Structured Laser Radiation in Optical Inhomogeneous Media Refractography

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Abstract— One actual and promising method of researching optically inhomogeneous media by using structured laser 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. It was considered case when inhomogeneity in liquid created by heating or cooling and diffusion in condensed mediums. Experimental setup for visualization refraction of SLR in different medium is shown. The method was shown for solving the inverse task of finding properties of the medium by analyzing 2D and 3D-refractograms.

1. INTRODUCTION

Nowadays research of optically inhomogeneous media represents great scientific interest. In such media the refractive index is not the same in any point 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 [1]. 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. This method is in essence different from the previously known methods for researching of optically inhomogeneity such as schlieren and shadowgraph techniques [2].

The report is devoted to the further development of new laser method for investigation of optical inhomogeneity media by using of structured laser radiation (SLR) obtained by passing a laser beam through refraction (ROE) and diffraction (DOE) optical elements. Discussed in this report structured laser radiation sources are continuous-wave semiconductor lasers equipped with diffraction optical elements (DOEs). Figure 1 presents typical forms of laser beams produced by DOEs. When the optical properties of the medium under study vary slowly enough as a function of coordinates, the propagation of laser beams can be described in terms of the geometrical optics approximation. In that case, the beam for structured laser radiation of any type should be represented in the form of a suitable family of rays. The theory and methods of obtaining these beams are quite fully described in [3].

Table 1: Main types of SLB obtained with DOEs.

Single Line	Crosshair	Parallel Lines	Single Dot	Single Circle	7 Concentric Circles

For investigations of optically inhomogeneous media the optical methods are widely used which based on using wide light beam such as shlieren and shadowgraph methods [2]. These methods were developed for investigations gas media basically. For optical inhomogeneous condensed matter investigations it's not used because of massiveness and high prices of designed devices.

The usage of the SLB gives the new possibility for laser refraction methods development. In [1] was considered the base principles of Laser Refractography (LAREF) — the new diagnostics and visualizations technology of the boundary thin layered heterogeneities and edge effects in liquids and gas. This technology is based on:

- refraction of a structured laser beam in optically inhomogeneous media,

- digital recording of the refraction patterns (refractogram) by CCD-camera ,
- digital processing of the refractogram by PC,
- digital comparison experimental and simulated 2D- refractograms for receiving the information about parameters of investigation medium,
- This measuring technology is designed for exploration of physical processes in transparent condensed media.

When the optical properties of the medium under study vary slowly enough as a function of coordinates, the propagation of SLB can be described in terms of the geometrical optics approximation [1]. In that case, the beam for structured laser radiation of any type should be represented in the form of a suitable family of rays.

2. SLR REFRACTION IN TRANSPARENT OPTICAL INHOMOGENEOUS MEDIA

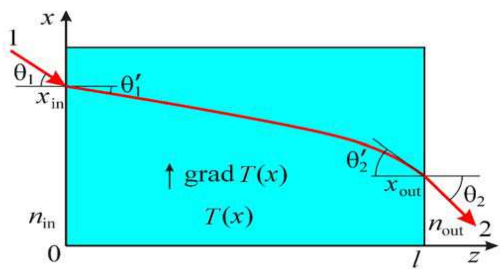


Figure 1: Ray trajectory in a plane layered medium with a decreasing refractive index: 1 — input ray, 2 — output ray, l — medium length, θ_1 — incidence angle, θ_2 — output angle.

2.1. Propagation of the Laser Rays in a Plane Single-layer Inhomogeneous Medium

Mathematical equations for calculating refraction of single ray in inhomogeneous media are given in the author's monograph [1]. Fig. 1 shows an example of calculating single ray trajectory in a plane layered medium (heated water), and Fig. 2 shows its trajectory in cylindrical inhomogeneity. In such inhomogeneities rays are deflected in the direction of increasing the refractive index gradient (for liquid its direction of decreasing temperature).

Output angle θ_2 can be calculated from formula $\sin\theta_2 = \sqrt{\frac{n^2(x_{\text{out}})-n^2(x_{\text{in}})+n_{\text{in}}^2\sin^2\theta_1}{n_{\text{out}}^2}}$.

2.2. Propagation of the Laser Rays in a Cylindrical Inhomogeneous Medium

$$\theta_2(r) = \theta_t - \int_{r_t}^{r} \frac{n_0\rho dr}{r\sqrt{r^2n^2(r)-\rho^2n_0^2}} \tag{1}$$

$$r_t n(r_t) = n_0\rho \tag{2}$$

$$\theta_t = \pi - \int_{r_t}^{x} \frac{n_0\rho dr}{r\sqrt{r^2n^2(r)-\rho^2n_0^2}} \tag{3}$$

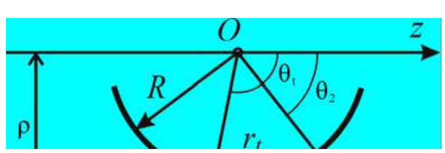


Figure 2: Propagation of a laser ray in a cylindrical inhomogeneous medium: where ρ is distance between axial line and laser ray, R – radius of heated cylinder, T — turn point of laser ray. Equations (1)–(3) allows to calculate parameters of deflected ray, i.e., turn angle and turn point.

2.3. Propagation of SLR in 2-layer Medium

The ray trajectories in the diffuse layer were calculated as follows. The refractive index gradient in the diffuse layer may be described by formula (4) below that agrees well with the experimental relationship:

$$n(x) = n_1 + (n_1 + n_2)/\{1 + \exp\left[(x - x_s)/h\right]\}, \tag{4}$$

where n_1 is the refractive index of the higher-density (bottom) liquid, n_2 is the refractive index of the lower-density (top) liquid, $h$is he characteristic half-breadth of the layer, and x_s is the position of the center of the layer.

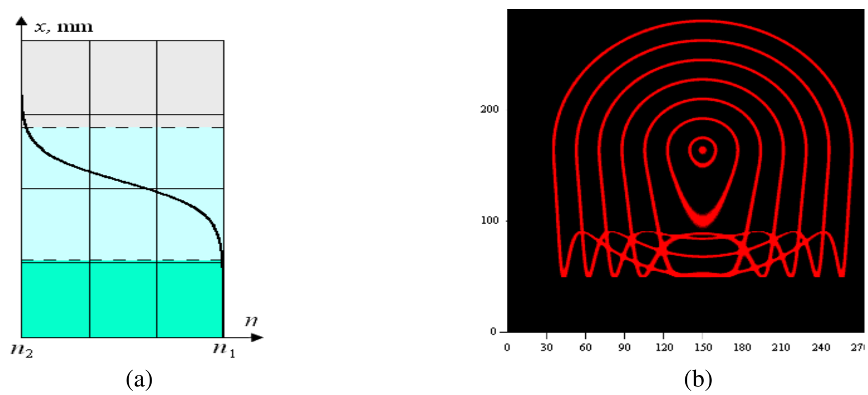


Figure 3: Propagation of laser rays in the diffusive layer of a two-layer liquid. (a) Refractive index in diffusive layer depending on height ($n_1 = 1.3400$, $n_2 = 1.3312$), (b) refractograms of cylindrical beams in diffusive layer.

3. SLR REFRACTION IN 3D INHOMOGENEOUS MEDIA

More complicated situation is observed in case of calculating SLB refraction when optical properties of medium is changes in three directions. This problem was solved for the first time in [4–7]. There an example of calculating three-dimensional refraction pattern for three-dimensional inhomogeneity ($n = n(x, y, z)$).

The following figures shows three-dimensional refractograms (refraction of SLB), for), egg-shaped radial inhomogeneity, radially inhomogeneous, the soliton in the pycnocline layer type (inclined LB) respectively.

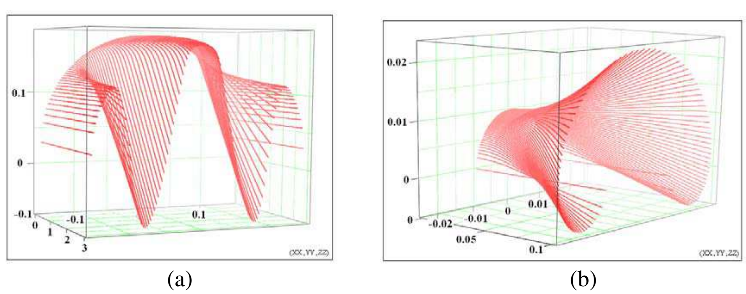


Figure 4: Calculated refractograms of a cylindrical beam in the volume of the following three-dimensional inhomogeneities: (a) egg-shaped radial inhomogeneity; (b) soliton in the pycnocline layer type.

4. 3D-REFRACTOGRAMS FOR CYLINDRICAL BEAMS IN DIFFUSIVE LAYER OF LIQUID

Figures 5–6 shows calculated 3D-refractograms of cylindrical SLB in diffusive layer of liquid, which describes by difference of refractive indices of upper and lower liquids, position of its center, characteristic half-width, distribution function of refractive index on vertical axis and length of medium. Axis beams are located at different distances from the middle of diffusive layer x_s: x_1 and x_2 [6,7].

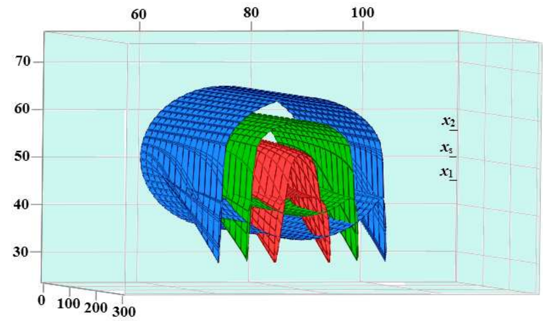


Figure 5: 3D-refractograms for three concentric cylindrical laser beams with different radii, propagating in diffusive layer of liquid: x_1, x_2 and x_3 — positions of beams centers, dimensions in mm.

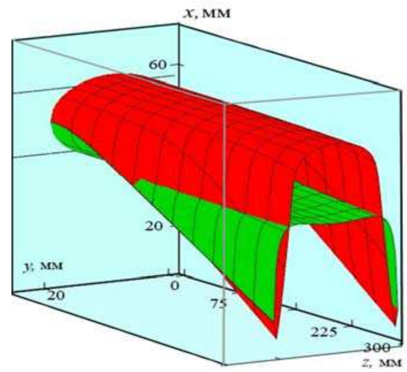


Figure 6: Refraction of two half-cylindrical beams in diffusive layer with length 300 mm. Middle of diffusive layer — 50 mm, position of two beams interface — 45 mm, beams radii 10 MM, difference between refractive indices in layer 0,02, its width 6 mm.

5. EXPERIMENTAL SETUP FOR INVESTIGATION OF REFRACTION SLR IN THE CONDENSED MEDIUMS

Figure 7 shows block diagram of experimental setup for registration of refraction patterns in transparent media. It consist of semiconductor laser 1 power 15 mW, optical element 2 for SLR obtaining, system 3 for beam scanning on vertical axis, cuvette 4 with liquid under investigation in which hot or cold bodies placed, screen 5 for refractograms imaging, digital camera 6 which connected to PC 7 with special software for refractograms processing [8]. Fig. 8 shows stages of experimental investigations.

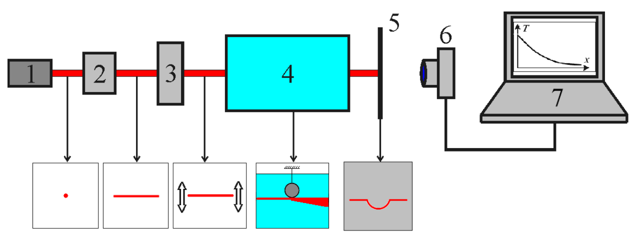
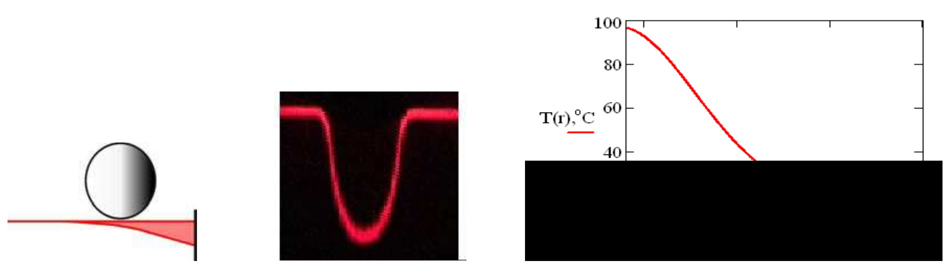


Figure 7: Scheme of experimental refractographic system: 1 — laser, 2 — optical unit SLR, 3 — beam scanning unit, 4 — investigated medium, 5 — screen, 6 — digital camera, 7 — PC with special software.



(a) (b) (c)

Figure 8: Experimental refractogram processing: (a) — experimental setap, (b) experimental refractogram, (c) — reconstructed radial temperature profile.

6. CONCLUSION

Developed method Laser Refractography based on using SLR and can be used for: investigation of 1D, 2D, and 3D optical inhomogeneities; stationary and nostationary process diagnostics in condensed mediums; investigation of heat processes in liquids and gas; investigation free convection in liquids [9, 10], investigation of different liquids mixing; investigation of sound field in liquids; diagnostics of process in micro channels; etc....

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