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Measurements of Nonlinear Coefficient in OS2 Optical Fiber

J. Porins, G. Ivanovs, A. Supe
Institute of Telecommunications, Riga Technical University,
Azenes st. 12, LV-1010 Riga, Latvia, phone: +371 27896222; e-mail: jurgis.porins@rtu.lv

Introduction

The fiber optic transmission systems (FOTS) extensively used now worldwide stem from the development of two main technological directions. First of them is obtaining low-loss SiO_2 fibers, whereas the other is the development of corresponding high-speed (R>10Tbit/s) optical devices (e.g. semiconductor lasers, light diodes, etc.) [1,4]. In the past years owing to cooperation of physics and chemistry branches, new fiber types with small dispersion and attenuation have been obtained, which are used in long haul FOTS and local area networks (LAN). Nowadays, the fiber optics is employed not only for creation of global and local computer networks but also for a private network's needs; at the same time, the rapid increase in the power put into an optical fiber (OF) gives rise to such side phenomena as nonlinear optical effects (NOE). Therefore, when planning and designing high speed (R>1Gbit/s) FOTS in which new fiber types of single mode OF (SMF) and standards are employed, such as the OS2, it is necessary to perform a preliminary estimation of their operation and the NOE in order to reduce their influence.

The OF used in communication technologies do not possess a high nonlinearity coefficient; however, the nonlinear phenomena can be observed at very high intensities of light and at large transmission distances [1]. Although the power used at transmission of signals is not very high− several mW or some tens of mW − the light intensity in a fiber is very high [4, 5]. This is owing to the fact that the cross-section of the optical fibers employed in communication technologies is very small− 10^{-7}-10^{-8} cm^2 for a single mode fiber− so the light intensities acting upon a fiber reach as much as several GW/cm^2. Such an intensity value is sufficient for inducing nonlinear effects, thus significantly influencing the light propagation in a fiber over different distances.

An optical fiber is characterized by nonlinear quantities, the most significant of which are its effective cross-section area, A_{eff}, and nonlinear length L_{NL} [1, 2].

The majority of NOEs arise in a fiber owing to nonlinear refraction, since at high light intensities the OF refractive index is determined by its dependence on the intensity:

$$n = n_0 + n_2 I = n_0 + n_2 \frac{P}{A_{eff}}, \qquad (1)$$

where n_0 – the linear refractive index; n_2 – the nonlinear refractive index; I – the light radiation intensity; P – the maximum radiated power; A_{eff} – the OF effective cross-section area.

The nonlinearity effect in an OF is growing with the intensity increasing, which, in turn, is inversely proportional to its core area. The light radiation power spreads non-uniformly over the OF core cross-section; it is greater along the OF central axis as compared with that in the vicinity of the core covering surface; when spreading, this power is even pressing into the covering, following the real profile of the OF refractive index. The OF cross-section area is very significant for NOE manifestation; therefore it is necessary to know the distribution of light radiation power in a fiber. Due to non-uniform propagation of radiation in the communication technologies the OF effective cross-section area, A_{eff}, is employed. The definition of this parameter takes into account/includes the OF cross-section area and the intensity distribution over the cross-section. In the general case, A_{eff} is defined as [1]:

$$A_{eff} = \frac{\left(\iint_{-\infty}^{\infty} |F(x,y)|^2 \, dxdy\right)^2}{\iint_{-\infty}^{\infty} |F(x,y)|^4 \, dxdy}, \qquad (2)$$

where $F(x,y)$ – the mode distribution in a fiber. It is clearly seen that A_{eff} is dependent on the OF parameters: the core radius and the difference in the core and cladding refractive indices. Approximating $F(x,y)$ with Gaussian distribution, for a single-mode fiber we obtain:

$$A_{eff} = \pi w^2, \qquad (3)$$

where w – the mode width parameter. This approximation cannot be applied to a fiber whose refractive index profile is not step index, for example, to a DSF. Depending on the OF type and producer, the A_{eff} value usually varies in the range 20-100 μm^2 at a wavelength of 1.5 μm. Besides, fibers with a large effective area A_{eff} are produced– this value is increased in order to reduce the OF nonlinearity [1, 6].

The nonlinear phase shift ϕ_{NL} depends on the OF length L and the effective length L_{eff}, where $L_{eff} < L$ owing to losses α. The effective length is defined as [1]

$$L_{eff} = \frac{1-e^{-\alpha L}}{\alpha}. \qquad (4)$$

The phase maximum is found from the relationship [7]

$$\phi_{max} = L_{eff} / L_{NL} = \gamma P_0 L_{eff}, \qquad (5)$$

where L_{NL} – the OF nonlinear length; P_0 – the power; γ – the nonlinear coefficient. In turn, the nonlinear coefficient is expressed as [1, 10]

$$\gamma = \frac{2\pi n_2}{A_{eff}\lambda}. \qquad (6)$$

From relationship (6) the physical sense of L_{NL} follows as the effective propagation length at which $\phi_{max} = 1$.

In order to determine n (1) at high intensities it is necessary to compare this coefficient with some constant value. For this purpose the nonlinear coefficient

$$\gamma = \frac{2\pi \cdot n_2}{\lambda_s A_{eff}} \qquad (7)$$

is often measured. In this expression λ_s is the signal wavelength in vacuum. The determination of refractive index n_2 is usually done first measuring γ and A_{eff}, and then calculating n_2 [10].

Experimental and simulation scheme and parameters

For determination of coefficient γ for different OF types various methods are offered– both interferometric and non-interferometric [3, 7]. In this research we used three methods (continuous wave self phase modulation (CW SPM), pulse phase self-modulation (P-SPM) and cross phase modulation (XPM)), but better results, compared simulations and experiments, we obtained by the P-SPM method. The advantage of the measuring method is that it is not necessary to use a separate pulse source but a continuous wave laser can be used instead.

Our simulation and experimental scheme (Fig. 1.) employs one optical channel with external intensity modulation (IM). The high power tunable laser source with wavelength resolution 1pm (full-width-at-half-maximum (FWHM) of 50 MHz), reference wavelength λ = 1550 nm always switched on and its light waves are modulated via the electro-optic Mach-Zender modulator (MZM) by data 10Gbit/s pulse sequence output of a pulse pattern generator (PPG). MZF optical insertion loss by 10.7 Gbit/s is < 5 dB. The signal is amplified by the erbium-doped fiber amplifier (EDFA). After amplification signal is sent to various type of fibers (OS2, SSMF and DSF), where optical pulses are propagating over a 1 km [9]. Attenuation was changed with variable optical attenuator. The simulation method of calculation is based on solving a complex set of differential equations, taking into account optical and electrical noise, linear and nonlinear effects. We used model where signals are propagating as time domain samples over a selectable bandwidth. The Time Domain Split Step (TDSS) method is used to simulate linear and nonlinear behavior for both optical and electrical components.

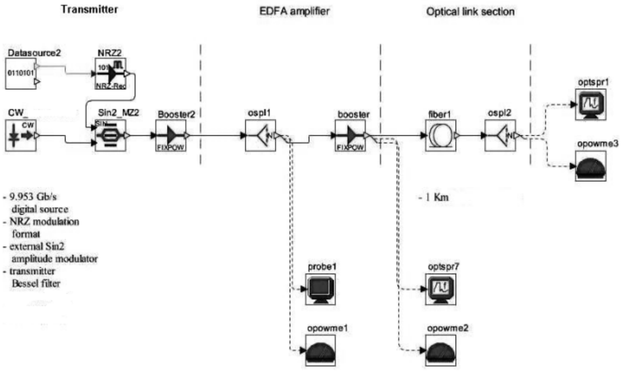

Fig. 1. Experimental and simulation scheme

During its propagation in an OF the pulsed signal is subjected to the SPM action, which leads to a nonlinear phase shift and appearance of sidebands in the optical spectrum of the signal or generations of spectral components. From the spectral picture, which can be observed with the help of OSA, it is possible to calculate the relationship between the initial frequency and generated 1st order side frequency intensities by the following expression [7]:

$$\frac{I_0}{I_1} = \frac{J_0^2(\phi_{SPM}/2) + J_1^2(\phi_{SPM}/2)}{J_1^2(\phi_{SPM}/2) + J_2^2(\phi_{SPM}/2)}, \qquad (8)$$

where I_0 and I_1 – the intensities of the zeroth and 1st order harmonics; J_n – the n-th order Bessel functions. Ignoring dispersion, the nonlinear phase shift ϕ_{SPM} can be expressed as a function of I_0/I_1 from formula (8). The variables of this formula can be measured easily enough with the help of this scheme. The measurements are performed for short OFs only, so that the OF losses and dispersion do not affect the measurement results [11]. P-SPM measuring method requires a relatively low average power that is concentrated in very short pulses supplied by a laser pulse source with high peak intensity. The spectral extension for the Gaussian pulses under P-SPM influence can be calculated as

$$\frac{(\Delta\omega)_{out}}{(\Delta\omega)_{in}} = \sqrt{1 + \frac{4}{3\sqrt{3}}(\gamma \cdot P \cdot L_{eff})^2}, \qquad (9)$$

where $\Delta\omega$ is the mean-square value of the spectral width, and P is the peak power. Performing the measurements by this method it is possible to obtain very precise results. However to do this, detailed information is needed about the shape of the introduced pulse; also, it is necessary to know the fiber's dispersion and attenuation, since these parameters can significantly affect the output spectrum. To describe results mathematically we use the least square method [12]. Measurement accuracy was 3%. Measurement results with P-SPM method with and without VOA for DSF and OS2 fibers shown in Fig. 2 till 5. Calculated values of n_2 and n_2/A_{eff} for different fibers, which is measurement P-SMP method shown in Table 1.

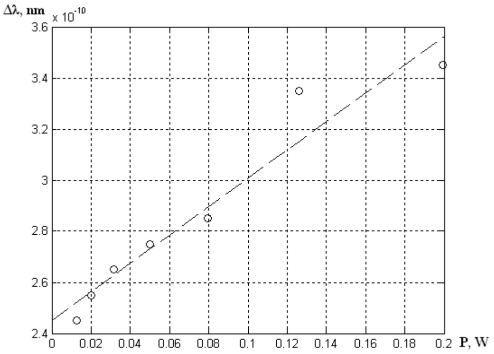

Fig. 2. Measurement results with P-SMP for DSF fiber

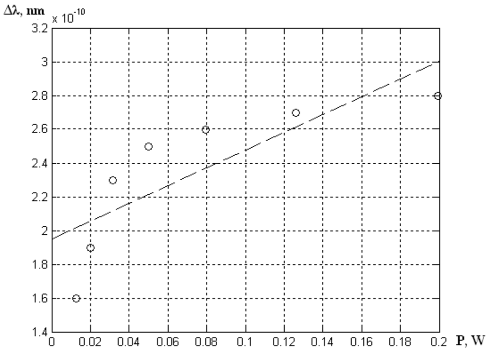

Fig. 3. Measurement results with P-SMP for OS2 fiber.

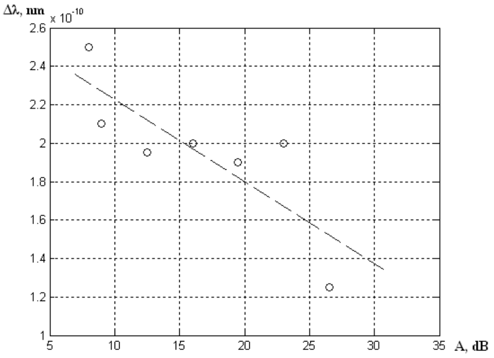

Fig. 4. Measurement results with P-SMP and VOA for OS2 fiber

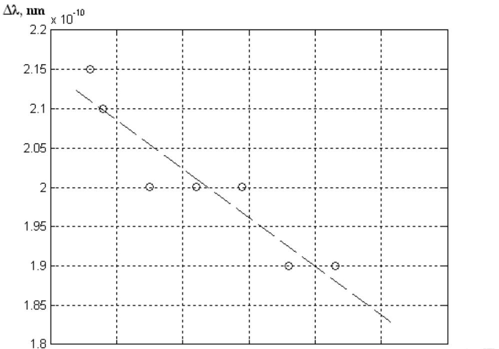

Fig. 5. Measurement results with P-SMP and VOA for DSF fiber

To study the P-SPM measuring methods with simulation software OptSim output spectrum for 10Gbits scheme shown in Fig. 6. Knowing that the NOEs arise under the influence of light intensity, the input power of the CW lasers is changed from 15 to 23 dBm

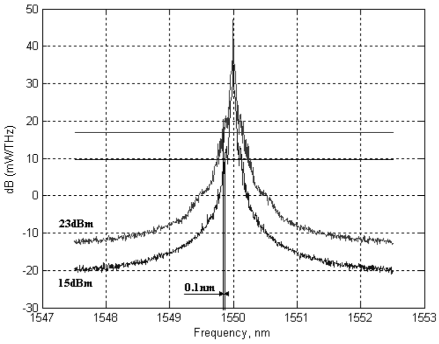

Fig. 6. Output spectrum for 10Gbits 15 till 23dBm with P-SMP

Table 1. Values of n_2 and n_2/A_{eff} for different fibers

Parameter	OS2	SSMF	DSF
n_2, (m^2/W)	$2.883*10^{-20}$	$3.609*10^{-20}$	$4.210*10^{-20}$
n_2/A_{eff}, (1/W)	$2.362*10^{-10}$	$5.552*10^{-10}$	$5.263*10^{-10}$

Conclusions

The computer simulations and experiments of the P-SPM and CW SPM measuring techniques allow for the statement that in the method with a laser source of pulses the OF influence on the propagation of optical signal is noticeably greater, since there is pronounced pulse spectrum extension due to a shift in the nonlinear phase; in turn, in the case of a CW laser source in the spectrum infinitesimal additional spectral components arise. This means that the FOTS SPM would give rise to considerable pulse extension, and, consequently, also to a decrease in the data transmission speed. With the help of CW SPM, P-SPM and XPM measuring methods the following parameters have been determined experimentally: nonlinear coefficient n_2/A_{eff} and nonlinear refractive index n_2; accordingly, n_2/A_{eff} is calculated to be in the range $1.24 \cdot 10^{-12}$ - $5.26 \cdot 10^{-10}$ 1/W, whereas n_2 − in the range $3.38 \cdot 10^{-23}$ - $4.21 \cdot 10^{-20}$ m^2/W depending of the fiber type; it is established that at increasing laser power the values of these coefficients decrease but the nonlinear phase shift φ_{SPM} increases. As seen from results the OS2 fibers have smaller variation of nonlinear coefficient values at different measurement methods in contrast to SSMF and DSF fibers. OS2 fiber n_2 value stability are in the limits from $2.88 \cdot 10^{-20}$ in case of P-SMP method to $2.9 \cdot 10^{-21}$ m^2/W in case of CW SMP method.

When using EDFA amplifiers in the measurements it should be taken into account that increase in the input signal power above the noise power at the amplifier's input will lead to changes in amplification. To avoid this, the input signal should be smaller than -45 dBm.

The results obtained could be used at planning and implementation of the fiber optic transmission systems, and especially high speed LAN where are OS2 fiber type is required.

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The nonlinear coefficient of the various optical fibers types has been experimentally and with OptSim 5.0 simulation software studied. With the help of CW SPM, P-SPM and XPM measuring methods the following parameters have been determined experimentally: nonlinear coefficient n_2/A_{eff} and nonlinear refractive index n_2; accordingly, n_2/A_{eff} is calculated to be in the range $1.24\cdot10^{-12}$ - $5.26\cdot10^{-10}$ 1/W, whereas n_2 − in the range $3.38\cdot10^{-23}$ - $4.21\cdot10^{-20}$ m^2/W. As seen from results the OS2 fibers have smaller variation of nonlinear coefficient values at different measurement methods in contrast to SSMF and DSF fibers. OS2 fiber n_2 value stability are in the limits from $2.88\cdot10^{-20}$ m^2/W in case of P-SMP method to $2.9\cdot10^{-21}$ m^2/W in case of CW SMP method. Ill. 6, bibl. 12, tabl. 1 (in English; abstracts in English, Russian and Lithuanian).

Ю. Поринс, Г. Ивановс, А. Супе. Измерения нелинейного коэффициента в оптическом волокне OS2 // Электроника и электротехника. – Каунас: Технология, 2010. – № 5(101). – С. 53–56.

Экспериментально и с помощью программного обеспечения OptSim 5,0 для моделирования изучен нелинейный kоэффициент различных типов оптических волокон. С помощью CW SPM, P-SPM и XPM методов измерения были экспериментально определены следующие параметры: нелинейный коэффициент n_2/A_{eff} и нелинейный показатель преломления n_2; соответственно, n_2/A_{eff} рассчитывается в диапазоне $1.24 \cdot 10^{-12} – 5.26 \cdot 10^{-10}$ 1 / W, а n_2 - в диапазоне $3.38 \cdot 10^{-23} – 4.21 \cdot 10^{-20}$ m^2/W. Как видно из результатов, при различных методах измерения, OS2 волокна имеют меньшие изменения нелинейного коэффициента, в отличие от SSMF и DSF волокон. Коэффициент n_2 OS2 волокна стабилен в пределах $2.88 \cdot 10^{-20}$ m^2/W и $2,9 \cdot 10^{-21}$ m^2/W значений, в случае использования P-SMP и CW SMP методов соответственно. Ил. 6, библ. 12, табл. 1 (на английском языке; рефераты на английском, русском и литовском яз.).

J. Porins, G. Ivanovs, A. Supe. OS2 optinio pluošto netiesinių koeficientų matavimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2010. – Nr. 5(101). – P. 53–56.

Eksperimentiškai ir programiniu modeliavimu nustatyti OS2 optinio pluošto netiesiškumo koeficientai. Surastas netiesiškumo koeficientas – $3,38\cdot10^{-23}–4,21\cdot10^{-20}$ m^2/W. Pastovumo koeficientas gautas kur kas geresnis už klasikinio optinio pluošto. SSMF ir DSF koeficientas sudaro $2,88\cdot10^{-20}$ $m^2/W–2,9\cdot10^{-21}$ m^2/W. Il. 6, bibl. 12, lent. 1 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).