Influence of Optical Fiber Nonlinear Effects in HFC Television Networks with WDM Multiplexing

Krasen Angelov[1], Kiril Koitchev[2] and Stanimir Sadinov[3]

Abstract – **The modern hybrid cable TV networks use for a backbone network high speed fiber-optical rings. Different nonlinear modulation effects have serious influence on the transmitted signals in the optical fiber as well as nonlinear effects due to lightwave scattering. These effects are directly related to the power of the transmitted signal and therefore they cause limitation in the launched in the optical fiber top permissible power. The nonlinear effects are main limiting factor for the transmission rate of digital information on optical fibers. This paper will deal with the analysis of the optical fiber nonlinear effects and an evaluation of their influence on the transmitted signal.**

Keywords – **SBS, SRS, SPM, FWM, HFC**

I. Introduction

The fiber optical cables as a transmission environment are very widely applied as a backbone network for signal transmission in hybrid fiber-coaxial (HFC) cable television networks. The main purpose is transmitting the signals with carrier-to-noise ratio (*CNR*) bigger than *46dB*, composite second order distortions (*CSO*) not worse than *-62dBm*, and composite third order distortions (*CTB*) not worse than *-65dBm*.

In wavelength division multiplexing (WDM) system a multiplexing is realized when transmitting a few optical carrier wavelength in one optical flow and demultiplexing when receiving the flow. The signal gain on the transmission channel is realized by EDFA optical amplifier. The gain factor of about *20* to *25 dB* of the amplifier allows losses compensation input by the passive elements of the multiplexer and demultiplexer, including many other devices [1, 2, 3].

In order to achieve longer transmission distances or to provide more fiber splits, higher optical power needs to be launched into the optical fiber. In this situation the nonlinear interactions between the optical signal and the optical system start making sense.

The optical fiber nonlinear effects could be divided into two main groups:

– nonlinear effects related to light scattering – stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS);

– nonlinear effects related with variation of the reflection index- they are a result of the dependence of refraction index of optical power intensity – self- phase modulation (SPM), the cross-phase modulation (XPM) and the four wave mixing (FWM).

The main problem with the nonlinear distortions is that they are always related to the power level of the transmitted signal, therefore they cannot be removed at the point of signal receiving without its parameters being changed.

In this paper an analysis of the optical fiber nonlinear effects will be made and an evaluation of their influence on the characteristics of the transmission medium and signals transmission.

II. Nonlinear effects influence related with light scattering

A. Stimulated Brillouin Scattering Effect

The stimulated Brillouin scattering (SBS) effect converts the transmitted optical signal in the fiber to a backward-scattered signal, and thus limits the maximum optical power that can be launched into the single-mode fiber (SMF). The SBS process generates a backward-propagating light beam at a lower frequency. Above the so-called SBS power threshold, the optical power of the backward-scattered signal increases exponentially, leading to significant optical power losses. The injected optical power level at which this increase happens, is defined as SBS threshold. Based on Smith's condition [4], the SBS power threshold is defined when the backward-scattered power is equal to the injected power, which for a uniform fiber is given by [5]

$$P_{SBS} = \frac{21\alpha A_{eff}}{\left(1-e^{\alpha L}\right)g_B}\left(1+\frac{\Delta v_L}{\Delta v_B}\right), \tag{1}$$

where A_{eff} is the effective fiber core area, α – fiber loss coefficient, L – total fiber length, g_B – peak Brillouin gain and is given by

$$g_B = \frac{2\pi K n^7 p_{12}^2}{c\lambda^2 \rho_0 V_a \Delta v_B}, \tag{2}$$

where n is the fiber refraction index, ρ – material density, V_a – acoustic velocity, p_{12} – elasto-optic coefficient, K – accounts for the optical field polarization, Δv_L – laser

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linewidth, Δv_B – spontaneous Brillouin linewidth of the fiber. For silica-based fibers, the Brillouin gain bandwidth is about *20MHz* at *1550nm*.

From Eq. (1) is viewed that the SBS threshold depends on the fiber length where the dependence is conversely proportional to the effective fiber length L_{eff} ($L_{eff}=(1-e^{\alpha L})/\alpha$) and exponential to the total fiber length L (Fig.1).

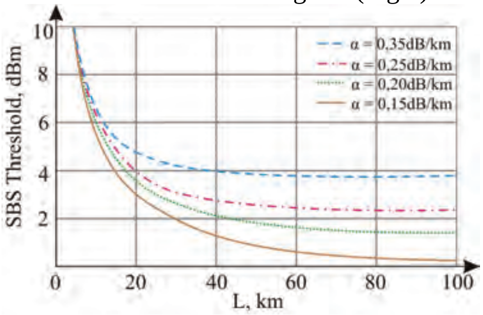

Fig. 1. The dependence of the SBS threshold level of the total fiber length for different fiber loss coefficient

Eqs. (1) and (2) indicate that the SBS threshold is directly proportional to Δv_B. For a standard single-mode fiber, $g_B=2.10^{-9}cm/W$ and the SBS threshold without modulation is approximately *6dBm* (*4mW*) at *1550nm* and *9dBm* (*8mW*) at *1310nm*. In addition to the dependence of the SBS threshold on the fiber type and uniformity along its length, the SBS threshold depends on the specific optical system requirements such as modulation format, symbol rate, and modulation type (i.e., direct or external). At the same time it does not depend on the WDM channel number.

As injected optical power is increased above *+6dBm*, the SBS scattered power dramatically picks up and the *CNR* rapidly degrades. The SBS also includes *CSO* and *CTB* distortion degradations in externally modulated *1550nm* laser transmitters, which are typically used due to the chromatic dispersion degradation. The *CSO* and *CTB* distortions can be approximated by [6]

$$CSO_{(dB)} = 10\lg\left\{ N_{CSO}\left[\frac{(1-\sigma)m}{4\sigma}\right]^2 \right\}, \tag{3}$$

$$CTB_{(dB)} = 10\lg\left\{ N_{CTB}\left[\frac{3(1-\sigma)m^2}{16\sigma}\right]^2 \right\}, \tag{4}$$

where $\sigma=(1-R_{BS}/0{,}85)/2$ is the fractional transmission coefficient for the single-mode fiber that was empirically estimated from the ratio of the backward-scattering power to the injected power (R_{BS}), m – modulation index, N_{CSO} and N_{CTB} are the *CSO* and *CTB* product counts.

To maintain the *CSO* distortion below *-62dBc*, the backward-scattered power should be less than *-20dB*, corresponding to a SBS threshold power of about *14dBm*, to achieve the necessary phase-modulation index.

The usual signal levels in CATV at wavelength *1550nm* often cause SBS effect because usually they range *8 - 14 dBm*, i.e. over the SBS threshold.

One of the most used methods for SBS effect reduction (i.c. increase of SBS threshold) is to apply a low frequency dithering of the optical frequency of the laser transmitter by modulating the laser bias current resulting in a broader effective laser line-width. The SBS threshold power increase can be obtained from

$$\Delta P_{SBS}^{th}(\Delta v_D) = 10\lg\left(1+\frac{\Delta v_D}{\Delta v_B}\right). \tag{5}$$

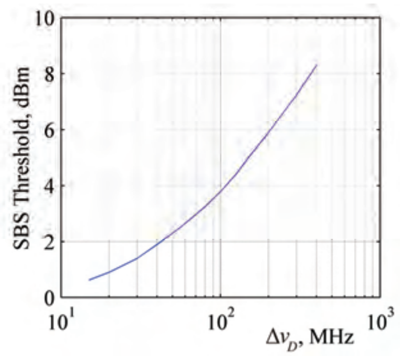

Fig. 2. SBS threshold versus the time average effective laser linewidth Δv_D

Fig. 2 shows the calculated from Eq. (5) SBS threshold increase versus the time average effective laser linewidth Δv_D. This method can easily provide an SBS threshold above *+20dBm* by allowing a frequency excursion above *1GHz*, and requires only a low-power laser current modulation.

It is necessary to note that the SBS threshold depends on the number of the EDFA optical amplifiers used; as well as knowing that with the increase of their number the power threshold decreases. For a system with optical amplifiers the SBS threshold power will be

$$P_{SBS\,N,[dBm]} = P_{SBS,[dBm]} - 10\lg N\,. \tag{6}$$

B. Stimulated Raman scattering effect

The stimulated Raman scattering (SRS) effect makes considerably lesser problems compared to the stimulated Brillouin scattering effect. This effect causes signal degrading only when the optical power level is high. In WDM systems the influence of this kind of light scattering is composed by lightwave scattering and its specter mixing in the long-wave area, where a redistribution of the optical power from short-wave to long-wave channels is realized.

The SRS threshold is much bigger (with about *3* levels) compared to SBS. The minimum SRS threshold power is given by [4]:

$$P_{SRS} \approx \frac{16\alpha K A_{eff}}{\left(1-e^{\alpha L}\right)g_R}, \tag{7}$$

where A_{eff} is the effective fiber core area, α – fiber loss coefficient, L – total fiber length, g_R – peak Raman gain, зависещо от честотата на излъчване на сигнала и от свойствата на материала, K – accounts for the optical field polarization.

The dependence of the SRS threshold level on the fiber length for fibers with different coefficient of optical losses is shown on Fig.3.

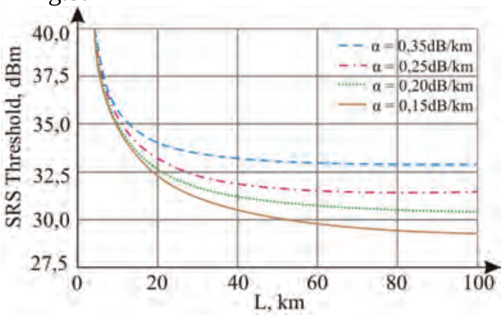

Fig. 3. The dependence of the SRS threshold level on the fiber length for fibers with different coefficient of optical losses

The power redistribution from short-waves channels to long-waves a result of the SRS effect leads to signal-to-noise ratio decrease for short-waves channels. As a result the total system's transmission capacity is limited, recognizing limitation of the total WDM channel number, channel spacing along wavelength, total system length and average launched power.

III. NONLINEAR EFFECTS INFLUENCE RELATED WITH VARIATION OF THE REFLECTION INDEX

A. Self-Phase Modulation Effect

The self-phase-modulation (SPM) effect occurs due to the interaction between the fiber's chromatic dispersion and the modulated optical spectrum of the propagating signal in the fiber. *CSO* and *CTB* distortions are generated when high-power (below the Brillouin threshold) optical signals are transmitted through a dispersive nonlinear optical fiber [7, 8 3]. The SPM effect named since the lightwave signal propagating through the fiber modulates its own phase.

The self-phase modulation leads to transmitted impulse expansion and temporary signal expansion or compression. In WDM systems with very small channel spacing, the spectral expansion caused by SPM influence, make result in interference between neighboring channels.

The analytical decision for the resulting SPM *CSO* distortions has the following view [9]

$$CSO_{SPM}(\Omega) = N_{CSO}\left[\frac{mP_0}{2A_{eff}}\left(\frac{L-L_{eff}}{\alpha}\right)\beta_2 k n_2 \Omega^2\right]^2, \quad (8)$$

where N_{CSO} is the *CSO* product count, m – optical modulation index per channel, P_0 – average optical power, A_{eff} – effective fiber core area, L – total fiber length, L_{eff} – effective interaction length, α – fiber loss coefficient, $\beta_2=-D\lambda^2/2\pi c$, D – dispersion coefficient of the fiber, n_2 – nonlinear refraction index of the fiber, Ω^2 – subcarrier frequency.

Since the resulting *CTB* distortion caused by SPM was more than *30dB* smaller than the *CSO* distortion, it is neglected.

B. Cross Phase-Modulation Effect

The cross phase- modulation (EXP) is quite similar to SPM but is completely typical for WDM systems [9]. XPM is a result of a refraction index variation of the fiber when lightwave intensity increases.

XPM effect increases the nonlinear phase shift with *2N*, where *N* is the number of the working optical channels in the optical fiber. At this situation a bigger dependence on fiber dispersion compared to SPM is viewed.

A XPM decrease could be achieved by using optical fibers with large effective fiber core area, and, if it is possible the level of the channel optical power to be decreased.

C. Four Wave Mixing Effect

The four wave mixing (FWM) occurs only in multichannel light-wave systems and by its character it is similar to *CTB* distortions. It can completely destroy the WDM system.

Every time when three or more signals are propagated along the fiber, a four wave mixing might be expected. These three lightwave signals ω_i, ω_j, ω_k, generate a forth signal ω_{ijk}, obeying the ratio:

$$\omega_{ijk} = \omega_i + \omega_j + \omega_k \,. \quad (9)$$

The FWM level is sensible to the following system characteristics:

– increase of the optical power in the channel;
– increase of channel number;
– channel spacing decrease.

For the WDM system with channel number *N*, the total number of originating as a result of the FWM activity frequencies is

$$N_\Sigma = \frac{N^2(N-1)}{2}\,. \quad (10)$$

For example for a four channel WDM system the number of the additional channels is *24*, and for eight channel system – *224*.

The FWM level significantly decreases in systems with channel spacing *100MHz.*

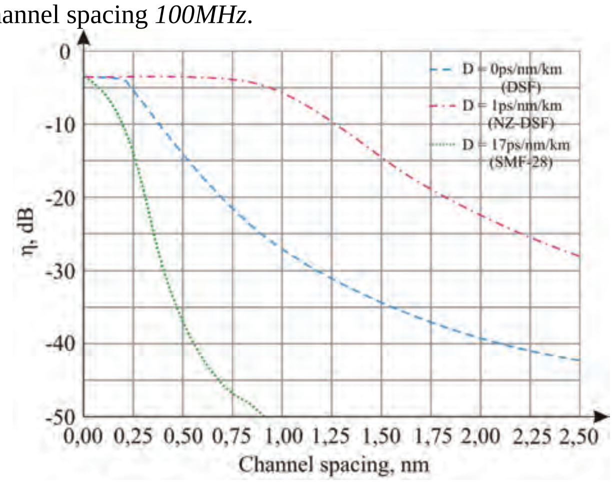

Fig. 4. FWM efficiency according channel spacing with different amounts of dispersion coefficient *D* of the fiber

In Fig.4 the FWM efficiency according channel spacing with different amounts of dispersion D coefficient of the fiber is shown.

The power level of the forth wave depends on multiple factors and can be written as

$$P_4(L) = \eta \left(\frac{1024\pi^6}{n^4 \lambda^2 c^2} \right) \left(\frac{L_{eff}}{A_{eff}} \right)^2 (DX_3)^2 P_1 P_2 P_3 e^{(-\alpha L)}, \quad (11)$$

where η is the four-wave mixing efficiency, L – total fiber length, L_{eff} – effective interaction length, λ – wavelength, c – light speed, DX_3 – degenerating factor depending on channel spacing and chromatic dispersion of the fiber, α – fiber loss coefficient. The four-wave mixing efficiency η could be deducted as

$$\eta = \frac{P_4(L,k)}{P_4(L,k=0)} = \frac{\alpha^2}{\alpha^2 + k^2} \left[1 + \frac{4e^{-\alpha L} \sin^2(kL)}{\left(1 - e^{-\alpha L}\right)^2} \right], \quad (12)$$

where k is a coefficient depending on the channel spacing and the condition of polarization sequence.

FWS decreases with the decrease of the absolute value of the chromatic dispersion. Moreover when the composite harmonics come to the working channel frequencies, a parametric interference originate, which might bring to an increase or to a decrease of the working impulse amplitude depending on the phase ratio among the working signal and the side-bands signals. The parametric losses cause close of the eye-diagram at the receiver outlet, resulting in worsening the BER level.

IV. Conclusion

The various nonlinear effects in an optical fiber limit the upper bound of the injected optical power in the optical part of HFC access network, which sets a limit to signal-to-noise ratio, and therefore a maximum transmission capacity of the optical system.

One of the possibilities for decreasing SBS and SRS influence is by decreasing the optical power of the channel below their threshold levels. But it is not a good decision, because it needs a using additional EDFA amplifier which worsens the threshold levels. Also the carrier-to-noise ratio is decreased.

The mostly used method for effects influence decrease is increasing the specter of the laser linewidth. Therefore laser sources with external modulation or continues wave are used, which also save the RIN level in its acceptable limits (*-155dB\Hz*).

The nonlinear effects mostly depend on the type of the optical fiber used. The threshold levels SBS and SRS could be changed depending on the type of the optical fiber. For DSF fibers (G.653) the SBS threshold is several times smaller than for systems with standard single-mode fibers (G.652). It could be concluded that this is true for all nonlinear effects.

At WDM systems it is suitable to use NZ-DSF fiber (G.655). In this fiber a limited chromatic dispersion is kept in working range. This leads to a decrease of the undesired influence of other nonlinear effects – self-phase modulation and cross-phase modulation. This type of fiber also reduces the effect of the four-wave mixing.

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