Influence of dispersion and non-linear effects in optical fiber on the parameters of CATV system

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Abstract – **The object of this paper is the analysis of the influence of dispersion and several non-linear effects in the fiber optic on the parameters of the transmitted digital and analog signals. Plot for an estimation of the maximum transmitted bandwidth, i.e. the symbol rate, is given taking into account the restriction caused by the chromatic and polarization mode dispersion. Thresholds that ensure acceptable received signal quality are determined. The worsening of the signal quality is explained as a result of stimulated scattering, self-phase and cross-phase modulation, and intermodulation.**

Keywords – **Chromatic and polarization mode dispersion; Stimulated Brillouin and Raman scattering; Self-phase and cross-phase modulation; four-wave modulation.**

I. INTRODUCTION

The trends in the CATV system development are related to the inculcation of digital and fiber-optic technologies. This allows a growth of the system traffic, additional services (Internet, e-commerce, interactive TV, VoIP), and expansion of the distribution system coverage area.

Modern CATV systems are hybrid fiber/coax (HFC) systems. The main part of such system is build up by fiber-optic and the peripheral part by coax. The parameters of the signals transmitted through the fiber-optic are worsening as a result of the dispersion and non-linear effects in the fiber and this put restrictions on the signal bandwidth (the symbol rate), the maximum allowed fiber-optic length, the optical transmitter output power etc. The design of the optical part of HFC system requires knowledge of the relations between the system and the fiber-optic parameters. The last are the main object of this work.

II. INFLUENCE OF THE DISPERSION

In the CATV systems a single mode fiber is established. This fiber has chromatic and polarization dispersion. Estimation of the chromatic dispersion is performed through the pulse spread τ_{chr} that is given by

$$\tau_{chr} = \sqrt{\tau_{out}^2 - \tau_{in}^2} = D_{chr}(\Delta\lambda)_S\, l\,, \qquad (1)$$

where τ_{in} and τ_{out} – optical pulse width in the input and the output of the fiber, respectively; D_{chr} – chromatic mode dispersion coefficient; $(\Delta\lambda)_S$ – spectral width of the laser; and l – the length of the fiber. The chromatic dispersion coefficient D_{chr} is defined as a spread (in picosecond) of an optical pulse with length of 1 nanometer in the fiber end that is 1 kilometer long i.e. the dimension is ps/(nm·km).

It is obvious that the laser is necessary to have narrow spectral width and the fiber to be with a small coefficient D_{chr} in order to decrease the pulse spread τ_{chr} and to increase the data rate. The relation between the coefficient D_{chr} and the optical wavelength for the frequently used in the CATV system fiber-optic is shown on Fig. 1.

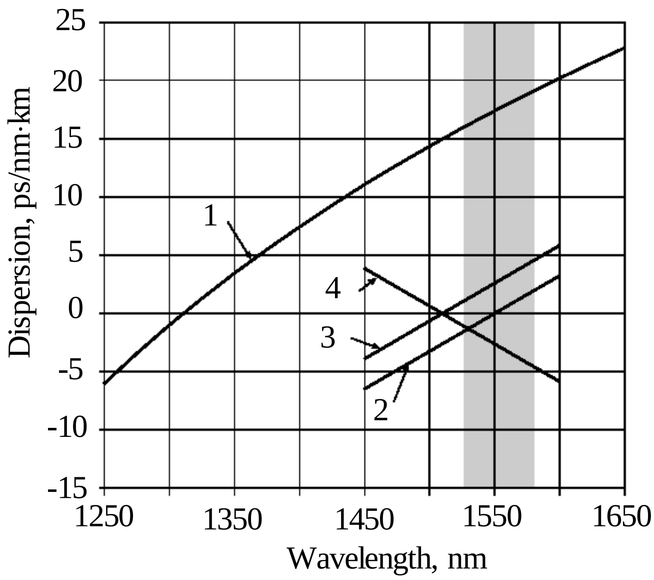

Fig.1 Influence of the optical wavelength on the coefficient D_{chr} for single mode fiber

The single mode fiber (SMF) is denoted by (1) and it is suitable for the wavelength λ about 1310 nm, where the chromatic mode dispersion coefficient D_{chr} is zero. Recently, the dispersion-shifted fiber (DSF), that is with D_{chr} = 0 for λ = 1550 nm (the curve denoted by 2), is used for 1550 nm fiber-optic network. In the present, the Dense Wavelength-Division Multiplexing (DWDM) is used and SMF fiber is

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unsuitable because of the great non-linear effects. This imposed a development of the fiber-optic and the result is so called Non-Zero Dispersion-Shifted Fiber (NZ-DSF). The chromatic dispersion coefficient D_{chr} is zero in the outside of 1550 nm range. By (3) and (4) is denoted on Fig. 1 the relations between D_{chr} and λ for this type of fiber. The first is related to the fiber with positive and the second with negative coefficient D_{chr}. It can be seen that the coefficient D_{chr} of fiber (+D) NZ-DSF and (−D) NZ-DSF has small values for the wavelength λ about 1550 nm.

The polarization mode dispersion is caused by the property of the fiber-optic to divide the ray in two mutual perpendicular rays. The fiber is not perfectly round and it is exposed to various mechanical forces and climatic conditions. Therefore, the two rays travel in the fiber with distinct velocities and have different delays at the fiber end. The described above phenomenon is the reason for the polarization mode dispersion.

The polarization mode dispersion is estimated by the deference between the delays of the two orthogonal components of the optical pulse at the fiber end or so called polarization mode dispersion pulse spread τ_{pol}. The pulse spread τ_{pol} is determined by the following expression:

$$\tau_{pol} = \sqrt{\tau_{out}^2 - \tau_{in}^2} = D_{pol}\sqrt{l} \ , \tag{2}$$

where by D_{pol} is denoted the polarization dispersion coefficient of the fiber in ps/√km. The typical values of D_{pol} for standard single mode fiber (SMF) varies in the interval 0,01...0,8 ps/√km and for the dispersion-shifted fiber (DSF) D_{pol} = 0,2...1,6 ps/√km.

III. Limitation due to the dispersion

In consequence of the chromatic mode dispersion, the signal spectral component has different delays at the fiber end. This result in decreasing of demodulated signal level P_{RF} at the optical receiver output by

$$P_{RF}/P_{RF\max} = \cos\left(\frac{\pi D_{chr}\, l}{c}\lambda^2 f_{RF}\right), \tag{3}$$

where λ is wavelength of the optical carrier, c − the velocity of lights in vacuum and f_{RF} − the frequency of the RF signal. If analog signals are transmitted then the acceptable losses due to chromatic mode dispersion are in order of 1 to 3 dB. It is obvious that the chromatic mode dispersion restricts the signal bandwidth and the length of the fiber.

According to the equation (3) on Fig. 2 are shown relations between the fiber length and the maximum frequency of the modulating RF signal. These plots can be used in the design of analog optical link intended for 1550 nm range and realized by standard single mode fiber (S-SMF) or Non-Zero Dispersion-Shifted Fiber (NZ-DSF) with D_{chr} = 3,5 ps/nm·km.

The bandwidth B_{RF} (in GHz) of optical CATV system with limitation due to chromatic dispersion can be roughly estimated by

$$B_{RF} \le 500(\Delta\lambda)_S/(D_{chr}\, l) \ . \tag{4}$$

In the digital optical link, the chromatic mode dispersion results in pulse spread, hence intersymbol interference is occurred and the probability of error is increasing. The “eye-diagram” is used for an estimation of the intersymbol interference and bit error rate (BER) in On-off keying (OOK) system.

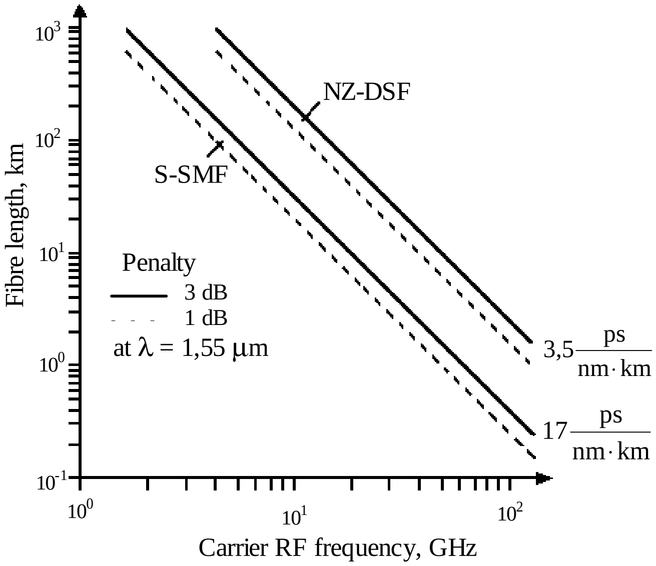

Fig. 2 Plots used for a design of analog optical link build by S-SMF and NZ-DSF

The acceptable distortions are these that correspond to the shrinkage of “eye-diagram” by 1 dB (as an exception 2 dB). This is indirectly estimated by the parameter p_{chr} that depends on the symbol bit rate (BR), the optical wavelength λ, the velocity of light in vacuum c, the length of the fiber l and the dispersion coefficient D_{chr}

$$p_{chr} = \frac{1}{\pi} BR^2 D_{chr}\, l\, \frac{\lambda^2}{c}. \tag{5}$$

It can be shown that the shrinkage of eye-diagram by 1 dB is achieved when the value of p_{chr} is equal to 0,252 and shrinkage by 2 dB for p_{chr} = 0,321. As plots shown above can be drawn by an equation (5) and the design of digital optical link could be performed by them.

The polarization mode dispersion restricts the maximum length of the fiber and the data rate. In that case, the main criterion for acceptable signal distortions is also the shrinkage of the “eye-diagram” by 1 dB. In order to confirm this requirement the pulse spread due to polarization mode dispersion τ_{pol} must fulfil the condition $\tau_{pol} \le T/10$, where T ($T = 1/BR$) is the symbol repetition time. Taking into account this requirement and equation (2) the length of the fiber can be given by

$$l \le \frac{1}{100\,BR^2 D_{pol}^2}\,. \tag{6}$$

If the fiber length is given then the maximum data rate can be estimated by the expression (6).

IV. Limitations originated from the stimulated scattering

According to the represented principles we can conclude that for a transmission of wideband signals (with high data rates) on a long distance it is necessary to employ lasers with narrow spectral line and great output power. Exactly, this is the objective of the research work in the recent years. At present, lasers on the market transmit optical signals with very narrow band about 10 MHz and at that the power is over 10 mW. The reduction of the optical signal spectrum and the increasing of the power result in several nonlinear effects in the fiber. Especially, that is the stimulated Raman scattering (SRS) and the stimulated Brillouin scattering (SBS). These effects must be taking into account when the design of optical CATV system is performed.

When the power is over a given threshold the SRS scattering is happened and in the fiber are excited undesirable molecular oscillations. These oscillations interact with the optical field and as a result a part of the signal is reflected and the spectral line shifts to the longer wavelength. In the WDM systems, this result in transfer of signal power from short-wave to long-wave channels.

The stimulated Raman scattering (SRS) can be described by so called SRS gain g_R that depends on the frequency shift Δf toward the channel central frequency. When the shift Δf is increased then the coefficient g_R grows and reaches its maximum value of $g_R \approx 7.10^{-14}$ m/W for $\Delta f \approx 13{,}2$ THz (respectively $\Delta\lambda = 100$ nm) after that it decreases. In other words, if the SRS scattering is occurred then the maximum optical power is transferred in the channel with a central frequency that is 13,2 THz lower than the desirable channel and the wavelength is 100 nm greater, respectively. The stimulated Raman scattering can be observed in a very wide frequency band Δf_R, to 40 THz, hence it makes problems in WDM systems where the channel spacing is 100 GHz. This effect has no influence over the single channel optical systems.

In a single channel the power scattering owing to the nonlinear effect described above result in a decreasing of the received optical power and a growth of the noise floor. In other words, the signal-to-noise ratio in the optical receiver output decreases; consequently, the received signal quality is made worse. The maximum power that can be fed to the fiber with absence of unacceptable signal quality worsening, owing to SRS scattering, is restricted by the threshold power $P_{Th}(SRS)$. This threshold is selected in such a way that the power loss in a single channel to be under 3 dB and it can be determined by following expression:

$$P_{Th}(SRS) \approx 16\,S_{eff} \big/ g_R\, l_{eff}\ , \tag{7}$$

where S_{eff} is effective area of the fiber core section and l_{eff} is the fiber length.

Usually in the fiber optic specifications is included the mode field diameter (MFD) and then $S_{eff} = \pi(MFD/2)^2$. The length l_{eff} is given by

$$l_{eff} = \frac{1}{\alpha^*}\left(1 - e^{-\alpha^* l}\right), \tag{8}$$

where l is the actual fiber length in km and α^* is attenuation constant in 1/km. In order to transform the dimension of α, its value in dB/km is divided by the term $10\lg e$ ($e = 2{,}718$).

The typical values of the SRS threshold power $P_{Th}(SRS)$ are close to 1 W (30 dBm), but with N amplifiers included in the optical link this threshold decreases N times.

The stimulated Brillouin scattering (SBS) is occurred when the power fed to the fiber approach a specifically threshold. At that threshold power, acoustic vibrations are excited in the fiber. Because of the interaction between the light and the acoustic wave, the part of the transmitted power is reflected backward to the laser. This results in a growth of the noise floor and decreasing of the received signal level. The SBS scattering is observed in a narrow band Δf_B ($\Delta f_B < 100$ MHz) and it makes problems only in one channel.

This scattering is estimated by the SBS gain g_B that varies in frequency band Δf_B as the SRS gain g_R. The maximum scattering is observed at frequency that has a small shift upward with respect to the channel frequency. For example, at optical frequency band about 1550 nm, respectively 193 THz, the maximum gain g_B is shifted 10 GHz upward to the channel frequency and has a value approximately 5.10^{-11}, m/W.

The threshold power $P_{Th}(SBS)$ in that case is given by

$$P_{Th}(SBS) \approx 21 S_{eff} \big/ g_B\, l_{eff}\ . \tag{9}$$

That is significantly lower (about three orders) than the Raman threshold power.

V. Influence of other nonlinear effects

In addition to the described above, in the fiber can be observed the following nonlinear effects: self-phase and cross-phase modulation and four-wave modulation. These are owing to the relation between the index of refraction n of the fiber core and the launch power P (so called Kerr effect) that can be represented by

$$n = n_1 + n_1^* P \big/ S_{eff}\ , \tag{10}$$

where n_1 is the index of refraction at low power levels and n_1^* - nonlinear index of refraction (for silicon its value is about $3{,}2\cdot10^{-20}$ m^2/W).

Self-phase modulation (SPM) is owing to the fluctuations of the index of refraction n that decreases the phase velocity of the pulse rise edge and increases the phase velocity of the pulse fall edge. These phase variations cause a parasitic frequency modulation (chirp) that spread the pulse spectrum. At the rise edge, the spread is toward the longer wave ("red" shift) and at the fall edge – the shorter wave ("blue" shift). The value of the phase shift for SPM depends on the launch power P, the effective length l_{eff} and the nonlinear propagation coefficient γ and this is given by

$$\Phi(SPM) = \gamma P l_{eff} \,, \qquad (11)$$

where $\gamma = 2\pi n_1^* / \lambda S_{eff}$ ($n_1^* = 3{,}2 \cdot 10^{-20}$ m^2/W). In order to avoid unacceptable distortions of the transmitted NRZ signals the maximum phase shift Φ(SPM) is restricted to π/2.

The cross-phase modulation (XPM) is as the SPM modulation but in that case the phase variation in a given channel depends on the optical power carried by the other channels. Hence, this nonlinear effect is typical for WDM systems. The estimation of the phase shift due to the XPM modulation in a single channel is performed by the following expression:

$$\Phi_i(XPM) = \gamma l_{eff} \left(P_i + 2\sum_{i \neq j} P_j \right), \qquad (12)$$

where P_i is the launch power in the channel and by P_j is denoted the power in the i^{th} channel. Here, the requirement $\Phi(XPM) \leq \pi/2$ is also valid.

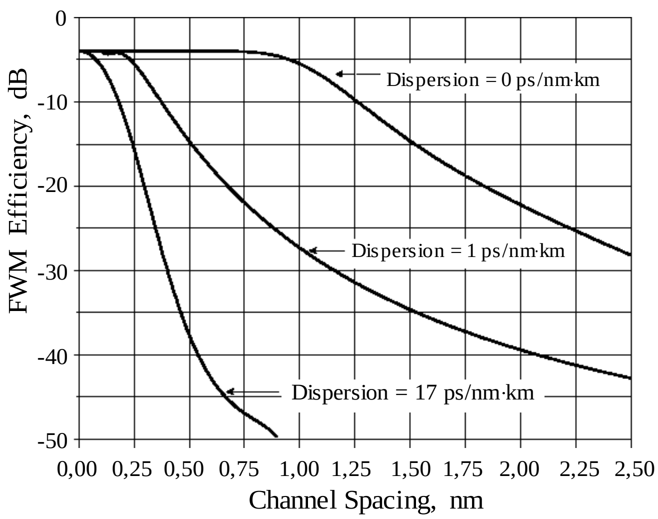

Fig. 3 A relation of the FWM efficiency from the dispersion and the channel spacing

The four wave mixing (FWM) is inherent to the fiber-optic systems that use the technology *DWDM*. This nonlinear effect arises due to the interaction between the signals from three channels with wavelength λ_i, λ_j и λ_k that result in intermodulation component $\lambda_F = \lambda_i + \lambda_j - \lambda_k$. For M-channel system the indexes i, j and k vary from 1 to M and the number of the intermodulation components rises by law $(M^3 - M^2)/2$. Part of these components fall in the main channel bandwidth and can significantly make worse the signals. The FWM modulation is obtained as the composite triple beat (CTB) distortion in the CATV systems.

The four-wave modulation efficiency η depends on the phase relations between the different signals and it has a maximum value when the signals are in-phase. The dispersion in the fiber results in a difference between the group velocity of the transmitted signals and due to the efficiency η decreases. Furthermore, the efficiency depends on the channel spacing, when the channel spacing increases then the efficiency decreases. These relations are shown on Fig. 3 and they are plot in accordance to expressions given in [3].

VI. Conclusions

The represented results allow the correct selection of the fiber. This is performed when the following parameters are given: the fiber length; the signal bandwidth or the data rate; the output signal-to-noise ratio or BER and the acceptable levels of intermodulation components.

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