Optical quartz fibers as non-linear media and four-wave mixing method for determination of fibers geometrical parameters

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Because of their ability to maintain high energy density over long distances due to the small cross sections and low optical losses the fused quartz fibers are very appropriate media for observation of nonlinear optical effects. In this article the possibility is examined of using non-linear optical processes occurring in the fused quartz fibers to determine their geometrical parameters.

Keywords: non-linear optics, optical fibers, stimulated Raman scattering, four-wave mixing

INTRODUCTION

One of the most rapidly advancing areas in optics during the last few decades was non-linear optics. As a result, not only the fundamental dependencies of the non-linear processes were explained but also a lot of applied devices were developed. The non-linear optics gives wide possibilities for frequency conversion of coherent radiation thus strongly enlarging the laser technology abilities to create new coherent sources of light. We can hardly imagine the modern scientific researches without using the parametric light generators, without generating second and third harmonic, Raman lasers [1] and a lot of other devices [2]. Due to several reasons which we will discuss later the fused quartz fibers turn out to be very appropriate media for observation of the nonlinear optical processes. The following article is devoted to clarifying the possibilities for determining the geometrical parameters of the fibers by means of occurring non-linear optical processes. The proposed method is based on the fact that the frequency of the spectral components arising as a result of the four-photon mixing process directly depends on the fiber parameters. The method was experimentally verified.

Geometrical parameters of the fused quartz fibers

In its simplest form an optical fiber consists of a cylindrical core of silica glass surrounded by a cladding whose refractive index is lower than that of the core. This requirement is needed to ensure total internal reflection of the light on the core-cladding interface. The entire structure is covered by a protected jacket. Because of an abrupt index change at the core-cladding interface, such fibers are called step index fibers.

The fibers are characterized with their geometrical parameters such as core diameter $2a$, cladding diameter $2b$, core refractive index n_1, cladding refractive index n_2, and respectively, core cladding refractive index difference $\Delta n = n_1 - n_2$. These parameters are very important because they determine the fiber communication parameters, in particular the information speed. There is a most important integral parameter that describes the fiber properties. It is called normalized frequency or simply V parameter and is defined as:

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} \approx \frac{2\pi a}{\lambda}\sqrt{2n_1\Delta n} \qquad (1)$$

We have to mention that two fibers with different geometrical parameters are identical if their V parameters are equal. It means that their information properties are the same.

During its propagation through the fiber, light forms waveguide modes that have a different effective propagation constant β. The number of excited waveguide modes depends on the parameter V. When a parameter V is less than 2.405 only one mode is formed in the fiber. Such fibers are called single-mode fibers. With parameter $V > 2.405$ more than one mode gets excited and these fibers are classified as multi-mode fibers. As can be seen from formula (1) each fiber can be single-mode for one wave length and multi-mode for other shorter wave length. Therefore, with appropriate choice of the light launched into the fiber multiple modes can get excited.

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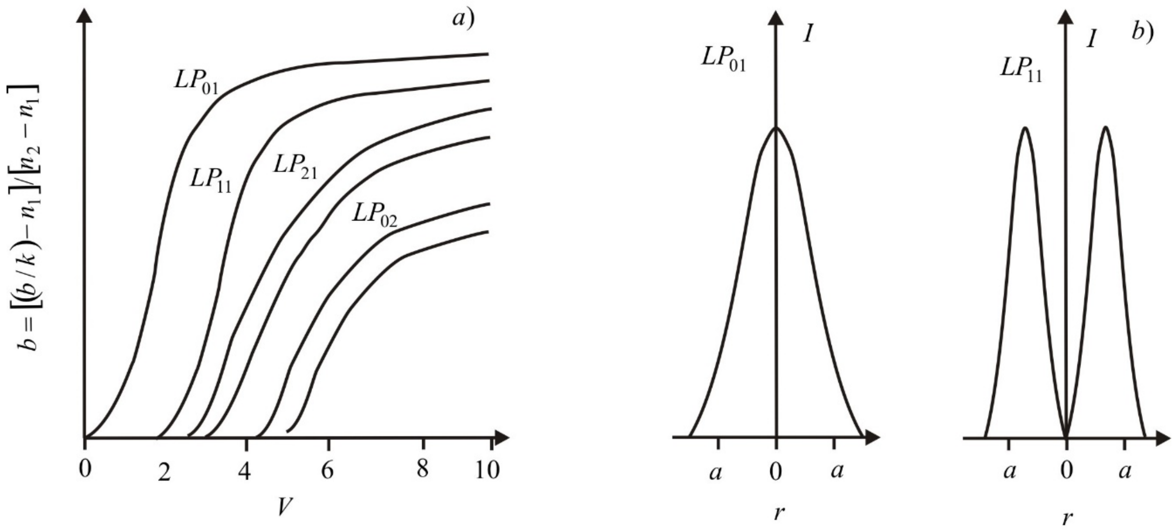

Fig. 1. Normalized propagation constant (a) and field distribution (b) for first two fibers modes.

The propagation constants for the different modes can be calculated in dependence to the V parameter of the fiber. The result is shown in Fig. 1a. Furthermore, the wave analysis gives information about the distribution of the light intensity in the cross section of the fiber. Fig. 1b shows the results for the first two modes marked as LP_{01} and LP_{11}. As can be seen at the figure the axially symmetrical LP_{01} mode has maximum intensity at the center of the core. This conclusion turns out to be true for all the axially symmetrical modes (all modes with first index 0). On the contrary, axially nonsymmetrical mode LP_{11} has minimum intensity at the center of the fiber. This also turns out to be correct for all the other modes with first index different from zero.

Fused quartz fibers as nonlinear media

It is well known that fused quartz has a very low coefficient of nonlinearity in comparison to the other conventional nonlinear media. This fact is the main disadvantage of quartz as a nonlinear medium. However, the fibers have a lot of other advantages. The small cross sections of the cores of the fibers give them the ability to maintain high density of the energy. Also, the small losses and the great lengths of the fibers guarantee a great interaction length between the waves. As a result, in the fibers the product of the coefficient of nonlinearity and the length of interaction which determines the effectiveness of the nonlinear process exceeds many times those of the volumetric media. This makes the fibers very effective media for non-linear processes [3]. The non-linear processes occurring in the fibers are quite numerous. We will focus our attention on two of them – stimulated Raman scattering (SRS) and four-wave mixing (FWM) with an accent on the second one which, we believe, allows determining the geometrical parameters of the fibers. The Raman scattering is a non-linear process where a new wave length in the Stokes area is generated which frequency shift from the pumping radiation corresponds to the maximum in the spontaneous vibrational spectrum of the nonlinear medium. The amplification line of spontaneous Raman scattering in the fused quartz is quite wide but has a maximum at $\Delta\nu$ = 440 cm^{-1}. That is why the occurring stimulated Raman scattering has this frequency shift. The process is very effective because phase synchronism is not required.

As it is well known, the stimulated FWM is a non-linear process, when two pump photons of frequency ν_p are transformed in Stokes and anti-Stokes pair of frequency, respectively ν_s and ν_a, which obey the energy balance:

$$\nu_p - \nu_s = \nu_a - \nu_p$$

The process is efficient if the phase matching condition is fulfilled:

$$\Delta k = k(\nu_s) + k(\nu_a) - 2k(\nu_p) = 0$$

Perfect phase-matching cannot be achieved in volumetric optical glasses because in the normal (anomalous) dispersion region Δk is always greater (less) than zero. Exact phase-matching is possible in optical fibers, when the material dispersion is compensated by the modal dispersion for a suitable combination of the modes [4, 5] (Fig. 1a), i.e.

$$\Delta\beta = \beta_{p1} + \beta_{p2} - \beta_a - \beta_s \ . \qquad (2)$$

The dynamics of both processes *versus* the pump power is shown on Fig. 2. The fiber is pumped with second harmonic radiation of Q switched Nd:YAG laser.

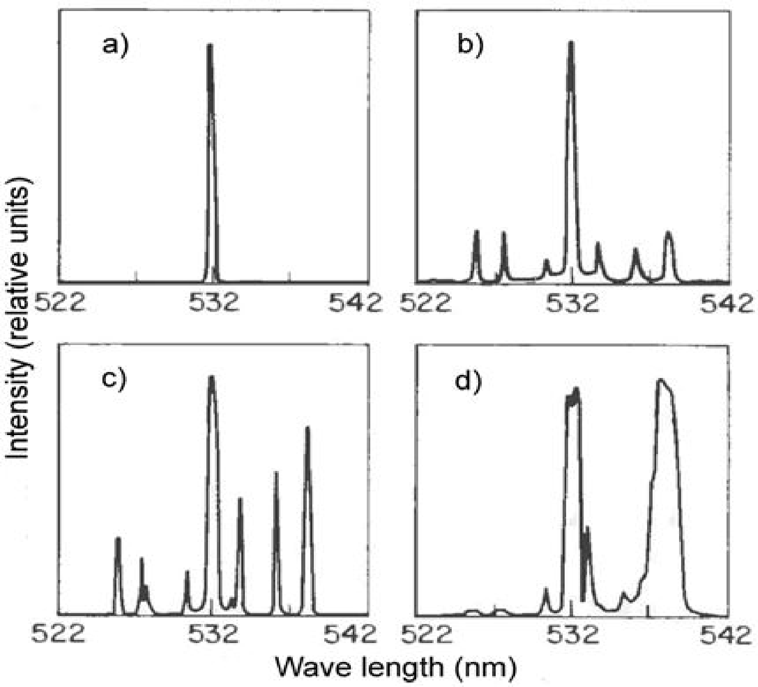

Fig. 2. Dynamics of SRS and FWM processes *versus* the power of the pumping pulses.

In Fig. 2a the power of the pump radiation is low and at the out of the fiber only the pumping radiation is registered. With increasing of the pumping power radiation (Fig. 2b) several new components symmetrical to the pump frequency appear. These spectrum lines occur as a result of the FWM process. The energy of the Stokes and anti-Stokes components is approximately equal. Further increasing of the pumping power (Fig. 2c) leads to increased power of the Stokes components because they get additional amplification as a result of the SRS process because these lines are within the spontaneous Raman amplification. The last Fig. 2d presents the spectrum of a very high pumping power. In this case the SRS process occurs. The energy of the pumping frequency almost completely transforms into Raman line and there is not enough energy left for the FWM process.

Non-linear method for determining of fiber parameters

The frequencies generated by the FWM process can be exactly predicted, if the parameters of the fiber are known. Our aim is the solving of the inverse problem – to find the fiber parameters from the given FMW frequencies.

For the case of weakly guided fibers [6] in a divided pump process (that is the Stokes and one of the pump waves propagate in one fiber mode, while the anti-Stokes and other pump wave propagate in another fiber mode) the frequency shift $\Delta\nu$ is determined by fiber parameters and can be written as follows:

$$\Delta\nu\lambda_p D(\lambda_p) = \Delta n\left[\frac{d(bV_s)}{dV} - \frac{d(bV_{as})}{dV}\right] \qquad (3)$$

where V is the normalized frequency, λ_p is the pump wavelength, $D(\lambda) = \lambda^2\left(\frac{d^2n}{d\lambda^2}\right)$ is the core material dispersion and the expression $\frac{d(bV)}{dV}$ is differential mode delays of the propagating Stokes and anti-Stokes waves. For two distinct combinations of modes the following characteristic equation for the parameter V can be written [7]:

$$\frac{\Delta\nu^{(1)}}{\Delta\nu^{(2)}} = \frac{\frac{d(bV_s^{(1)})}{dV} - \frac{d(bV_{as}^{(1)})}{dV}}{\frac{d(bV_s^{(2)})}{dV} - \frac{d(bV_{as}^{(2)})}{dV}} = R(V) \qquad (4)$$

Indices 1 and 2 denote the first and the second modal combination, respectively. The right side of eq. 4 depends only on the V parameter. This fact established the possibility to obtain V parameter, and then the other fiber parameters.

Fig. 3 shows the dependencies $R(V)$ for the rectangular refractive index profile for three different combinations of the pump wave modes, including 0, 1 and 2 axially symmetrical modes, respectively. Curve 1 corresponds to $\Delta\nu^{(1)}$ obtained with the pair LP_{31} - LP_{21} and to $\Delta\nu^{(2)}$ obtained with $LP_{21} - LP_{11}$, curve 2 to $\Delta\nu^{(1)}$ obtained with LP_{31} - LP_{21} and $\Delta\nu^{(2)}$ obtained with $LP_{11} - LP_{01}$, curve 3 to $\Delta\nu^{(1)}$ obtained with $LP_{02} - LP_{11}$ and $\Delta\nu^{(2)}$ obtained with $LP_{11} - LP_{01}$. It is interesting to mention that these are combinations of the lowest order modes.

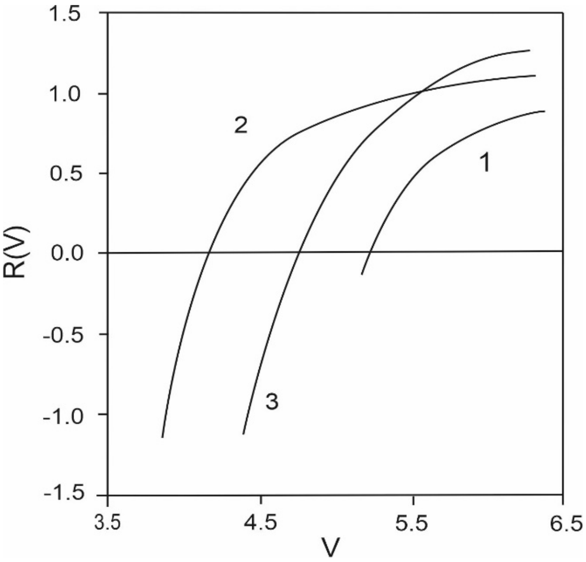

Fig. 3. Dependencies *R(V)* for rectangular refractive index profile of the fiber. curve 1 – $\Delta\nu^{(1)}$ obtained with $LP_{31} - LP_{21}$, and to $\Delta\nu^{(2)}$ obtained with $LP_{21} - LP_{11}$; curve 2 - $\Delta\nu^{(1)}$ obtained with $LP_{21} - LP_{11}$, and $\Delta\nu^{(2)}$ obtained with $LP_{11} - LP_{01}$; curve 3 - $\Delta\nu^{(1)}$ obtained with $LP_{02} - LP_{11}$ and $\Delta\nu^{(2)}$ obtained with $LP_{11} - LP_{01}$.

From Fig. 3 it is seen that *R(V)* has zeros for certain values of *V*. Consequently, for those values of *V* the normalized group delays participating in the numerator of eq. 4 are equal. The negative value of *R(V)* corresponds to the case when the anti-Stokes wave of the modal combination in the numerator of eq. 4 propagates in a higher mode than the Stokes wave. The positive values correspond respectively to the case when the Stokes wave is in the higher mode.

If the V parameter is already known, the determination of the other parameters (core radius a and core cladding refractive index difference Δn) requires information about the doping composition of the fiber. As its concentration is very small we can use the data for the pure fused quartz and obtain good accuracy.

In order to examine experimentally the possibility of determining the fiber parameter using FWM process, we studied a fiber with known V parameter, which was approximately 3.9 at pump wavelength $\lambda_p = 532$ nm. An experimental set up, which is widely used for studying non-linear phenomena in optical fibers, was employed for obtaining the stimulated FWM spectra. The fiber was pumped by the second harmonic of a Q-switched and mode-locked CW Nd:YAG laser. The fiber had pure silica cladding and Ge-doped core.

In the experiments the excitation of the different groups of modes was accomplished by varying the launching conditions for the pump beam. The modal structure of the generated radiation was identified visually, after splitting a fraction of the fiber output with a grating. FWM frequencies were recorded by OMA.

In Fig. 4 the anti-Stokes sides of the FMW spectra are shown. The Stokes sector of the spectra expects the symmetrical Stokes frequency, contains also the stimulated Raman scattering (SRS) line. It seriously complicates the spectra. This figure shows also the modal combination of the Stokes and anti-Stokes components for the respective frequency.

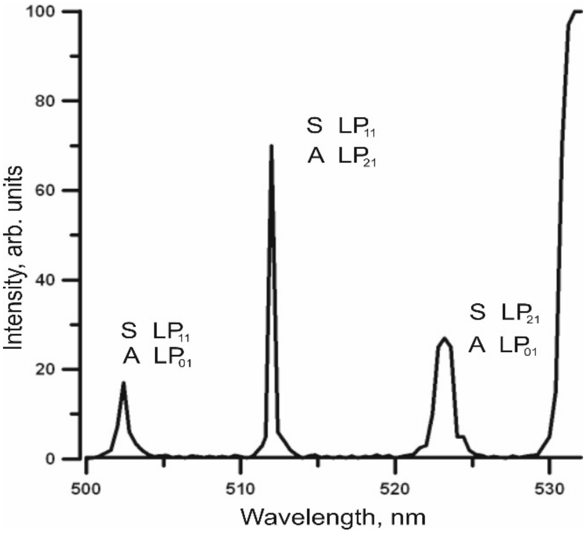

Fig. 4. Anti-Stokes components of the experimental FWM spectrum.

For this sample we used as first line the one with $\Delta\nu^{(1)} = 722$ cm^{-1} obtained for modal combination $LP_{21} - LP_{11}$ and as second line that with $\Delta\nu^{(2)} = 1089$ cm^{-1} for modal combination $LP_{11} - LP_{01}$. The frequency shift $\Delta\nu^{(1)} = 722$ cm^{1} was obtained when the anti-Stokes component was in the higher mode. That's why we take this value as a negative. Using eq. 4 we found that the V value of the pump wavelength is 3.96.

Using this value, the parameters of the fiber were easily calculated. The standard optical fibers are made from pure silica with Ge-doped core. But the doping concentration weakly affects the core refractive index n_1, core material dispersion $D(\lambda) = \lambda^2 \left(\frac{d^2 n}{d\lambda^2} \right)$ and differential mode delays $\frac{d(bV)}{dV}$ [8]. Then if we use the data for pure silica the error will be negligible. Solving eq. 3 we obtain for the core-cladding refractive index difference $\Delta n = 3.04\times10^{-2}$. From eq. 1 we find out for the core diameter $2a = 2.25\ \mu m$. We have to mention that the passport data are correspondingly $\Delta n = 3.2\times10^{-2}$ and $2a = 2.2\ \mu m$.

CONCLUSION

In conclusion, a method based on a nonlinear optical process is proposed for the first time to determine the geometrical parameters of optical quartz fibers. The method is based on the dependence of the frequency shift of the spectral components arising as a result of the four-photon mixing process on the fiber parameters. Unlike the others classical methods, the proposed method allows simultaneous determination of all practically important parameters of light guides - core radius, core refractive index, difference in refractive index between the core and the sheath, and the corresponding normalized frequency. These parameters directly determine the information capacity of optical communication lines. The method was experimentally demonstrated. The accuracy of the obtained results is completely satisfactory.

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