THE NONLINEAR PROPERTIES OF OPTICAL FIBERS WITH STRUCTURED MEMBRANE

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The calculative and experimental data for microstructured fibers, carried out on the base of quartz, layered materials of A_3B_6 and $LiNbO_3$ type are given.

The experimental and theoretical works in the area of cable transmission of light energy had been begun in 60-ties of XX century. The practical realization and introduction of these works became possible from the moment of creation of stable optical connection lines, the main role in which the fiber-optical cables on the base quartz and glass, light sources – optical quantum generators, optical parametric regenerator amplifiers of optical signals, optical holographic diffractional lattices, CCD-receiving matrixes, optoelectronic devices of decoding were played. The maximally possible parameter values, corresponding with theoretical estimations and models, treated in refs of Kogelnik (1958), Kayzer (1974), Rassel's group (1996), Stegeman's group (1986) and others have been already achieved for the traditional direction of technology development of optical cables in last decades. It is need to note, that the list of single-mode optical fibers by G652 is given in second number of "light-wave", 2003 journal.

The high technology, simplicity and the main, wide accessible materials for the carrying out – glass, quartz, causes to MS (microstructured), and especially PhC (photonocrystallic)-fibers, as the development analysis of this direction shows. The optical fiber with record small damping (0,151 db/km on wave length 1568 nm, losses on Rayleigh scattering are 0,128 db/km, summary losses on the absorption are 0,018 db/km, losses on perfect fibers are 0,004 db/km, common losses aren't than 0,16 db/km) has been created in "Sumitomo" company. The fiber had been prepared with core from pure quartz of high degree of homogeneity, surrounded by two membranes from quartz, doped by fluorine. The theoretical estimations show, that use of this fiber in communication system allows us to increase the distance between the transponders till 330km.

Usually, MS-fibers present themselves the quartz or glass microstructure with periodical or aperiodic situated air apertures. Such structure allows to rule the dispersion of waveguide modes because of the nonlinear properties of material membrane, changes of membrane structure, and also localization value of electromagnetic radiation in their core, connected as with radiation power, diffusive on the fiber, so with difference of indexes of refraction of core and cladding as the refs [1-8] show. The waveguide modes in such fibers form because of the phenomena of internal reflectance on the boundary between quartz or glass core and MS-membrane, the effective index of refraction of which is lower, cladding index of refraction because of the presence of air apertures, and also interference of reflected and scattered waves [9-10]. The important result of periodicity of situation of air apertures is the appearance of photon forbidden bands. The ruling of degree of radiation localization in fiber core and parts of radiation power, diffusive in it, is achieved because of the change of gas concentration in membrane [11-13].

The calculative and experimental data for microstructured fibers, carried out on the base of quartz, layered materials of A_3B_6 type, for example GaSe and $LiNbO_3$ are given in the given message.

The quartz MS-fibers were prepared on standard method, by the way of drawing at high temperature from mold, taken from hollow tubes. In the case of $LiNbO_3$ monocrystals the aperture system with periodical structure was drifted on. The crystal structure of Gas, GaSe, InSe crystals present itself the consecution of loosely coupled layers; the gap between the layers is 3-4Å [14]. These layered materials are related to photon crystals. Many investigations, for example refs [15-17] are dedicated to the investigation of optical properties, and also band structure. The $LiNbO_3$ is well known nonlinear crystal [18-19].

Taking under the consideration, that interaction length in mode of hard focusing is limited by length of stop mark region, in case of Gaussian beam the values of specific enlargement factor of efficiency of nonlinear-optical processes in fiber, are defined by well known expression [20] $\frac{I_f l_{eff}^f}{I_t l_{eff}^t} \approx \frac{\lambda}{\pi w_0^2 \alpha}$, where α is loss factor (αl>>1), l is fiber length; l_{eff} is effective interaction length; w_0 is radius of stop mark of focused beam; λ is radiation wave length; f and t are indexes, taking under the consideration the conditions for fiber and hard focusing, $I_{eff}^t \approx \frac{\pi w_0^2}{\lambda}$. $\xi = \frac{I_f l_{eff}^f}{I_t l_{eff}^t} \approx \frac{\lambda\eta}{\pi a^2 \alpha}$ is obtained, taking under the consideration the radiation distribution between core and membrane fiber for factor of waveguide efficiency increase of nonlinear process without taking under the consideration of radius a of fiber core, and also imaging $I{\cdot}l_{eff}$ in the $I_f l_{eff}^f = \int_0^l dz \frac{P\eta}{\pi a^2} \exp(-\alpha z)$ form, where η is radiation part, localized in core (αl>>1). The radiation part, localized in core of MS fiber was defined according to [7,21], when after the simplifications it is followed:

$$\eta = \frac{\Xi_{core}}{\Xi_{core} + \Xi_{clad}}$$

$$\Xi_{core}=\frac{\beta}{J_1^2(u)}\left\{a_1a_3\left[J_0^2(u)+J_1^2(u)\right]+a_2a_4\left[J_2^2(u)+J_1(u)J_3(u)\right]\right\}$$

$$\Xi_{clad}=\frac{\beta}{K_1^2(w)}\frac{u^2}{w^2}\left\{a_1a_5\left[K_0^2(w)-K_1^2(w)\right]+a_2a_6\left[K_2^2(w)+K_1(w)K_3(w)\right]\right\}:$$

Here

$$a_1=\frac{f_2-1}{2};\ a_2=a_1+1;\ a_3=\frac{f_1-1}{2};$$
$$a_4=a_3+1;\ a_5=a_3+\Delta;\ a_6=a_4-\Delta;$$

$$f_1=\frac{(uw)^2}{v^2}\left[b_1+(1-2\Delta)b_2\right];\ f_2=\frac{V^2}{(uw)^2(b_1+b_2)};$$
$$b_1=\frac{1}{2u}\left(\frac{J_0(u)}{J_1(u)}-\frac{J_2(u)}{J_1(u)}\right);b_2=\frac{1}{2w}\left(\frac{K_0(w)}{K_1(w)}+\frac{K_2(w)}{K_1(w)}\right);$$

$$\Delta=\frac{1}{2}\left(1-\frac{n_{clad}^2}{n_{core}^2}\right);\ v=kan_{core}\cdot\sqrt{2\Delta};\ k=\frac{2\pi}{\lambda};$$
$$\beta=\frac{n_{core}}{\sqrt{1-\left(\frac{u}{akn_{core}}\right)^2}};\ w=\sqrt{v^2-u^2};\qquad ;$$

v is waveguide parameter; β is constant of mode distribution; w is mode parameter in membrane; $J_n(u)$ is Bessel function of genre one; $K_n(u)$ is modified Bessel function of genre two; u is mode parameter in fiber core [28].

The dependence ξ on a, calculated on ratio data is given on the fig.1. Let's consider the limit cases of a and λ ratio, when v>>1 and v<<1. Choosing the expression for character angle beam width from [21] and presenting the waveguide parameter as the ratio of θ_c sliding critical angle to θ_d character angle beam width, we obtain the following formula for case of Gaussian profile of radiation intensity by w_0 width:

$$v=\frac{2\theta_c}{\theta_d};\ \theta_c\approx\sqrt{2\Delta};\ \theta_d\approx\frac{\lambda}{\pi n_{core}a}.$$

It is seen from here, that waveguide parameter v can be considered in the capacity of the balance measure of influence of diffraction effects and waveguide limit of light beam because gradient of profile of refractive index. At v>>1 we have the case of big waveguide radiuses, for which the diffraction effects are insignificant, and significant part of radiation power is concentrated in core and is defined from $\eta\approx 1-\frac{u^2}{v^3}$ expression. At v<<1 the fiber radius is small, diffraction plays the significant role and significant part of radiation power spreads in fiber membrane. In this case:

$$\eta\approx 1{,}261\frac{v^2+2}{v^4}exp\left(-\frac{4}{v^2}\right).$$

The given expressions for η are proved experimentally and describe the ξ behavior. From the fig.1a it is followed, that value of optimal radius of core of quartz fiber lies in range 0,24-0,26 mcm, for GaSe – 0,015-0,025 mcm, for $LiNbO_3$ – 0,1-0,13 mcm. The maximum is achieved at radius of fiber core, which is equal to 1,5 mcm for weakly directing quartz fibers with Δ parameter near $5\cdot10^{-3}$ for $\lambda\approx$1mcm. In practices, maximal parameters are achieved for pulled and MS-fibers with high factors of membrane filling by air [22, 23].

The refractive index of core is less, than refractive index of membrane in hollow waveguides. That's why, the constants of mode distribution have imaginary components, differing from zero and pass of light in these waveguides accompanies by radiation losses. The attenuation coefficient of radiation intensity is defined by the expression [24] for EH_{mm} hollow waveguide with n_{core} near 1.

$$\alpha=\left(\frac{u_{mm}}{2\pi}\right)^2\frac{\lambda^2}{a^3}\frac{n^2+1}{\sqrt{n^2-1}},$$

Where $n=n_{clod}$ and from when it is followed, that attenuation coefficient of main mode of hollow waveguide with quartz membrane and internal radius 7 mcm for λ=1mcm exceeds 6,5 cm^1. Such fiber isn't useable for practical application. The loss decrease is decreased by the creation of photon-crystal membrane. The decrease of optical loss coefficient, relatively to losses in hollow waveguide with entire membrane, in this case is characterized by the ratio of logarithms of refractive indexes from wall of hollow waveguide core and periodical structure. The increase of layer number of periodical structure leads to the decrease of loss factor $\frac{\alpha_{PBG}}{\alpha_h}\propto a\exp\left(-2|\chi|Nd\right)$, where χ is coupling factor of direct and opposite waves in periodical structure; d is modulation period of refractive index in membrane in center of photon forbidden band.

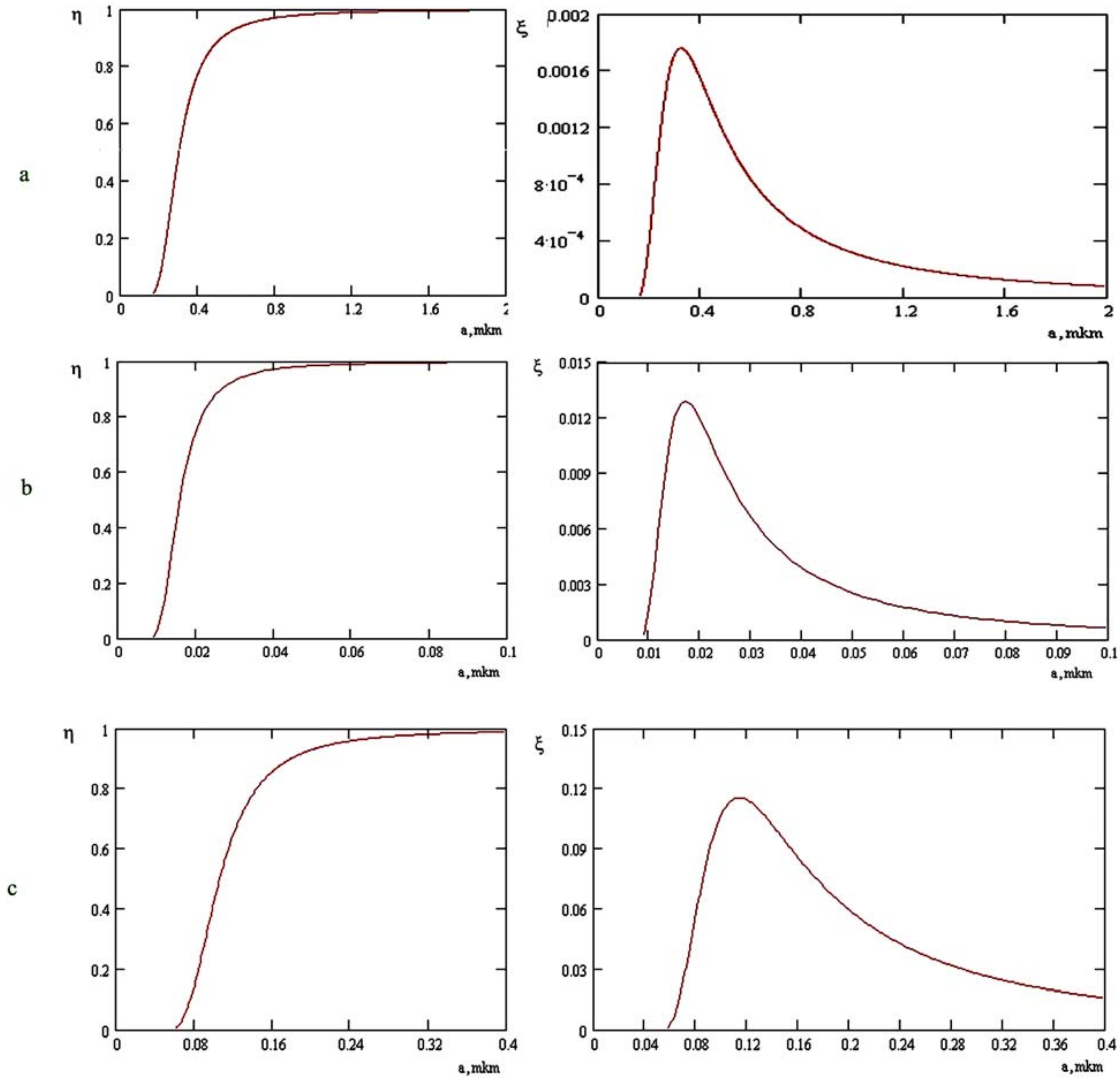

Fig.1. The dependence of factors of ξ-waveguide increase of efficiency of nonlinear-optical processes and η-part of radiation, localized in the center, on a radius of fiber core, carried out from: a. quartz, λ=1 mcm; b. GaSe, λ=0,2 mcm; c. $LiNbO_3$, λ=0,8 mcm.

The influence estimation of waveguide losses in hollow waveguide with entire or PhC-membrane, having the l length for the stationary FCSc, in the neglect of effects of rating depletion gives the following:

$$I_s(l) = I_s(0)\exp(gI_0 I_{eff} - \alpha_s l); \quad l_{eff} = \frac{1}{\alpha_p}\left[1 - \exp(-\alpha_p l\right],$$

where g is coefficient of FCSc-amplification; I_0 is initial intensity of rating signal; α_p and α_s are loss factors on the rating frequency and Stokes signal. The increase of Stokes signal is carried out only at the condition $gI_0 > \alpha_s$ (for gI_0=0,3 cm^{-3} fig.2), in opposite case the waveguide losses lead to the damping of Stokes signal. The value of Stokes signal linearly depends on fiber length, if $\alpha_p l$, $\alpha_s l$, $gI_0 l$ <<1. In case $\alpha_p l$>>1, the waveguide modes lead to rating weakening and intensity of Stokes signal exponentially decreases as l function. Taking under the consideration the limits, we obtain the following for the optimal fiber length and maximal coefficient of FCSc-amplification in hollow waveguide:

$$l_{opt}^{SRS} = \frac{1}{\alpha_p}\ln\frac{gI_0}{\alpha_s}; \quad G = \frac{gI_0}{\alpha_p} - \frac{\alpha_s}{\alpha_p}\left(1 + \ln\frac{gI_0}{\alpha_s}\right).$$

In case gI_0>>α_s, α_p the maximal increase of integral coefficient of FCSc-amplification in mode of hard focusing has the form, obtained earlier.

The length of nonlinear-optical interaction limit is limited by effects of group lateness, which lead to the "scattering" of rating pulses and Stokes signal on character length $l_w = \frac{\tau}{\left|\upsilon_p^{-1} - \upsilon_s^{-1}\right|}$, where υ_p and υ_s are group velocities of rating and Stokes pulses, correspondingly, τ is rating pulse duration. The dispersion of group velocity leads to the smearing of short pulses on character length $l_d = \frac{\tau^2}{|\beta_2|}$. The influence of tuning of group velocities and dispersion of group velocity in waveguide mode FCSc can be decreased by the way of the selection of waveguide and gas parameters with taking under the consideration the waveguide component dispersion. It is need to note, that mode number "k" in pure gas isn't the propagation constant $k=n\omega/c$ for the own mode of hollow waveguide.

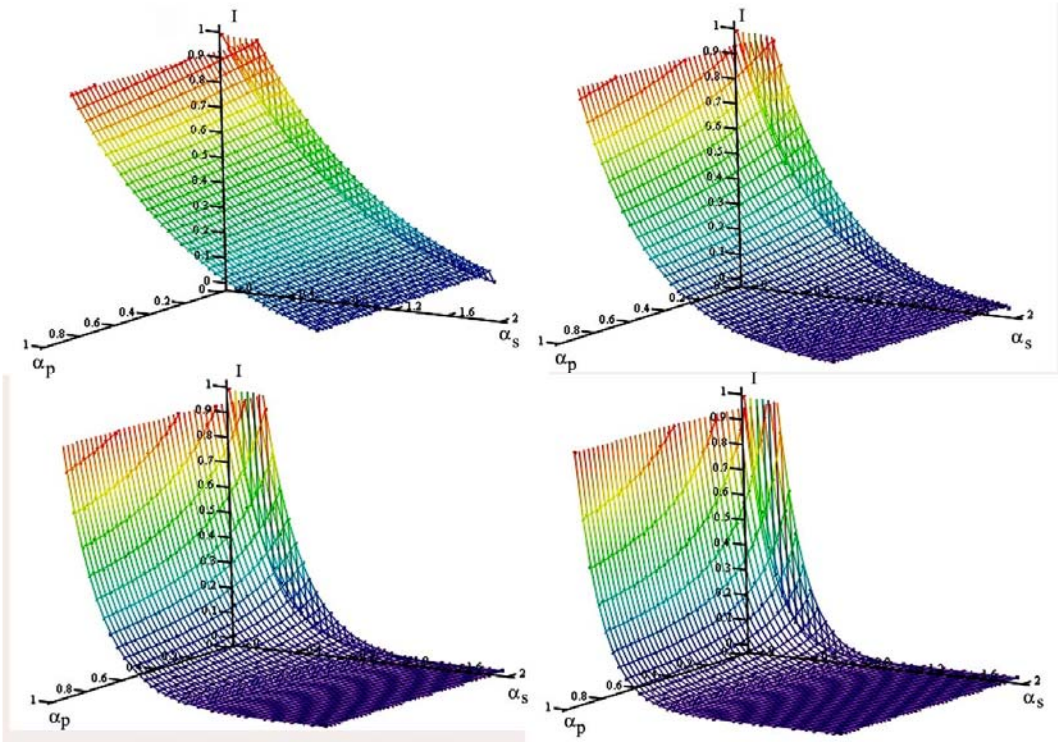

Fig.2. The dependence of FCS signal on fiber length 1 and loss coefficients on radiation frequency of rating and Stokes signal. The duration of rating pulses is 100 fs, energy is 0,01-1 mcJ, 1=1,2,4,6 cm.

The last is defined by the expression $K^{pq} = (k^2 - h_{pq}^2)^{\frac{1}{2}}$, where the value h_{pq} is obtained from the characteristic equation for own mode of waveguide. As the results show, the carrying out of the condition gI_0=0,3см$^{-3}$ can be achieved for the molecular hydrogen or nitrogen. This point of view is proved by results of ref [30]. The analysis of fig.3 shows, that the entire compensation of material and waveguide components of dispersion of group velocity can be achieved for the hollow waveguide with internal radius 50 mcm, filled by molecular hydrogen, on wave length 530 nm. The wave length for zero dispersion point can be obtained from the expression for the propagation constants of waveguide mode $k_2 = \upsilon_0^{-2}\left(\frac{\lambda}{2\pi n}\right)^3\left(\frac{u_m}{a}\right)^2$, where $\upsilon_0 = \frac{c}{n}\left(1 + \frac{\omega}{n}\cdot\frac{\partial n}{\partial\omega}\bigg|_{\omega_i}\right)^{-1}$.

It is followed from here, that wave length of zero dispersion point of group velocity can be reconstructed, changing the internal radius of waveguide, or choosing the type of waveguide mode, or choosing the gas and changing of its pressure in waveguide.

The hydrogen distribution in interplane crystal spaces is the peculiarity of GaSe, intercalated by hydrogen, as it was mentioned in ref [29].

In case of photon crystal $LiNbO_3$, the conclusions, obtained for quartz fiber coincide with experiments, if the change of refractive index doesn't take place under the influence of exciting radiation.

In last both cases intercalation process doesn't present big troubles technologically.

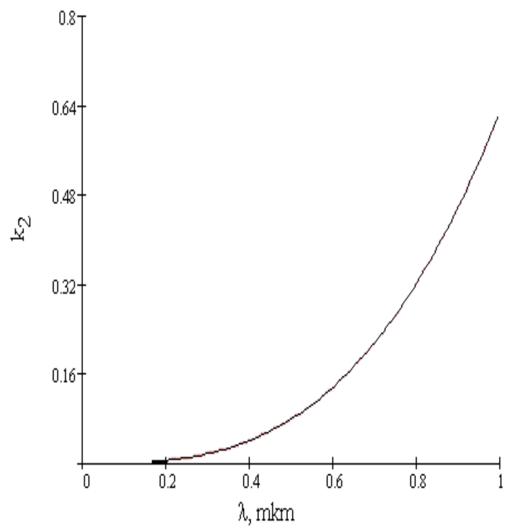

Fig.3. The spectral dependencies for the zero dispersion point of group velocity in hollow quartz waveguide, filled by molecular hydrogen. The internal radius of waveguide, train width and canal radius are 50 mcm, gas pressure is 0,5 arm, wave length is 530 mcm.

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STRUKTURLAŞDIRILMIŞ SƏTHLİ OPTİK FİBERLƏRİN QEYRİ-XƏTTİ XÜSUSİYYƏTLƏRİ

Kvars, A_3B_6 qrup laylı materialların və $LiNbO_3$ əsasında yerinə yetirilmiş mikrostrukturlaşdırılmış fiberlər üçün hesabi və eksperimental göstəricilər verilmişdir.

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НЕЛИНЕЙНЫЕ СВОЙСТВА ОПТИЧЕСКИХ ВОЛОКОН СО СТРУКТУРИРОВАННОЙ ОБОЛОЧКОЙ

Приведены расчетные и экспериментальные данные для микроструктурированных волокон, выполненных на основе кварца, слоистых материалов группы A_3B_6 и $LiNbO_3$.

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