ACOUSTICAL AND ACOUSTOOPTICAL PROPERTIES OF GRADIENT GLASSES

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Abstract

In the present work the results of acoustic and acoustooptical investigations of inhomogeneous glasses with specially produced gradients of elastic and optical properties are discussed. Such glasses were made by means of two methods: ion-exchange process and fusion/diffusion process.

Relative deviations of refractive index $\Delta n/n$ and bulk velocity of ultrasonic waves (USW) $\Delta v/v$ in the layers with depth up to 20 mm come to 5-10% and 10-20% accordingly.

It was shown that on the base of gradient glasses transparent waveguides capable to focus or defocus the USW beam, propagating along axis of waveguide can be produced. It can result in optimization of modes of light and USW beams interaction in some acoustooptical devices made from glasses.

Introduction

In many devices of ultrasonic engineering, acousto-electronics and acousto-optic as working medium (waveguide) for USW propagation glasses with special elastic and optical characteristics are applied, the samples of homogeneous glass (i.e. having identical physical properties in volume of a sample) using usually. Since the early seventies the processes and materials for synthesis of solid media with gradients of various physical properties (index of refraction, elasticity, conductivity etc.), suitable in particular for the creation of optical elements and in other spheres of modern engineering heavily are investigated [1].

There are different technologies of creation of gradient glasses: ion-exchange [2], fusion/diffusion process [3], implantation, technology of radiation-induced gradient and others. For acoustic gradient glass, it is important to create considerable difference of elastic properties in the sample volume. As regards that, the technology of fusion/diffusion process of a few homogeneous glasses with different velocities of USW is more perspective. The other method is creating the gradient layers by penetrating the atoms of the one kind through the surface of glass, containing the atoms of other kind, change the elastic properties only up to 5-10% depending on kind of glass. However, the latter allows to realize practically smooth distributions of physical properties in glass samples of any geometrical form (cylinders, spheres et al.), whereas fusion/diffusion process is convenient only for samples in form of plates and rectangular bars.

To realize effect of USW focusing in a sample volume it is created such conditions at which the velocity v of longitudinal USW increases in direction to sample edges, and it is minimum in the center. So the USW front is transformed such that the beam narrows (fig. 1 a). Necessary for that distribution of USW velocity is shown on fig. 1 b. To reach qualitative focusing of the USW it is necessary to make the sample with distribution $v(x)$ obeying special law.

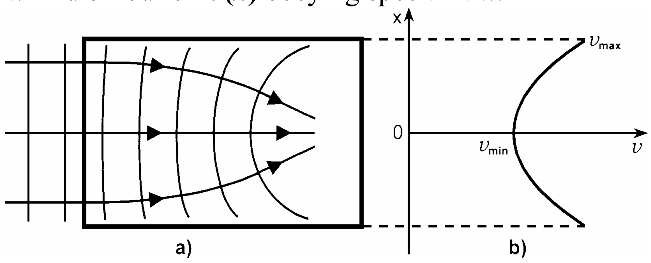

Figure 1 : a) Schematic of USW propagation in gradient acoustic (or optical) waveguide, b) distribution of velocity of longitudinal USW (or velocity of light) in the waveguide

For the simplest case – the cylinder waveguide, in which is created the special axial symmetrical distribution of elastic properties along a radius of the cylinder, $n(r)$ is obeyed to the following law:

$$n(r) = \frac{n_0}{1+2\pi^2 \frac{r^2}{L^2}}, \qquad (1)$$

where n_0 and $n(r)$ – acoustic (or optical) index of refraction on an axis of the cylinder and at a distance r from it, accordingly, and L – the length of periodicity of oscillation of an acoustic (or optical) ray inside the cylinder. The distribution indicated in the formula (1) is called «focusing», since it results to a focusing of a beam USW, propagating along an axis of inhomogeneous (gradient) the cylinder at the following ratio L and length of the cylinder z : $z < L/4 + kL$, where $k = 0, 1, 2, 3 \ldots$. The formula (1) is similar to a known ratio for distribution of optical index of refraction in the focusing optical waveguide and it is borrowed from work [4] (fig. 2).

Methods

We have made two types of USW waveguides having «focusing» properties: with square and round profile. Each type of waveguide has lengths from 20 to 80 mm. The base material for them is special synthesized optical multicomponent glasses. For making waveguides with square profile was used set of plates of homogeneous glasses with longitude USW velocities from 3400 to 4200 m/s; plates were connected by «fusion/diffusion» method [5].

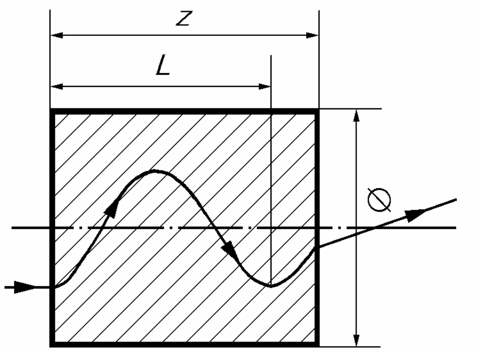

Figure 2 : Schematic of propagation of acoustical ray in the gradient cylinder with «focusing» distribution of elastic properties according to (1)

Process of making the samples for acoustic study is similar to the fusion/diffusion process (LightPath Technologies [3]), however goal is to make a sample with distribution $v(x)$ that is demonstrated on fig. 1 b. Homogeneous glasses with different USW velocities form together a waveguide preform. Glasses are transformed into the unit by fusion/diffusion process, and then two units are connecting by fusion/diffusion process into gradient acoustic waveguide.

In «ion-exchange» process [2, 4] the initial homogeneous glass is placed in a molten salt. Then, at the temperature of above than temperature of glass transition (the high-temperature ion-exchange) interdiffusion of cations takes place, at which the ion of alkali metal presenting in a structure of glass, «leaves» it in a molten salt and the ion of other alkali metal containing in a molten salt substitutes the former in glass. Selecting by appropriate way pairs of exchanged cations, it is possible to achieve purposive smooth change of a structure of an initial glass, receiving thus a layer of a variable structure, obviously, having a gradient of physical properties, such as an index of refraction, elasticity and others.

Fig. 3 shows «geometry» of acoustic testing the samples. Two ways of scanning were done: along direction of USW velocity gradient (fig. 3) and in direction perpendicular to him. For making an electrical contact between a sample and a piezoquartz transducer, the sample was covered with a Ag layer on the one hand. The USW generator installed at one sample butt-end was piezoquartz element with 20-mm diameter, and the small piezoquartz waveguide was working as USW detector scanning the other sample butt-end surface. The accuracy of detector moving was 0,01 mm, and the standard deviation of data of measurement of USW amplitude was up to 5% depending on conditions of measurement. The propagation of the pulse of longitudinal USW with frequency 14 MHz, extending in a direction of a large axis of the samples was researched. Measurements of longitudinal USW amplitude were done at different values of shift x concerning the sample edge. To interpret correctly obtained results similar measuring were carried on in homogeneous samples of the same dimensions.

Cylinder USW-waveguides making by ion exchanging diffusion process [6] were investigated by the same method.

Acoustooptical measurements were carried out, as usually, i.e. direction of USW propagation was perpendicular light beam.

Results and discussion

Focusing USW waveguides with square profile from gradient glass («fusion/diffusion» process)

The experimental results are presented on fig. 4. Results of research of homogeneous samples (fig. 4 a) are given only for comparison with results of similar researches in gradient samples. Overall, the distribution of USW amplitude in homogeneous samples demonstrates composite nature of their propagation, namely mutual transformation of USW types (longitudinal USW – shear USW – longitudinal USW), their interference inside a sample and results of this interference when registering USW by detector (these effects explicitly are described in monograph [7]). In gradient samples (fig. 4 c) the distribution of USW amplitudes has different nature in comparison with homogeneous samples and it is connected, to our mind, to availability of a «focalizing» of the elastic properties gradient in cross-section of a sample. Practically, in all researched gradient samples a series of peaks on distribution curves of USW amplitudes are observed and main peak is usually registered on the middle of a sample.

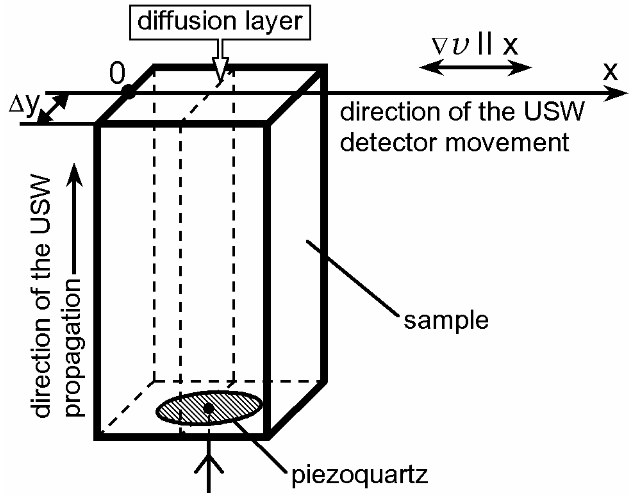

Figure 3 : Schematic of scanning the sample butt-end by the USW detector in two directions: $\nabla v \parallel x$ or $\nabla v \perp x$. ∇v - elastic properties gradient direction, Δy - shifting of USW detector concerning the sample butt-end edge

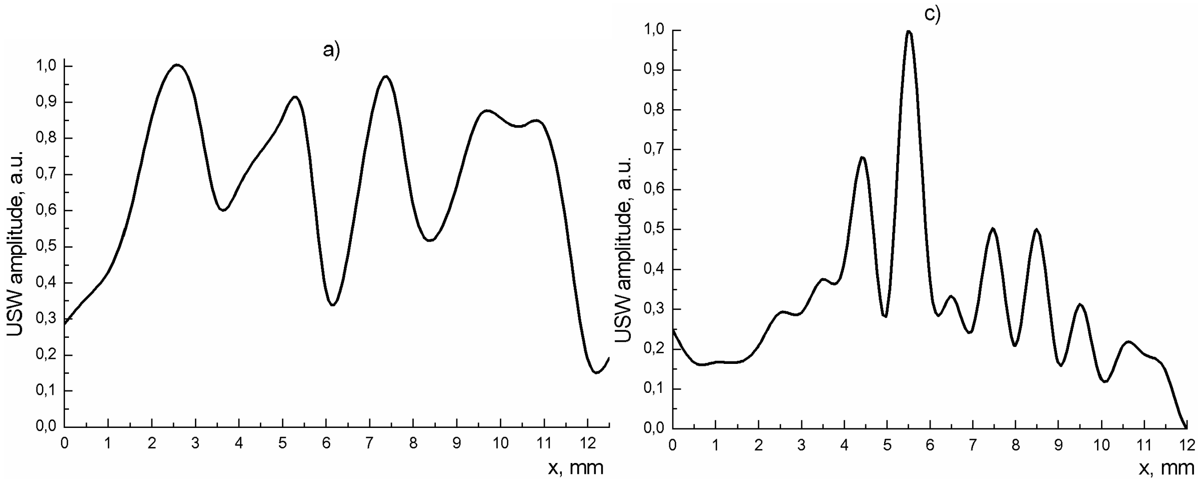

Figure 4 : Amplitude distribution of longitudinal USW on butt-ends of the samples in direction $\boldsymbol{x}$: a) homogenous sample with length of 60 mm (H60), $\Delta \boldsymbol{y} = 6$ mm, c) gradient acoustic sample (waveguide) made from glass with length of 60 mm (G60), $\Delta \boldsymbol{y} = 6$ mm ($\nabla \boldsymbol{v} \parallel \boldsymbol{x}$)

Focusing USW waveguides with round profile from gradient glass («ion-exchange» process)

In a fig. 5 the real «focusing» distribution of elastic properties along a radius of the gradient glass cylinder obtained according to earlier developed method, using connection of optical and elastic properties in gradient glasses is shown [2]. Thus, gradient glass cylinder waveguides, in which the «focusing» distribution of elastic properties is created can play a role of acoustic lenses, the technology of which obtaining is described in details in [2, 6]. The manifestation of focusing properties of such lenses at propagation in them of longitudinal pulse USW with frequency 14 MHz and duration of 5 mcs is shown in a fig. 6. From a fig. 6 it follows, that for the gradient cylinder (∅ 15×60 mm) the narrowing of the peak-coordinate characteristics (fig. 6 a) in a comparison with similar in the homogeneous cylinder (fig. 6 b) of the same sizes is observed.

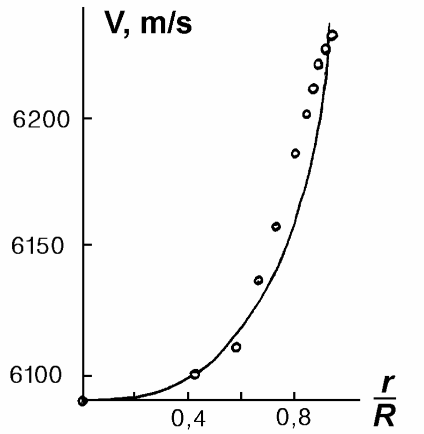

Figure 5 : Actual distribution of longitudinal USW velocities in the gradient glass cylinder (circles) and calculated by (1). $\boldsymbol{R}$ – cylinder radius

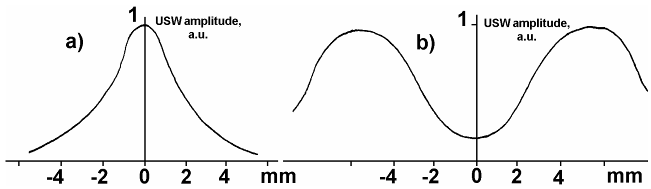

Figure 6 : Distributions of amplitude of longitudinal pulse USW with frequency 14 MHz at an end face: a) of the gradient glass cylinder with «focusing» distribution of elastic properties (fig. 9), b) of the homogeneous glass cylinder (of the same sizes)

Acoustooptical cell on the base of gradient glass («ion-exchange» process)

For the sample from multicomponent silicate glass of dimensions 5×9×9 mm in which $\nabla \vec{n}$ and $\nabla \vec{v}$ were parallel to direction of USW propagation were obtained: distribution $\boldsymbol{n}(\boldsymbol{x})$ for investigated sample (fig. 7), the dependence of external Bragg angle Θ_{ext} on coordinate (fig. 8). In addition, note that for this kind of gradient glass relative change of velocity USW is less by an order than relative change of refractive index. Therefore, in the following we consider that sample is practically isotropic body, optically inhomogeneous and acoustically homogeneous.

For the first time acoustooptical measuring in gradient glasses were carried on in work [8], where the authors wanted to definite the profile of refractive index $\boldsymbol{n}(\boldsymbol{x})$ from dependence $\Theta_{ext}(\boldsymbol{x})$. In this work, acoustooptical method was used as nondestructive method, allowed to study the local characteristics of gradient glasses, i.e. these small areas, which are formed by crossing of USW and light beams.

Fig. 8 demonstrates nonlinear dependence $\Theta_{ext}(\boldsymbol{x})$, although for homogeneous media $\Theta_{ext}(\boldsymbol{x}) = \mathbf{const}$. In our case $\Theta_{ext}(\boldsymbol{x}) = \mathbf{const}$ in the middle (homogeneous) part of sample, and sharp changes Θ_{ext} is observed on sample edges and nonlinearity reaches 0,2 - 0,3 deg/mm.

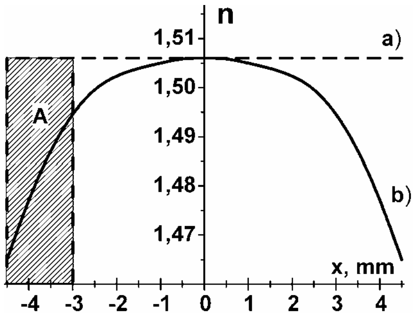

Figure 7 : Refractive index distribution along x–axis for samples: a) for glass preform, b) for gradient waveguide. $x = 0$ corresponds to $\nabla \vec{n}$ direction change, A – gradient area of the sample

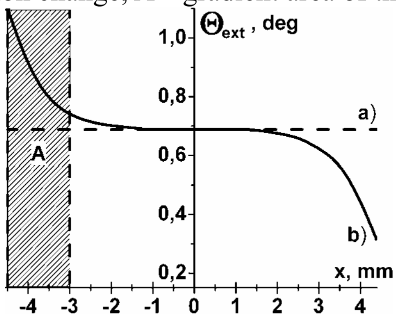

Figure 8 : External Bragg angle Θ_{ext} versus x-coordinate of beam entrance into samples: a) for glass preform, b) for gradient waveguide (A – gradient area of the sample). ν = 210 MHz, v = 5600 m/s, λ_0 = 632,8 nm

We consider that probable realization of the dependence for acoustooptical deflectors made from gradient glass is interest.

The dependence $\Theta_{int}(x)$ can be understood if taking into account curvilinearity of light beam propagation in the gradient part of the sample, so there is its own Bragg angle $\Theta_{ext}(x)$ for each area:

$$\Theta_{int} = \arcsin\left(\frac{\lambda_0 \nu}{2n(x)\cdot v(x)}\right), \qquad (2)$$

where: λ_0 - wavelength of light in vacuum, ν - USW frequency, $n(x)$ and $v(x)$ - distribution laws of refraction index and USW velocities along axis of the sample.

If the sample thickness in direction of light beam propagation is much smaller than radius of light ray curve, we can suppose:

$$\Theta_{ext} \approx \arcsin\left(\frac{\lambda_0 \nu}{2v(x)}\right). \qquad (3)$$

Therefore, knowing distribution $v(x)$, we can calculate Θ_{ext} for thin sample.

It should notice that our sample we cannot consider as thin because $v = \mathbf{const}$ for it (see above), but there is a noticeable dependence $\Theta_{ext}(x)$ (area «A» on fig. 8).

For voluntary thickness sample calculations will be more difficult and it can be shown [8], that Θ_{ext} will depend (see (3)) on refractive index of points where the beam enters into the sample n_A and where it interacts with USW n_B :

$$\Theta_{ext} = \arcsin\left\{ n_A \sin\left[\arccos\left(\frac{n_B}{n_A}\cos\Theta_{int} \right)\right]\right\}. \qquad (4)$$

Thus, knowing from experiment $n(x)$ and $v(x)$, $\Theta_{ext}(x)$ can be calculated and areas of the sample, where $d\Theta_{ext}(x)/dx$ are maximal (the area «A» on fig. 8), can be localized. From fig. 8, it follows that small shift Δx of initial light beam on gradient part of sample are able lead to considerable changes $\Theta_{ext}(x)$. We think this effect can be used for constructing of acoustooptical deflector having high angular resolution. It requires shift of falling light beam to be controlled (in area «A» on fig. 8), for example, by other deflector.

Conclusion

Thus it can be supposed that acoustical and acoustooptical properties of gradient glasses studied in present work can be useful for some devices of ultrasound technique such as focusing USW waveguides used in USW delay lines and acoustooptical cells. Apparently, for realization of that it is necessary additional invention of wide range of acoustical glasses convenient for creation in them a considerable gradient of elastic properties and besides having small absorption of ultrasonic waves.

References

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