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The Influence of Phase Shift of Interference on Signal Propagation along the Optical Fiber

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Introduction

In this paper, propagation of the optical signal at $\lambda = 1550\ nm$ (the lowest fiber atenuation) is considered. We supposed that DFB (distibuted feedback) laser makes good distribution of wavelengths for different channels, so we omitted the influence of interchannel crosstalk. The influence of crosstalk due to reflection along the fiber, is considered, too. In last few decades, fiber optics have become main medium for transmission of different kinds of signals. A new technology called WDM (Wavelength Division Multiplexing) allows transmission of multiple optical channels at different wavelengths along the fiber.

Multichannel WDM exists in two new technologies: CWDM (Coarse WDM) and DWDM (Dense WDM). DWDM has allowed transmission of at first 32 and 40 channels, and now, the most advanced fiber optic communication systems offer simultaneous transmission of 100 to 150 channels at 10 Gb/s, in a single optical fiber. DWDM system has a narrow channel spacing (100GHz – 0,8 nm or 50 GHz – 0,4 nm). As a source, temperature stabilized DFB lasers are used. Well designed DWDM systems show good performances and therefore present the bases for the future all-optical networks.

In such a system, there are many degrading effects that must be minimized or controlled. The most prevalent effects are certainly chromatic dispersion, polarization-mode dispersion, amplifier noise and crosstalk. Intramodal dispersion results from frequency dependence of refractive index and mode propagation constant, and it appears in both linear and nonlinear optical fiber. Intramodal dispersion leads to pulse deformity, i.e. pulse broadening during its propagation along the fiber.

Dispersion coefficient β_2 is parameter showing magnitude of dispersion. It defines dispersive regime of optical fiber. If $\beta_2 > 0$ then optical fiber works under normal dispersive regime, otherwise, if $\beta_2 < 0$, the optical fiber is exposed to anomalous dispersion regime [1]. Refractive index depends on intensity of pulse propagating along the fiber. If signal is strong enough, Kerr's nonlinearities (self-phase modulation, cross-phase modulation and four-wave mixing) can not be neglected. It is found that these effects can decrease influence of dispersive effects in anomalous dispersive regime of the fiber, although can not annul them [1].

Crosstalk is a kind of disturbance in the optical communication system. It can be coherent (the same frequency as a useful signal) or noncoherent (different frequencies). Coherent crosstalk can not be eliminated by optical filtering in receiver [2,3], so in this paper we reffer to it.

Equation of propagation

Pulse propagation along nonlinear-dispersive optical fiber can be described as [1]:

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

where A - slowly varying amplitude of the pulse, α - optical losses, β - mode-propagation constant,

$\beta_1 = \frac{\partial \beta}{\partial \omega}\bigg|_{\omega=\omega_0} = \frac{1}{v_g}$; $\beta_2 = \frac{\partial^2 \beta}{\partial \omega^2}\bigg|_{\omega=\omega_0}$, v_g - group velocity and γ - nonlinearity coefficient:

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

where n_2 - nonlinear index coefficient, λ - wavelength of signal and A_{eff} - effective core area.

We introduce the next normalization:

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

where T_0 - half-width, i.e. the time when signal power declines to $1/e$ of its peak value and P_0 - the peak power of useful optical signal, and then we introduce:

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

then equation (1) becomes:

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

Equation (5) is well-known as nonlinear Schrödinger equation. Optical losses are neglected, i.e. $\alpha = 0$. In this paper symmetrical split-step Fourier method is used for solving Schrödinger equation because it is fast and accurate method. Parameter defining working regime of the optical fiber is:

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

For N^2 <<1 dispersion dominates, and for $N^2 \approx 1$, dispersive and nonlinear effects are balanced [1].

Influence of interference

In optical telecommunication systems useful signal is Gaussian and it can be written as [1-3]:

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

Parameter a depends on transmitted information ("1" or "0"). At the beginning of the fiber useful signal is:

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

where $\omega_r = \omega T_0$ is normalized frequency.

Coherent interference has the same frequency as useful signal and it has Gaussian envelope, too. Crosstalk is time and phase shifted in relation to useful signal. At the place where the interference appears:

$$s_i(z_i,\tau) = U_i(z_i,\tau)\cos(\omega_r \tau + \varphi),$$
$$U_i(z_i,\tau) = a_i \exp\left(-(\tau - b)^2\right)/2, \quad (9)$$

where b – time shift and φ -phase shift, respectively. z_i denotes the place of arising of interference along the considered optical fiber. Parameter a_i depends on magnitude of crosstalk. Envelope and phase of resulting signal at the place of interference are [4, 5]:

$$U_r(z_i,\tau) = \sqrt{X} , \quad (10)$$

where

$$X = U^2(z_i,\tau) + U_i^2(z_i,\tau) +$$
$$+ 2\,U(z_i,\tau)U_i(z_i,\tau)\cos, \quad (11)$$

$$\psi(z_i,\tau) = arctg \frac{U_i(z_i,\tau)\sin\varphi}{U(z_i,\tau) + U_i(z_i,\tau)\cos\varphi} . \quad (12)$$

Time shapes of signals along the optical fiber are given by Schrödinger equation (5) solved by symmetrical split-step Fourier method [1, 6, 7]. The following values of parameters are used in all the cases: T_0 = 4 ps, β_2= - 19 ps^2 / km, L_D = 0.85 km, $L = 23L_D$, A_{eff} = 80 μm^2, λ = 1.55 μm.

Fig. 1 shows Gaussian pulse along dispersive optical fiber in case when N^2 <<1, under dominant anomalous dispersive regime without interference and with the interference at different places along the fiber. The influence of phase shift of interference on signal propagation is obtained cosidering the reference signal shown in Fig. 1 [6]. The influence of appearing place of interference signal on output envelope broadening compensation is greater when nonshifted signal interference appears at the end of fiber.

The peak power increases with increasing the distance of interference appearing place. Fig. 2 shows Gaussian pulse propagation under dominant anomalous dispersive regime in the presence of interference at previously considered places along the fiber and in case of phase shift φ = π, compared to useful signal. In this case, the output pulses are broadened and disturbed.

The largest pulse broadening occures when interference signal appears at the end of the fiber. In case of phase shifting the peak power decrease with the increasing of the distance from the appearing place of interference, because of non-aditional interference performance in this considered case.

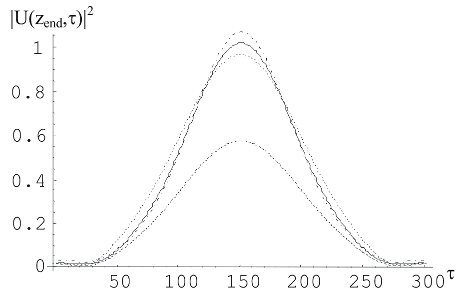

Fig. 1. Pulse shape at the end of the optical fiber in case of propagation of Gaussian pulse: z =23 L_D , (N^2<<1), SIR =10 dB, φ= 0; dashed curve – absence of interference; dotted curve - interference appears at z_{ap}=3L_D; solid curve – z_{ap}= 10L_D, dash-dotted curve – z_{ap}=20L_D

Fig. 3 and 4 show propagation of Gaussian pulse along the nonlinear and dispersive optical fiber under equal dispersion and nonlinearity influences, N^2 = 1, without interference and with interference at different places along the fiber. The peak power of output pulse is the highest when interference signal appears at the input of the fiber. There are pulse broadening and disturbances when the interference signal appear at the end of fiber. The nonlinear effects can reduce influence of crosstalk in such dispersion regime. Results obtained for this case are ilustrated in Fig.3.

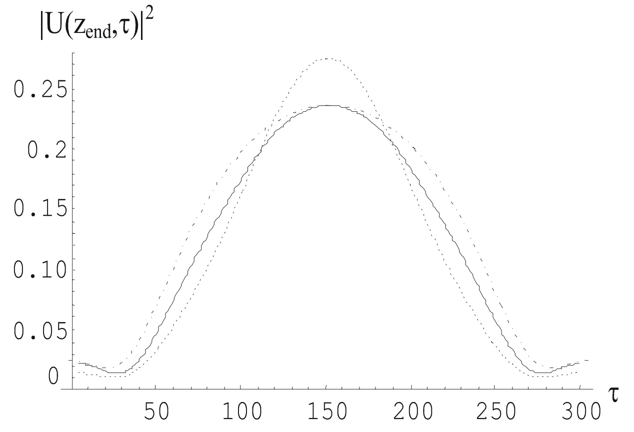

Fig. 2. Pulse shape at the end of the optical fiber in case of propagation of Gaussian pulse: z =23 L_D , (N^2<<1), SIR =10 dB, φ= π : dotted curve – interference appears at $z_{ap}=3L_D$; solid curve – $z_{ap}=10L_D$; dash-dotted curve – $z_{ap}=20L_D$

Fig. 3 depicts that in case of the opposite phase shift, the peak power increases (i.e. the width of output envelope decreases) when the distance of the interference appearing place from the fiber input arises. The output pulse is significantly disturbed compared to the case without presence of interference.

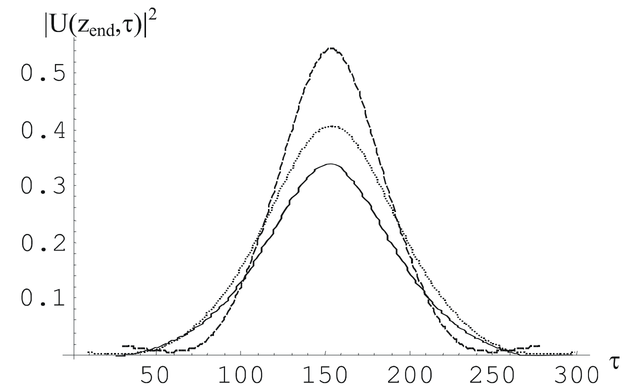

Fig. 3. Pulse shape at the end of the optical fiber in case of propagation of Gaussian pulse: z =23 L_D ($N^2 \approx 1$), SIR =10 dB, φ = π: solid curve – interference appears at $z_{ap}=3L_D$; dotted curve – $z_{ap}=10L_D$; dashed curve – $z_{ap}=20L_D$

Obviously, the best characteristics of the output envelope are obtained in case of nonlinear and dispersive fiber. In this case, a nonshifted interference signal appears at the end of the considered optical fiber.

The bit error probability

$P_{e/\varphi,b}$ iz determined on the bases of field envelope squared and IM-DD receiver variance, using *Gaussian* aproximation. The decision is made with respect to the signal

$$z = k\,n + y\,, \tag{13}$$

where *n* represents the number of electrons emitted from a diode, and *y* represents *Gaussian* noise appearing at the resistances and the amplifier inside the receiver:

$$p\,(\,y\,) = \frac{1}{\sqrt{2\pi}\;\sigma}\;\exp\left(-\,y^2\,/\,\left(2\sigma^2\,\right)\right), \tag{14}$$

where σ^2 is variance of *Gaussian* noise. Conditional probability density function for *z* is determined by:

$$p\,(\,z\,/\,n\,) = \frac{1}{\sqrt{2\pi}\;\sigma}\exp\left(-\,(\,z - kn\,)^2\,/\left(2\sigma^2\right)\right), \tag{15}$$

where *n* has the *Poisson* probability distribution:

$$p\,(n) = \frac{\lambda^n}{n\,!}\exp\;(-\lambda\;) = = \frac{\left|\,U_r\left(\xi_{end,}\;\tau\,\right)\right|^2}{n\,!}\exp\;\left(-\left|\,U_r\left(\xi_{end,}\;\tau\right)\right|^2\right), \tag{16}$$

here $U_{1r}(\xi_{end},\tau)$ i $U_{0r}(\xi_{end},\tau)$ are normalized total envelopes at the entrance of the receiver depending on the condition if "1" or "0 " is sent. Conditional probability density functions are:

$$p_0\,(z\,/\,\varphi) = \sum_{n=0}^{\infty}\,p_o(n)\,p_0\,(z\,/\,n,\varphi), \tag{17}$$

$$p_1\,(z\,/\,\varphi) = \sum_{n=0}^{\infty}\,p_1(n)\,p_1\,(z\,/\,n,\varphi)\,. \tag{18}$$

Decision threshold for estimation of value of the sent information is determined as:

$$V_p = \left(\,\overline{z_1}\,\sigma_0 + \overline{z_0}\,\sigma_1\,\right)/\left(\,\sigma_0 + \sigma_1\,\right). \tag{19}$$

For $P(H_0) = P(H_1) = 1/2$, P_e is obtained according to [7, 8]

$$P_{e\,/\,\varphi} = \frac{1}{2}\left[\int_{V_p}^{+\infty} p_0\,(z\,/\,\varphi\,)\,dz + \int_{-\infty}^{V_p} p_1\,(\,z\,/\,\varphi\,)\,dz\right]. \tag{20}$$

P_e is obtained for the worst case when *p(φ)* is uniform probability distribution.

$$P_e = \int_{-\pi}^{\pi} P_{e/\varphi,b}\;p\;(\,\varphi\,)\,d\varphi\,. \tag{21}$$

Fig. 4 shows the case of linear dispersive fiber (N^2<<1). It can be seen that in dispersive fiber interchannel interference causes performances degradations in communication system. We can see that the worst performances are obtained when interference appears close to the input of the optical fiber. Also, the higher the noise ratio, the higher is the bit error probability.

Fig. 5 shows that the presence of the phase opposite crosstalk significantly increases the bit error probability. Similarly in case of nonlinear dispersive fiber without the phase shift, the worst case of interference influence, is for $z_{ap} = 3L_D$. Although the interference appears close to the fiber input, the system performances are better due to balance of dispersive and nonlinear effects. If the phase shift is present the phase opposite crosstalk causes significant increasing of the bit error probability.

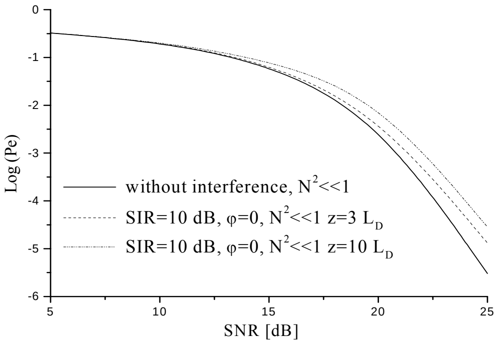

Fig. 4. Influence of interference without phase shift, z_{ap} = $3L_D$ and z_{ap}=$10L_D$ on the bit error probability for different values of SNR, SIR = 10 dB, N^2<< 1

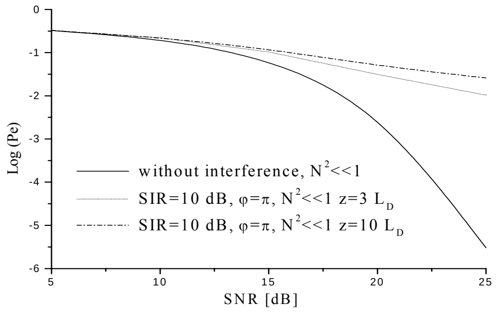

Fig. 5. The influence of interference with phase shift, for z_{ap} = $3L_D$ and z_{ap}=$10L_D$, on bit error probability for different SNR values, SIR = 10 dB, N^2<<1

Conclusions

Nonlinear effects are very important in anomalous dispersion regime of the optical fiber because they can reduce negative influence of dispersive effects on pulse propagation along the fiber. In this paper phase shift influence of interference on propagation of Gaussian pulse is considered.The phase shift of $\varphi = \pi$ has the biggest influence on pulse propagation. The negative influence of opposite phase is the worstwhen signal interference appears at the end of linear dispersive fiber. In the case of propagation along a nonlinear and dispersive fiber, the negative influence of opposite phase is the biggest when signal interference appears at the input of fiber.

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P. Spalevic, L. Spalevic, B. Milosevic, I. Petrovic. The Influence of Phase Shift of Interference on Signal Propagation along the Optical Fiber // Electronics and Electrical Engineering. – Kaunas: Technologija, 2007. – No. 2(74).– C. 29–32.

If signal propagates along optical communication system at high data rate and for long distance, influence of nonlinear effects on signal propagation should be taken into consideration. Nonlinear effects are desirable, if system works under anomalous dispersion regime, because they decrease negative influence of dispersive effects. Interference could appear at any point along the fiber. We compared the cases of crosstalk appearing at the fiber input and at the different points along the fiber. The influence of phase shift of interference on propagation of Gaussian signal along dispersive and nonlinear-dispersive optical fiber, as well as on peak power that is a function of fiber distance, for two cases of phase shifting and for SIR (signal–to-interference ratio) = 10 dB, is considered, too. Ill. 5, bibl. 8 (in English; summaries in English, Russian and Lithuanian).

П. Спалевич, Л. Спалевич, Б. Милошевич, И. Петрович. Влияние смещения фазы интерференции на распространение сигнала по оптическому пучку // Электроника и электротехника. – Каунас: Технология, 2007. – № 2(74). – С. 29–32.

Если сигналы распространяются по оптической коммуникационной системе на больших расстояниях, необходимо оценить влияние нелинейных воздействий на распространение сигнала. Нелинейные воздействия являются желательными, когда система работает при аномальном дисперсионном режиме, так как они уменьшают отрицательное влияние дисперсионных воздействий. Интерференция может проявиться в любом месте оптического пучка. Были сравнены случаи, когда взаимная интерференция происходит во входе в оптический канал или в разных точках на продолжительности канала. Анализируется влияние смещения фазы интерференции на сигналы Гауса, когда сигнал распространяется по оптическому пучку с дисперсионными и нелинейными дисперсионными свойствами. Рассмотрено влияние пиковой мощности, когда SIR = 10 dB. Ил. 5, библ. 8 (на английском языке, рефераты на английском, русском и литовском яз.).

P. Spalevic, L. Spalevic, B. Milosevic, I. Petrovic. Interferencijos fazės poslinkio įtaka signalo sklidimui optiniu pluoštu // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2007. – Nr. 2(74). – P. 29–32.

Jei signalai sklinda optine komunikacijų sistema dideliais atstumais ir didele sparta, būtina atsižvelgti į netiesinių poveikių įtaką signalo sklidimui. Netiesiniai poveikiai pageidautini, kai sistema veikia anomalios dispersijos rėžimui, nes jie sumažina neigiamą dispersinių poveikių įtaką. Interferencija gali pasireikšti bet kurioje optinio pluošto vietoje. Lyginome atvejus, kai tarpusavio interferencija pasireiškia optinio kanalo įėjime bei skirtinguose taškuose išilgai kanalo. Nagrinėta interferencijos fazės poslinkio įtaka Gauso tipo signalui, kai jis sklinda dispersinėmis ir netiesinėmis dispersinėmis savybėmis pasižyminčiu optiniu pluoštu. Taip pat analizuota pikinės galios įtaka, kai SIR = 10 dB. Il. 5, bibl. 8 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).