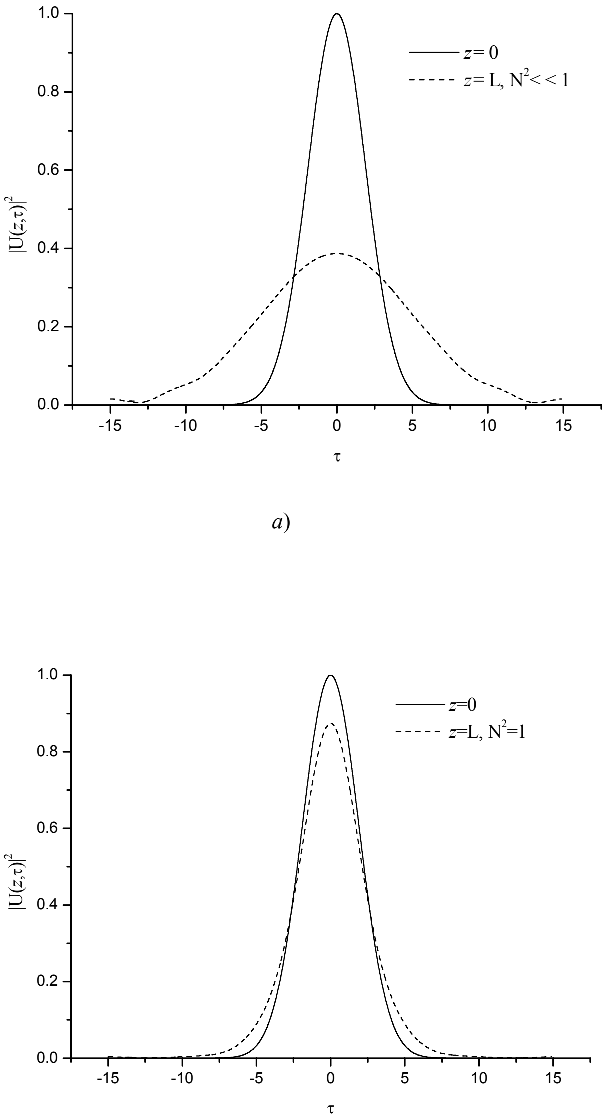
$$\psi(z_i,\tau) = arctg \frac{U_i(z_i,\tau)\sin\varphi}{U(z_i,\tau) + U_i(z_i,\tau)\cos\varphi} . \qquad (11)$$

All time shapes of signals at the end of optical fiber, showed below, are gained by solving Schrödinger equation (5) by symmetrical split-step Fourier method. The following values of parameters are used in all cases: T_0=4 ps, A_{eff}=50 μm^2, λ=1.55 μm, β_2=-23 ps^2/km and n_2=3.2·10^{-16}cm^2/W.

Fig. 1(a) and 1(b) show the propagation a Gaussian pulse along an optical fiber without the presence of interference under a dominant anomalous dispersive regime, i.e. under an anomalous dispersive regime where nonlinear and dispersive effects are balanced. This signal behaviour is well known but this figures are needed if we want to see to what extent the number, time shift of interferences and the place of interference appearance affect signal propagation. Fig. 1 (a) and 1 (b) are reference signals for the working regime of an optical fiber when N^2<<1, i.e. $N^2 \approx 1$, respectively [7]-[9].

Fig. 1 affirms that nonlinear effects can reduce the influence of dispersion, i.e. signal broadening, only under anomalous dispersive regime, which is shown by comparing Fig. 1 (a) and 1 (b).

Fig. 2, 3, 4 and 5 show the propagation of a Gaussian pulse in the presence of interferences that are time shifted and that appear along optical fiber.

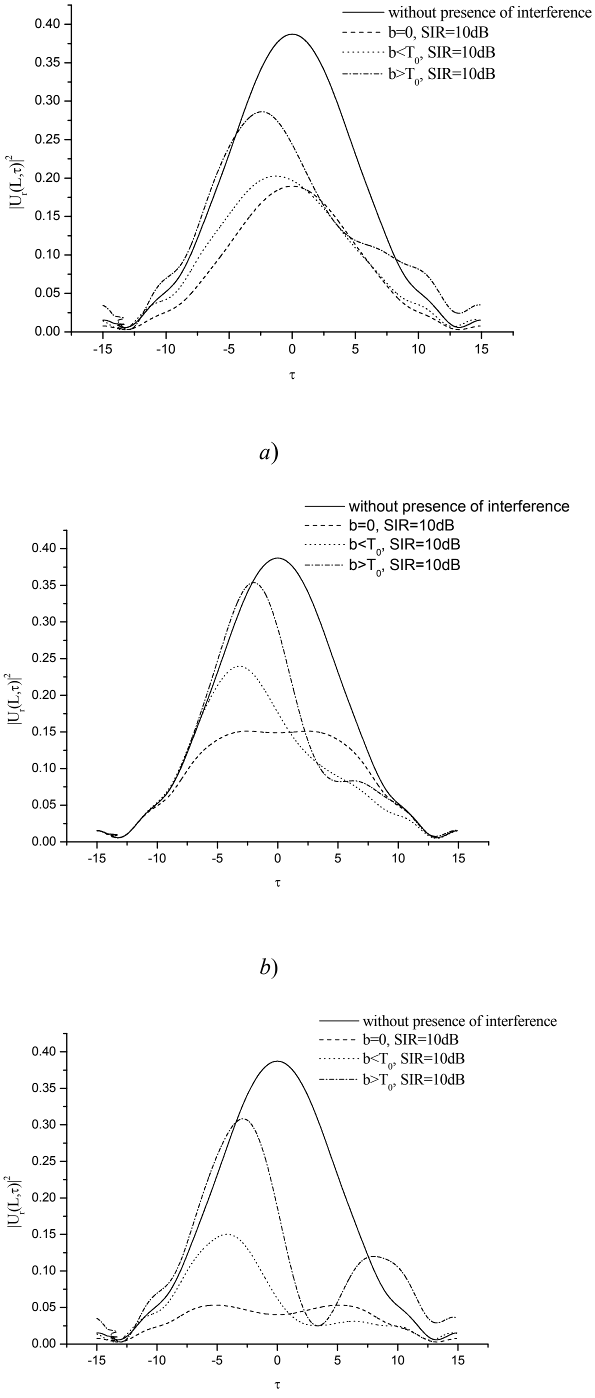


a)

b)

Fig. 1. Gaussian pulse shape at the end of optical fiber (L=6L_D): (a) N^2<<1, (b) N^2=1

Interference is phase shifted, too. To see the worst case we also must assume that phase shift of interference is π [4]-[5] and [7]-[8] as in following figures.

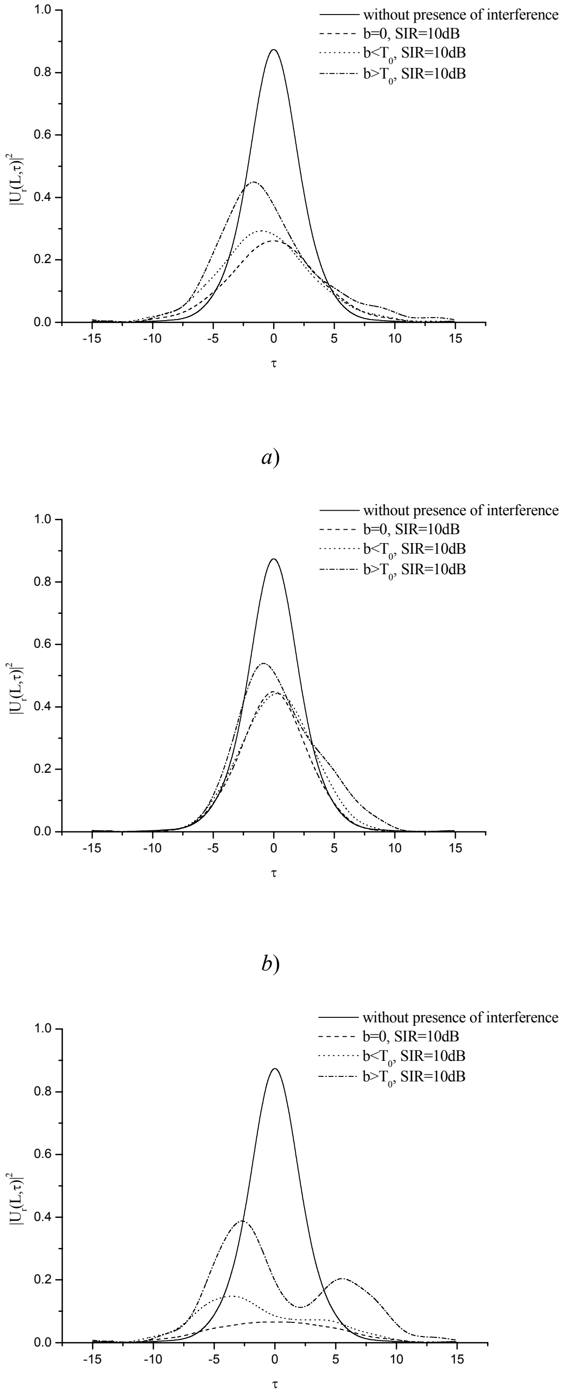


a)

b)

c)

Fig. 2. Signal shape: a - Gaussian pulse shape at the end of the optical fiber ($L=6L_D$) in the presence of time shifted interference (SIR=10dB) at the beginning of optical fiber ($N^2<<1$); b - Gaussian pulse shape at the end of the optical fiber ($L=6L_D$) in the presence of time shifted interference (SIR=10dB) in the middle of optical fiber ($N^2<<1$); c - Gaussian pulse shape at the end of the optical fiber ($L=6L_D$) in the presence of time shifted interferences (SIR=10dB) at the beginning and in the middle of optical fiber ($N^2<<1$)

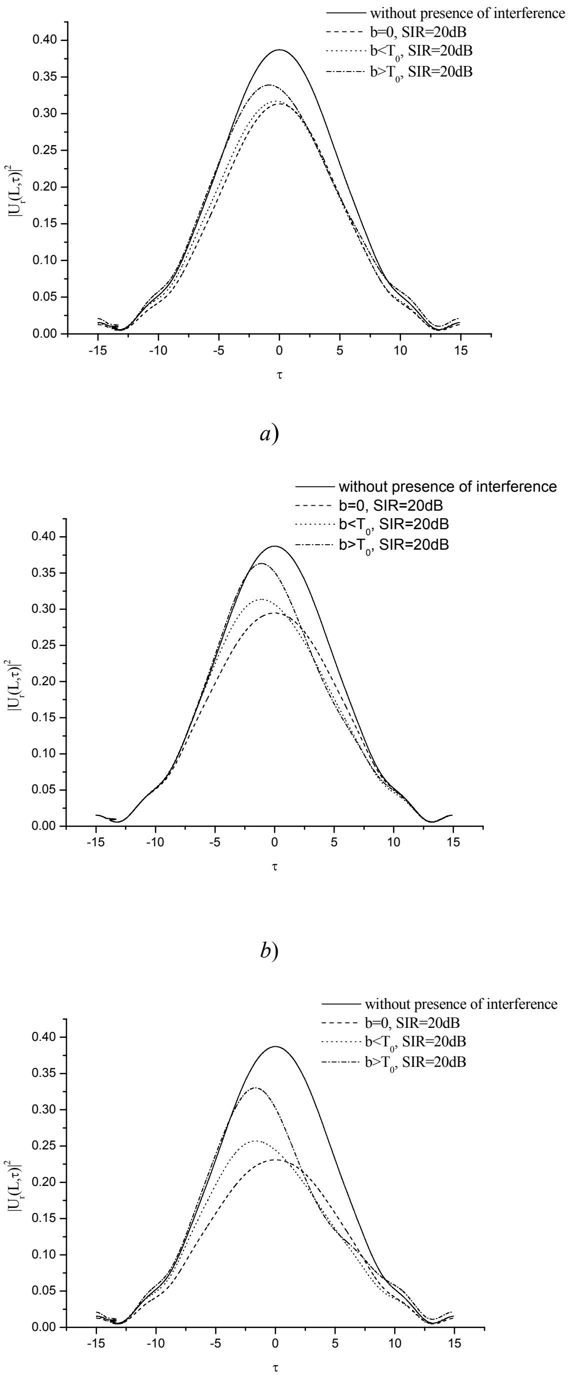


a)

b)

c)

Fig. 3. Signal shape: a - Gaussian pulse shape at the end of the optical fiber ($L=6L_D$) in the presence of time shifted interference (SIR=10dB) at the beginning of optical fiber ($N^2=1$); b - Gaussian pulse shape at the end of the optical fiber ($L=6L_D$) in the presence of time shifted interference (SIR=10dB) in the middle of optical fiber ($N^2=1$); c - Gaussian pulse shape at the end of the optical fiber ($L=6L_D$) in the presence of time shifted interferences (SIR=10dB) at the beginning and in the middle of optical fiber ($N^2=1$)

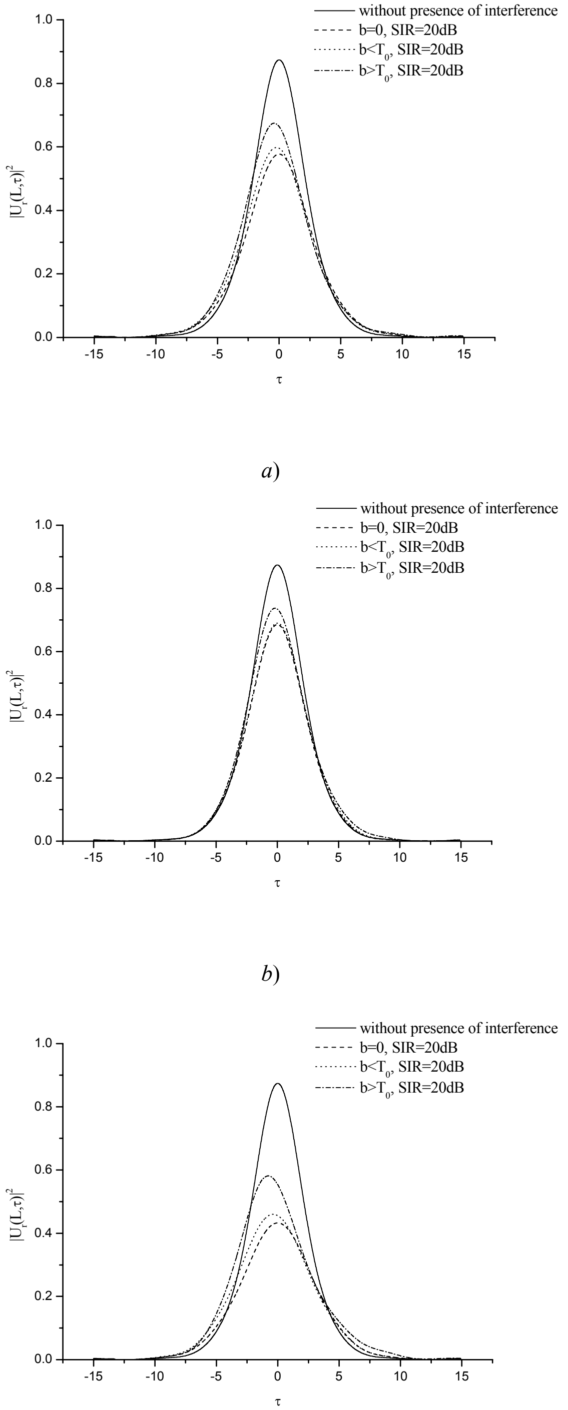


a)

b)

c)

Fig. 4. Signal shape: a - Gaussian pulse shape at the end of the optical fiber (L=6L_D) in the presence of time shifted interference (SIR=20dB) at the beginning of optical fiber (N^2<<1); b - Gaussian pulse shape at the end of the optical fiber (L=6L_D) in the presence of time shifted interference (SIR=20dB) in the middle of optical fiber (N^2<<1); c - Gaussian pulse shape at the end of the optical fiber (L=6L_D) in the presence of time shifted interferences (SIR=20dB) at the beginning and in the middle of optical fiber (N^2<<1)



a)

b)

c)

Fig. 5. Signal shape: a - Gaussian pulse shape at the end of the optical fiber (L=6L_D) in the presence of time shifted interference (SIR=20dB) at the beginning of optical fiber (N^2=1); b - Gaussian pulse shape at the end of the optical fiber (L=6L_D) in the presence of time shifted interference (SIR=20dB) in the middle of optical fiber (N^2=1); c - Gaussian pulse shape at the end of the optical fiber (L=6L_D) in the presence of time shifted interferences (SIR=20dB) at the beginning and in the middle of optical fiber (N^2=1)

Bit error probability is a parameter that shows the quality of information transmission along an optical fiber and it depends on the signal value at the decision time [4]-[5]. Figures 2 (*a*) and 2 (*b*), i.e. 4 (*a*) and 4 (*b*), show that bit error probability is greater when interference appears in the middle of a fiber than when it appears at the beginning of an optical fiber in case when dispersive effects dominate in an optical fiber and in case when time shift of interference $b \leq T_0$. This occurs because the interference, which appears in the middle of an optical fiber, is added to a useful signal that has already been expanded enough by dispersive effects and time shift is enough small that interference influences on signal propagation [7]-[8]. When $b > T_0$, interference has not as such great influence as case when $b \leq T_0$ when greater error can be made at the receiver in detection process.

When dispersive and nonlinear effects are balanced in an optical fiber, the worse case occurs when interference appears at the beginning of an optical fiber in which case interference degrades a useful signal, at the very beginning of an optical fiber preventing nonlinear effects to show the full height their positive influences [7]-[8]. In case of interference appearing in the middle of a fiber, a useful signal maintains an almost unaltered form up to the point where interference appears. On reaching this point it is degraded and the situation, which occurs at the beginning of a fiber, for the case 3 (*a*), i.e 5 (*a*), is repeated. This postponed effect of interference leads to a smaller error in the detection process for the case 3 (*b*), i.e. 5(*b*). than in the case 3 (*a*), i.e. 5 (*a*).

Under both working regimes of an optical fiber, the biggest error is made when two interferences appear in an optical fiber, at the beginning and in the middle of a fiber, respectively, although greater pulse deformation is happened when nonlinear effects do not presence in the optical fiber. Also, it can be concluded that this case is the most compliant on timing jitter.

Conclusion

Scientific contribution of this paper is to be found in its treatment of the influence of the position, number and time shift of interference on Gaussian signal propagation through an optical fiber. Interference has been treated in equations (10) and (11) in this paper, which represents a new approach in the analysis of the influence of interference on the form of a pulse at the entrance to a receiver. In other words, this is a new approach to the analysis of performances of optical systems in the presence of interference. Nonlinear effects are very important in an anomalous dispersive regime of an optical fiber because they reduce a negative influence of dispersive effects on pulse propagation. Bearing this is mind, we have considered the influence of interference both in the case of dispersive effect domination and the case of balance between dispersive and nonlinear effects. Based on everything discussed so far, we can conclude that interference is more dangerous if it appears later when an optical fiber works under a dominate anomalous dispersive regime. However, if dispersive and nonlinear effects are balanced in an optical fiber, it is preferable for interference to appear along the fiber than at the beginning. This paper has also demonstrated that it is preferable for a propagation useful signal to be exposed to interference with a great time shift. It can be concluded from this paper, that if SIR (signal-to-interference ratio) increases, then influence of interference time shift decreases. The worst case happened when two interference appear along optical fiber and in that case nonlinear effect can appease, but slightly, such great interference influence on signal propagation. Detection error is made by presence of timing jitter is the greates in this case.

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M. C. Stefanovic, D. Lj. Draca, A. S. Panajotovic. Laiko poslinkių ir interferencijos atsiradimo vietos įtaka signalo sklidimui optinėje skaiduloje // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2005. – Nr. 1(57). – P. 14-19.

Yra žinoma, kad dispersija turi įtakos signalo sklidimui optinėje skaiduloje. Signalui sklindant optinėse telekomunikacijų sistemose greitais tempais ir dideliu atstumu, reikia įvertinti netiesinių efektų įtaką signalo sklidimui. Kadangi netiesiniai efektai sumažina neigiamą dispersinių efektų įtaką, jie yra pageidautini, kai sistemos dirba esant anomaliam dispersiniam režimui. Optinėse sistemose dažnai pasitaikančių ir bet kur optinėje skaiduloje galinčių atsirasti interferencijų įtaka yra gana didelė. Išanalizuota vienos interferencijos, kuri atsiranda optinės skaidulos pradžioje arba viduryje, ir dviejų vienalaikių interferencijų atitinkamai atsirandančių skaidulos pradžioje ar viduryje įtaka. Nagrinėjama interferencijų laiko poslinkio įtaka gausinio signalo sklidimui optinėje skaiduloje. Visus šiuos poveikius lemia impulso forma optinės skaidulos gale, kadangi SIS (signalo ir interferencijos santykis) lygus 10 dB. ar 20 dB. Impulsas imtuve yra nustatomas panaudojant Schrödingerio lygtį. Il. 5, bibl. 9 (anglų kalba; santraukos lietuvių, anglų ir rusų k.).

M. C. Stefanovic, D. Lj. Draca, A. S. Panajotovic. The Common Influence of Time Shift and Appearing Place of Interference on Signal Propagation along Optical Fiber // Electronics and Electrical Engineering. – Kaunas: Technologija, 2005. – No. 1(57). – P. 14-19.

It is common knowledge that dispersion affects signal propagation along an optical fiber. Providing that a signal propagates along optical telecommunication systems at a high data rate and at a long distance, the influence of nonlinear effects on signal propagation should be taken into consideration. Since nonlinear effects decrease negative influence of dispersive effects, they are desirable if systems work under anomalous dispersive regime. The influence of interferences, which are often present in optical systems and can appear anywhere along the fiber, can be considerable. Bearing this in mind, the subject of this paper is to investigate the influence of one interference, that appears at the beginning or in the middle of an optical fiber and influence of two simultaneous interferences that appear at the beginning and in the middle of a fiber, respectively. In addition to the previously mentioned, the paper studies time shift influence of interference on propagation of Gaussian signal along an optical fiber, as well. All these influences are considered by pulse shape at the end of optical fiber for SIR (signal-to-interference ratio) equals 10dB or 20dB. The pulse at the receiver is determined by solving Schrödinger equation. Ill. 5, bibl. 9 (in English; summaries in Lithuanian, English and Russian).

М. Ц. Стефанович, Д. Л. Драца, А. С. Панайотович. Определение места возникновения интерференции при распределении сигналов в оптической среде // Электроника и электротехника. – Каунас: Технология, 2005. – №. 1(57). – С. 14–19.

Распространение сигнала в оптической среде, как правило, ограничивается дисперсией. Это особенно важно в оптических телекоммуникационных системах, где большие расстояния и где необходимо оценивать нелинейные эффекты влияния сигналов. Известно, что нелинейные эффекты, с одной стороны, уменьшают отрицательное влияние дисперсионных эффектов, а с другой стороны, возбуждают аномальные дисперсионные режимы. Это явление особенно велико в оптической среде и создает дополнительные интерференционные эффекты. Рассматривается влияние интерференций в начале или в середине среды и предлагаются возможности влияния интерференций гауссовского сигнала в среде. Доказывается, что форма сигнала в начале среды равна 10 dB или 20 dB, а сам сигнал устанавливается при использовании уравнения Шредингера. Ил. 5, библ. 9 (на английском языке; рефераты на литовском, английском и русском яз.).

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