Acoustic Studies of Gradient Glasses

A. A. Abramovich

St. Petersburg Technological University of Plant Polymers, ul. Ivana Chernykh 4, St. Petersburg, 198095 Russia
e-mail: andrew@ns2740.spb.edu

Received October 4, 2007

Abstract—The results of investigation of the propagation of longitudinal ultrasonic waves in glasses with a regular volume distribution of elastic properties resulting in the narrowing of a beam of ultrasonic waves at the output of the sample are presented. Such glasses have not been used in acoustics previously. They were used by us for the creation of the first samples of inhomogeneous acoustic lenses. The results obtained in the investigation of inhomogeneous acoustic lenses based on specially developed inhomogeneous glasses and methods for their production are discussed. It is shown that the noticeable effect of focusing ultrasonic waves in the range 2–14 MHz is observed already for glass samples with dimensions 10–20 mm. Other possible applications of inhomogeneous acoustic lenses, for example, as a medium for ultrasonic delay lines and acousto-optical cells, are discussed.

PACS numbers: 43.20.Mv, 43.35.Sx, 42.79.Ry

DOI: 10.1134/S1063771009030105

INTRODUCTION

Glasses play an important role among modern acoustic materials because of their wide variety of elastic and acoustic properties and inexpensive and simple production. Surveys devoted to the acoustic studies of glasses for optical and other designations developed in industry are known [1, 2]. In these surveys, basic attention is paid to elastic modulae and absorption of ultrasonic waves with different frequencies in glass samples with a homogeneous composition, although at glass melting, composition fluctuations (cords) randomly distributed in the volume are often formed; these cords worsen the optical and acoustic parameters of glasses. However, it is possible to create glasses whose chemical composition varies in the volume in a regular way with a certain purpose, for example, in optics for changing the trajectory of the light beam [3]. In this case, glasses are called gradient glasses, i.e., glasses whose physical properties vary in a gradient-like way.

Gradient glasses for optical purposes were developed in 1970–1980 and used for the manufacturing of elements of devices of fiber optic connection lines and integrated optics. The most important practical application of gradient glasses is an inhomogeneous optical lens, which allows one to transform a light beam into a converging or diverging beam due to the fact that the light ray propagates curvilinearly in a regular inhomogeneous medium, rather than due to curvilinear media interfaces. One of these such lenses of the “R-gradan” type is manufactured in the form of a cylinder with planar working edges, it is shown in Fig. 1a. The axially symmetric distribution of the refractive index \( n(r) \) is created inside the cylinder; for this distribution, the light velocity (Fig. 1b)

![Fig. 1](image-url)
increases along the cylinder radius from the axis to the surface as [3]

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

where \( n_0 \) and \( n(r) \) are the optical refractive index on the cylinder axis, and at the distance \( r \) from the axis, \( L \) is the spatial period of the beam oscillation along the cylinder axis. It was shown in [3] that the beam inside this gradient lens becomes curvilinear and oscillates with the spatial period \( L \) determined by the relation

\[ L = \pi R \sqrt{\frac{2n_0}{\Delta n}}, \] (2)

where \( \Delta n = n_0 - n(R) \) and \( R \) is the lens radius.

By changing the lens length \( z \), different beams can be obtained at the output of the lens: (a) converging beam (focusing) at \( z < L/4 \), (b) diverging beam (defocusing) at \( L/4 < z < L/2 \), and (c) parallel beam at \( z = L/2 \). Obviously, the above considerations are valid also for the propagation of elastic waves in such a lens if ultrasonic wave velocities in it are distributed according to formula (1). It is also necessary that the diffraction criterion is satisfied: \( R \) and \( z \) of the acoustic lens should be considerably larger than the ultrasonic wavelength, which in turn requires considerable transverse dimension of glass samples in the low frequency region.

The objective of this paper is the discussion of a set of problems at the development and manufacturing of the first trial samples of inhomogeneous acoustic lenses from glass and the results of their studies.

**EXPERIMENTAL EQUIPMENT AND SAMPLE PREPARATION**

Gradient glasses for optics are created using different methods. The most well studied and most widely used are the methods of high-temperature ion-exchange diffusion and fusion. These methods, with some modification were used for the synthesis of gradient acoustic glasses. In the first method, the lens blank from the initial homogeneous multicomponent glass is heated to a temperature higher than the vitrification temperature and placed into a melted salt bath in which the diffusion replacement of the glass cation by the salt melt cation (ion-exchange diffusion) takes place with time; in this case, the composition of the blank glass changes smoothly from the surface into the volume depth, which results in the spatial distribution of the physical, in particular, elastic properties in the sample [4–6]. In the second method [7], a file of thin plates from glasses with different properties is heated to a temperature at which simultaneous fusion and interdiffusion of these plates takes place, after which a solid sample with the linear gradient of physical properties is formed. The advantage of the first method is the possibility of creating practically any spatial distribution of elastic properties, as compared to the linear (one-dimensional) distribution in the second method, and the disadvantage of the first method is a small depth of glass modification. This limits the acoustic lens diameter by 20–30 mm, while the advantage of the second method is the possibility of obtaining lenses with large dimensions and a noticeably larger change of elastic properties in the sample volume due to the choice of initial homogeneous glasses with strongly different elasticities.

The most difficult part of the methods described above is the development of the compositions of initial homogeneous acoustic glasses which possess simultaneously high diffusion, strength, acoustic, and heat-resistant properties. This work was performed and resulted in the creation of a number of new multicomponent glasses of acoustic designation described in [4, 5, 8].

This paper describes the results of acoustic studies of trial samples of cylindrical inhomogeneous acoustic lenses obtained based on the glasses developed by us using the method of ion-exchange diffusion and samples of inhomogeneous glasses in the form of parallelepipeds with a linear gradient of elastic properties manufactured by “LightPath®” Company (USA) according to our recommendations [7].

Acoustic studies of lenses were performed both in the mode of continuous ultrasonic waves using the Toepfer’s schlieren method and in the pulsed mode by measuring the amplitude of the ultrasonic signal passed through the lens by scanning the edge of the surface of the lens by the receiving piezo transducer. One of the gradient glass samples was studied using the acousto-optical method at a frequency of 210 MHz, the other studies were performed in the frequency range 2–14 MHz.

**EXPERIMENTAL RESULTS AND DISCUSSION**

Figures 2a and 2b show the “schlieren image” of the passage of longitudinal ultrasonic waves with a frequency of 2 MHz in the continuous mode. Ultrasonic waves propagated from the source on the left (not shown in the figure), passed through the distilled water and cylindrical samples 1 with the same dimensions (Ø 10 × 40 mm) fastened in metal frames 2: (a) homogeneous glass cylinder, i.e., initial acoustic lens blank (Fig. 2a); (b) inhomogeneous glass cylinder with specially created axially symmetric distribution of ultra-