Formation of Caustics by Refraction of Structured Laser Radiation in the Diffusive Layer of Liquid

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Abstract— One of actual and promising method of researching optically inhomogeneous media by using electromagnetic radiation is the method of the laser refractography. It is based on the phenomenon of refraction of structured laser radiation in optically inhomogeneous media and registration of its form deviations with the digital video camera. The case when inhomogeneity in liquid is created by diffusion. It was researched conditions for the occurrence of caustics in longitudinal probing of optical stratified inhomogeneous media by plane and cylindrical laser beams were researched in this work. Experimental setup for caustics visualization was shown. The method was shown for solving the inverse task of finding properties of the medium by analyzing caustics' location.

1. INTRODUCTION

Nowadays researching of optically inhomogeneous media represents great scientific interest. The refractive index is not the same in any point in such media and light passes due to refraction not rectilinearly. It is often important to know what occurs when two or more mediums with different physical characteristics contact each other, how the refractive index of liquid changes by heating or cooling objects inside it.

One method of researching optically inhomogeneous media is the method of the laser refractography. It is based on the phenomenon of refraction of structured laser radiation (SLR) in optically inhomogeneous media and registration of its form deviations with the digital video camera [1, 2]. This method is essentially different from the methods of researching of optically inhomogeneity that were known previously such as schlieren and shadowgraph techniques [3].

Application of laser techniques for the reconstruction of physical characteristics of medium, causing inhomogeneity of the refractive index it is advisable to probe medium by structured laser beams formed by diffractive optical elements (DOE).

Light lines with a fanciful form appear on the table, when a glass of water is located on it. Similar moving curves can be seen at the bottom of a shallow pond, water surface of which is roughness. These curves are caustics. Caustic is the envelope of light rays reflected or refracted by the curved surface or object [4]. Nevertheless, in this method caustics are special lines and special surfaces, and beside them the intensity of the light field increases sharply [5]. When probing inhomogeneity by SLR caustics appears, its location can be determined by using refractogram processing program with high precision, it is possible to solve the inverse task of finding properties of the inhomogeneous medium. Theory of caustics is directly related with one of mathematical section — the theory of catastrophes [6].

2. DIFFUSIVE LAYER OF LIQUID

Diffusive layer of liquid is a special type of inhomogeneity, which appears near interface of two liquid media with various physical characteristics. Liquids with various refraction indexes are considered in this work. Refraction index of optically denser liquid is n_1, less dense — n_2 ($n_1 > n_2$) (Fig. 1). Distribution of the refraction index in diffusive layer can be described by different function such as linear or hyperbolic tangent, in this paper exponential model is used [7]:

$$n(x) = n_2 + \frac{n_1 - n_2}{1 + \exp(\frac{x - x_s}{h})}, \tag{1}$$

where h — characteristic half-width of layer, x_s — middle of layer.

Let layered-inhomogeneous medium in which there is the diffusive layer has following parameters: $n_1 = 1.3410$, $n_2 = 1.3310$, $x_s = 50\,\mathrm{mm}$, $h = 1.1\,\mathrm{mm}$. Distribution of the refraction index is presented in Fig. 2.

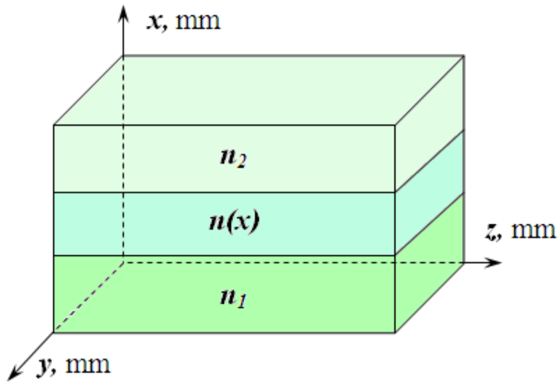

Figure 1: Diffusive layer's model.

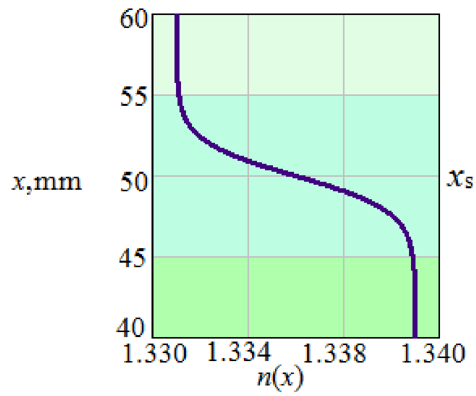

Figure 2: Distribution of refraction index in diffusive layer of liquid.

Relation (2) is the equation of the ray trajectory in a plane-layered medium, given the refractive index distribution $n(x)$ and the initial conditions $z_0 = z(0)$, α_0 — the angle at which the ray enters the medium, n_0 — refraction index in entry point of the ray in medium.

$$z(x) = z_0 + \int_0^x \frac{n_0 \sin\alpha_0 dx}{\pm\sqrt{n^2(x) - n_0^2 \sin^2\alpha_0}}. \tag{2}$$

Using this expression it is possible to simulate on a propagation of a plane laser beam in diffusion layer of liquid by approximating it with a set of infinitely thin rays. Fig. 3 shows formation and confluence of two caustic surfaces. With the help of this refractogram we can model and determine the location, shape of caustics and the point of confluence it will be possible to solve the inverse task of finding properties of the medium in comparison with the experimental results [8].

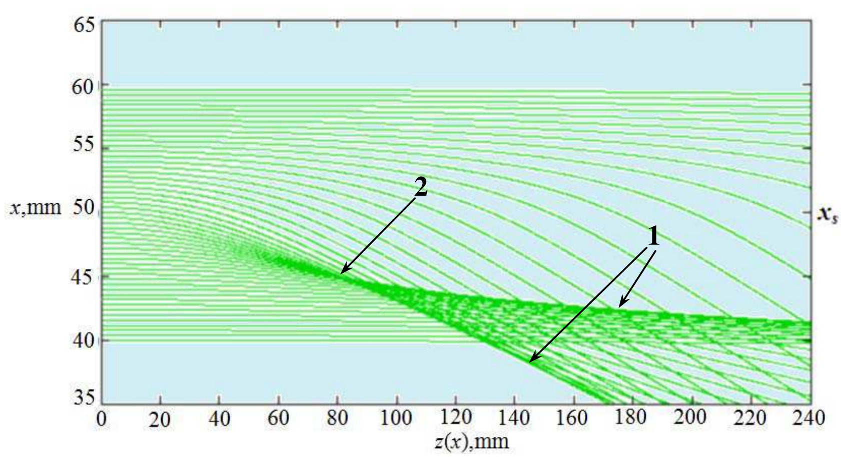

Figure 3: Formation of caustics (1) and point of their confluence (2) in the propagation of a plane laser beam in diffusive layer.

3. CAUSTICS' FORMATION IN EXPERIMENT

In order to observe and register refractogram of plane laser beam propagation in inhomogeneous media it is possible to use setup, which is presented in Fig. 4. Laser 1 and built-in optical system 2 form plane laser beam, which probes cuvette 3 with created diffusive layer 4 in it. 2D-refractogram 6 is registered by digital camera 5 and processed by using special algorithm on personal computer 7.

For creation of diffusive layer of liquid we used distilled water and water-NaCl mixture. Refractogram storing was made by recording the scattered radiation on special particles added in water. Parameters of medium: refractive indexes of saline water $n_1 = 1.3410$ and distilled water $n_2 = 1.3310$. Photo, which was received during experiment is presented in Fig. 5.

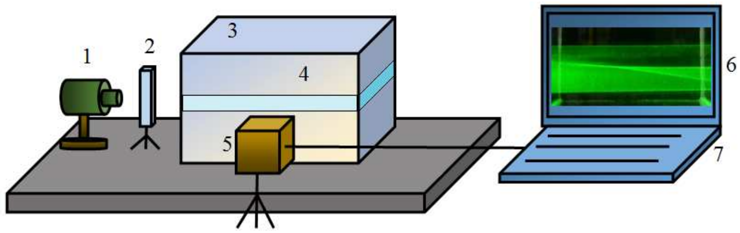

Figure 4: Setup for experiment with the diffusive layer of liquid and probing plane laser beam: 1 — laser, 2 — optical system, 3 — transparent cuvette, 4 — diffusive layer, 5 — digital camera, 6 — 2D-refractogram, 7 — PC.

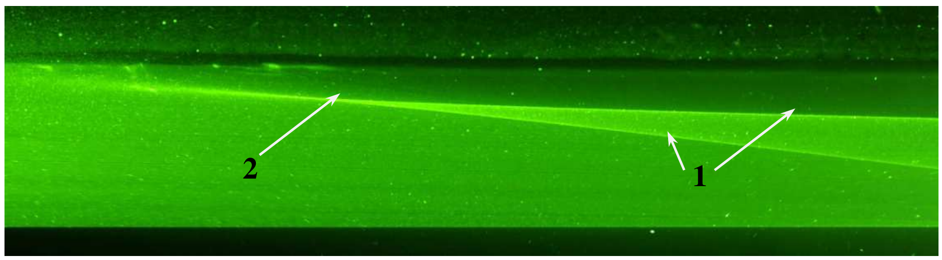

Figure 5: Experimental 2D-refractogram with presence of caustics (1) and point of their confluence (2) in diffusive layer of liquid with probing plane laser beam.

Using a specially devised algorithm for refractogram processing it is possible to separate caustic surfaces. By comparing their position and coordinating of their confluence with the calculated ones we can get distribution of the refractive index or the value h. By registering refractograms at variable moments of time at constant interval we can determine the dependence of the refractive index distribution on time, that gives an indication on how liquids diffuse each other.

4. 3D-VISUALIZATION OF CYLINDRICAL BEAM'S REFRACTION

Experimental setup is presented in Fig. 6.

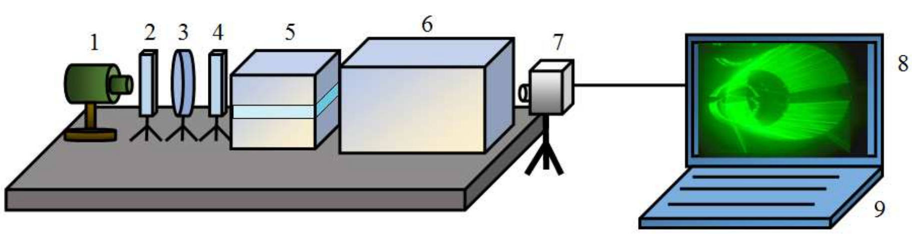

Figure 6: Experimental setup: 1 — laser, 2, 4 — lenses, 3 — DOE, 5 — cuvette with diffusive layer of liquid, 6 — cuvette with scattering particles in water, 7 — digital camera, 8 — 3D-refractogram, 9 — PC.

To form cylindrical laser beam it was created optical system, which consists of laser 1, lens 2 for focusing beam in registration area, DOE 3 and lens 4 for making beam parallel. In order to observe and register 3D-refractogram of cylindrical laser beam spreading in inhomogeneous mediums it is possible to use two cuvetts [9]. Creation of diffusive layer is taking place in cuvette 5 but 3D-refractogram's registration is not possible there because of distortion presence. That is why registration of refractogram realizes in the second cuvette 6. Registration of 3D-refractoram 8 was made by digital camera 7 and processed by personal computer 9.

3D-refractogram of the laser beam propagating in a homogeneous medium is shown in Fig. 7. During the experiment it was changing position of laser beam's center. There are three characteristic main positions: laser beam's center lies in the planes of the upper, lower boundaries layer and in the plane of middle of layer. The third case is presented in Fig. 8.

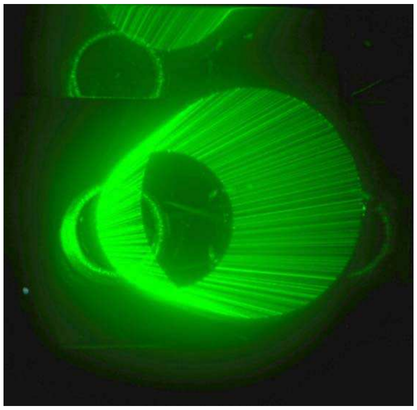

Figure 7: 3D-visualization of cylindrical laser beam propagation in homogeneous medium.

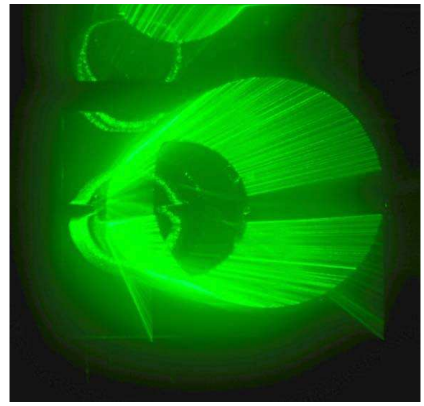

Figure 8: 3D-visualization of cylindrical laser beam propagation in diffusive layer of liquid.

5. CONCLUSION

Modeling of laser beams' caustics and researching of their shape give possibility to foresee laser beam actions in inhomogeneous media. It is very important to know the area of caustics' occurrence that allows optimizing experiments. At the consideration experimental refractogram, which was made in diffusive layer, it is possible to analyze how mediums can diffuse each other and estimate distribution of refraction index.

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