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Refraction of the Flat Optical Beam in a Transparent Heterogeneous Environments

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Abstract

Presents a method of visualization and laser diagnostics of optically inhomogeneous media based on the phenomenon of refraction of the structured laser radiation (SLR). The described method of studies of the diffusion layer of the optical refractography method. Experimental setup for digital recording refractive pattern (refractograms). Shown for examples application of methods of the laser refractography thermal processes.

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1. Introduction

Optical refractography has all the advantages inherent in optical measurements. This method is a quantitative integral method applicable to the study of transparent stationary and non-stationary environments. Visualization of inhomogeneous on the basis of flat optical beam allows you to explore the thin boundary layers of fluid near the heated bodies, and to carry out quantitative diagnostics of optically inhomogeneous media in conditions of strong refraction.

2. Optical Refraction Methods

The recent active application of laser methods for the diagnostics of acoustic pressure, temperature, density, salinity, and current velocity fields in transparent media is due to their substantial advantages over other methods. The present-day stage of development of laser and computer techniques is characterized by the advent of visible semiconductor lasers and diffractive optical elements (DOE), digital video and photocameras capable of resolving over a million of picture elements (pixels), and computers with an operating speed in excess of 3 GHz and a memory capacity over 100 GB, along with the development of novel efficient digital methods for processing optical images.

Laser refractography (LR) is a novel laser method for the diagnostics of optically inhomogeneous media, based on the phenomenon of refraction of structured laser radiation (SLR) in optically inhomogeneous media, digital recording of the refraction patterns (refractograms), and their computer processing. This method is being used for the visualization and quantitative investigation of transparent stationary and non-stationary inhomogeneous media. The refractogram (image) of SLR passing through the inhomogeneous medium under study is recorded in the plane of observation with a multiposition receiver and compared, following its preliminary processing, with standard images corresponding to various inhomogeneous models [5, 6].

As follows from Fig. 1, the basis of the given classification is the division of the visualization methods according to the character of the optical radiation they use.

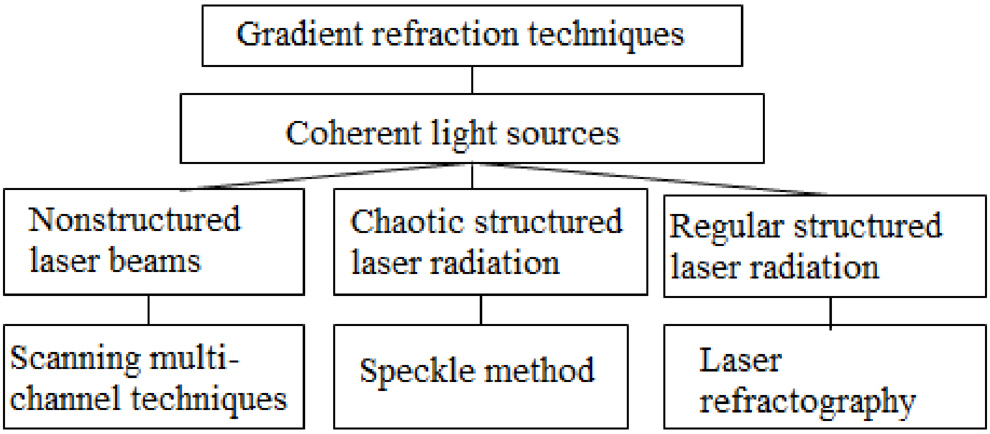


Figure 1: Classification of gradient refraction techniques.

3. Main Types of Structured Laser Radiation(SLR)

Structured laser radiation is spatially amplitude-modulated radiation obtained with the aid of classical optical elements, diffraction optical elements (DOEs), or structured screens.

The diffraction optical elements (DOEs) that have only recently become commercially available have the form of a thin phase plate with a special phase relief laser engraved in it. The diffraction of laser radiation by such an optical element produces various kinds of spatially modulated radiation known as structured laser radiation. DOEs are used with both gas and semiconductor lasers generating highly astigmatic beams [3]. The main elements of structured laser radiation are listed in Table 1.

Table 1: Main types of SLR obtained with DOEs.

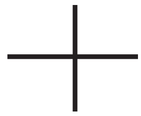
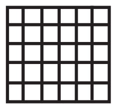
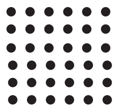
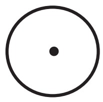
Line	Cross	Horizontal line
		
Vertical line	Grid	Point
		
Dotted line	6 by 6 matrix	Ring
		

Table 2. Lists the refractive indices of some gases and liquids, as well as their temperature coefficients. The refractive index temperature coefficient is proportional to the density temperature coefficient.

Table 2: Refractive indices of some gases and liquids for λ = 0.6328 μm [1, 2].

Nos.	Medium	N	dn/dT(°C^{-1})
1	Air	1.0002724	0.927×10^{-6}
2	Oxygen	1.0002791	0.864×10^{-6}
3	Nitrogen	1.0002793	0.949×10^{-6}
4	Water vapor	1.0002354	0.798×10^{-6}
5	Water	1.3314000	-0.985 ×10^{-6}

Linear extrapolation of the refractive index is permissible to small temperature differences (10–20°C) only. The temperature dependence of the refractive index of water for laser radiation with a wavelength of λ = 0.6328 μm is determined by the approximation relation

$$n(T) = 1.3328 - 0.000051T - 0.0000011T^2, \quad (1)$$

obtained on the basis of the dispersion formula and the data presented by [1, 2], are shown in Table 3.

TABLE 3: Refractive indices of distilled water for λ_D= 589.3 nm.

T(°C)	n_D	T(°C)	n_D	T(°C)	n_D	T(°C)	n_D
0	1.33395	5	1.33388	10	1.33369	15	1.33339
1	1.33395	6	1.33385	11	1.33364	16	1.33331
2	1.33394	7	1.33382	12	1.33358	17	1.33324
3	1.33393	8	1.33378	13	1.33352	18	1.33316
4	1.33391	9	1.33374	14	1.33346	19	1.33307

4. Theoretical model of plane-layered medium

In the case of plane-layered medium, when the properties of the medium under study are changing very slowly 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. To derive the trajectory equation, we will proceed from Snell's law for the plane inhomogeneous medium,

$$n(x)\sin\alpha(x) = n_0 \sin\alpha_0. \tag{2}$$

As follows from Fig. 2,

$$\tan\alpha(x) = \frac{dz}{dx}, \tag{3}$$

and so, integrating (3), we receive

$$z(x) = z_0 + \int_0^x \tan\alpha(x)dx, \tag{4}$$

where z_0 = z(0).

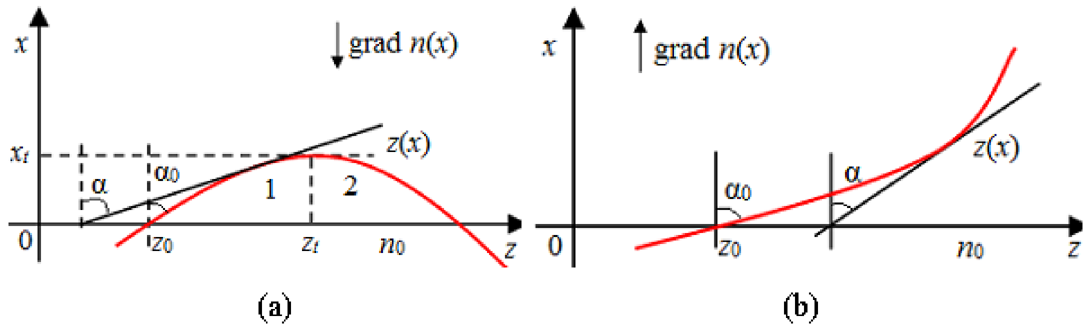


Figure 2: Ray trajectories in a plane-layered medium, (a) the refractive index of the medium decreases, (b) the refractive index increases.

From formula (2) we obtain expression for tan α(x) and substitute it into Eq.(4) to have

$$z(x) = z_0 = + \int_0^x \frac{n_0 \sin \alpha_0 dx}{\pm\sqrt{n^2(x) - n_0^2 \sin^2 \alpha_0}}. \tag{5}$$

The sign of the square root is determined by that of tan α(x).

Relation (5) 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) and α_0=α(0).

Let's review the propagation of laser beam along the Oz axis in inhomogeneous medium, consisting of three parts (Fig.3). The first part (0 – z_1) – optically homogeneous medium with refractive index n_0. The second part (z_1 – z_2) – optically inhomogeneous and dynamically medium with refractive index $n(y,t)$, depending on y and t, at that $n(z_2)$ = n_0; the third part (z_2 – z_3) – optically homogeneous medium with refractive index n_0. If the laser beam falls normally on such a medium, then in the first part it will propagate straightforward along the Oz axis. In the second part the beam will deviate toward the positive refractive index gradient. In the third part – the beam will propagate straightforward at the angle $\alpha_1(t)$ to the Oz axis [4].

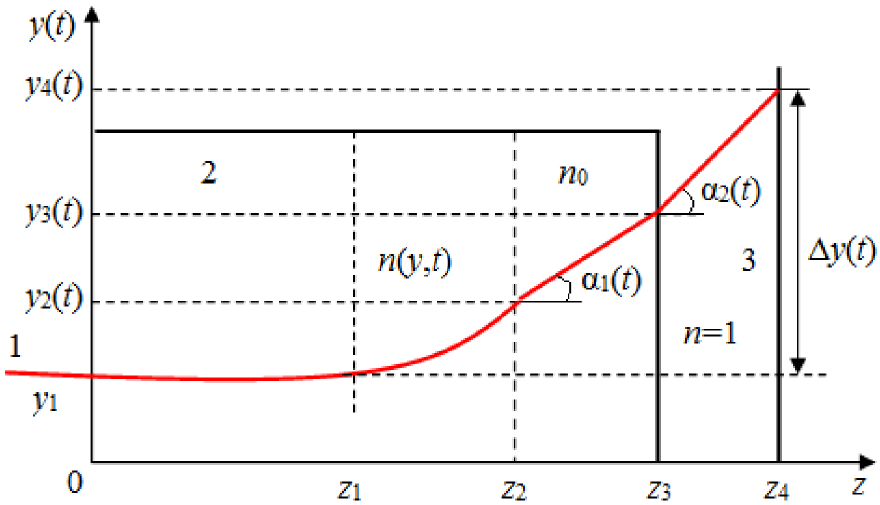


Figure 3: Laser beam propagation in dynamic plane layer medium: 1 – laser beam, 2– investigated medium, 3 – screen.

In laser refractography (LR) technique the laser beam image shift is measured and it can easily be determined by geometry optics approach on the basis of ray propagation laws or by beam optics approach, or the basis of wave propagation laws.

The angle of beam shift at the exit point of the second part of the media in the direction of y – axis α_1 is described by the equation

$$n(y_2, t) \sin\left[\alpha_1(y_2, t)\right] = n_0, \tag{6}$$

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where $n(y_2,t)$ – refractive index in point y_2 at time t.

The exit point y_2 of the second part of the media can be obtained from the integral equation

$$z_2 = z_1 + n_0 \int_{y_1}^{y_2} \left[\sqrt{n^2(y) - n_0^2} \right]^{-1} dy. \tag{7}$$

The exit angle at the second part of the medium is

$$\alpha_1(t) = \arcsin\left[n(y_2, t) n_0^{-1} \right]. \tag{8}$$

Full laser beam shift in the registration plane is

$$\Delta y(t) = y_2(t) - y_1 + \left[z_3 - z_2 \right] \tan \alpha_1(t) + (z_4 - z_3) \tan \alpha_2(t). \tag{9}$$

The form of the function $n(y,t)$ is determined by the properties of liquid and the refractive index distribution in the boundary layer. It should be mentioned, that expressions (6) and (7) do not contain restrictions for the refractive index gradient magnitude.

If we know, the law of refractive index variation, then the equation (7) gives the opportunity to calculate the trajectory of the beams in optically inhomogeneous medium. Expressions (6-9) allow calculate laser beam shift in the screen plane, which can be easily determined experimentally.

It is clear, that for rebuilding $n(y,t)$ only the measurement of the laser beam shift is insufficient. In order to make LR technique a quantitative one, it is supposed to compare two refractograms: the first one calculated according to (7) and the second one obtained by experiment. For calculation the refractogram it is necessary to carry out the calculation of the refractive index distribution in the investigation area by means of computation software and to use the medium refractive index dependence on temperature. For example for water at wavelength λ= 0.6328 μm the following refractive exponent dependence on temperature can be used $n(T) = 1.3328 - 0.000051T - 0.0000011T^2$. Temperature T is measured in °C.

For exposure of beam propagation basic physical rules, let's consider exponential refractive index dependence on coordinate with time dependent parameters:

$$n(y,t) = n_0 \left\{ 1 + \Delta n(t) \exp\left[-y/a(t) \right] \right\}, \tag{10}$$

where $a(t)$ – typical width of temperature inhomogeneous layer near the heated body, $\Delta n(t)$ – maximum refractive index change. In the Fig. 3 trajectories of rayes passing on different distances from the surface are shown.

5. Description of the experimental setup

For experimental research of physical processes in liquids widely used method of optical refractography, namely, the sounding of the studied medium structured coherent optical radiation and digital recording of parameters of the past radiation. Visualization of the refraction images is fundamental methods of research when conducting quantitative diagnostics of optically inhomogeneous transparent media.

In Fig.4 shows a scheme of optical refractography system. Radiation from the optical module 1, in the form of a flat beam, is directed into the water-filled cell from the bottom 2, the heated body 3 mounted on the alignment table 4. On the screen 5 is observed refractogram, which is photographed by a digital camera 6 and is processed by the computer 7 to determine the process of cooling of heated bodies.

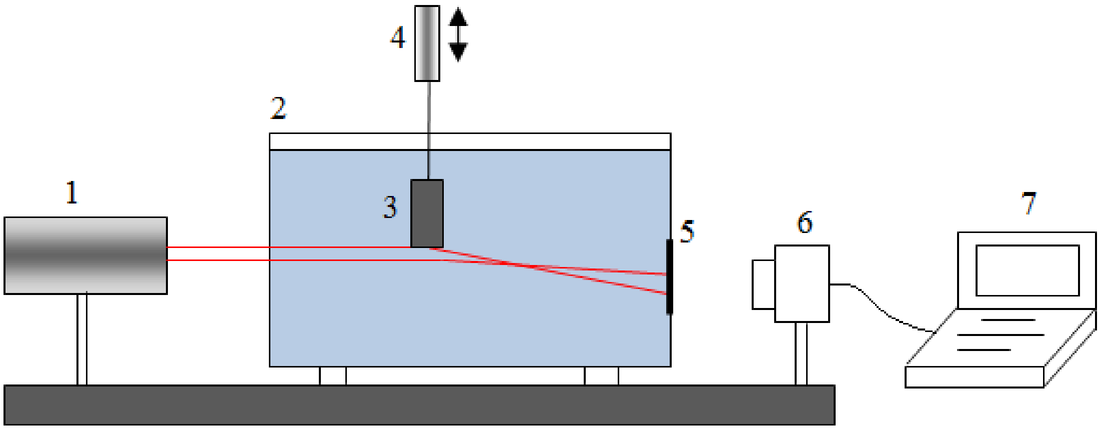

Figure 4: Scheme of optical refractories system: 1 – optical module, 2 – water-filled cell, 3 – heat body, 4 – alignment table, 5 – screen, 6 – digital camera, 7 – personal computer.

The installation uses a radiation source with a capacity of 5 mW. The wavelength of the radiation is equal to 0.53 μm. Distance from the metal element to the screen is18 mm, see the element is heated to a temperature of 90 ° C and is lowered into the water-filled cell, the temperature of which was 20 °C. The temperature of the thermal element is measured by a thermocouple. Fig. 5-7 shows the experimental refractograms flats optical beam obtained at the screen in 5 different points in time, which allows to determine the temporal process of cooling of heated bodies.

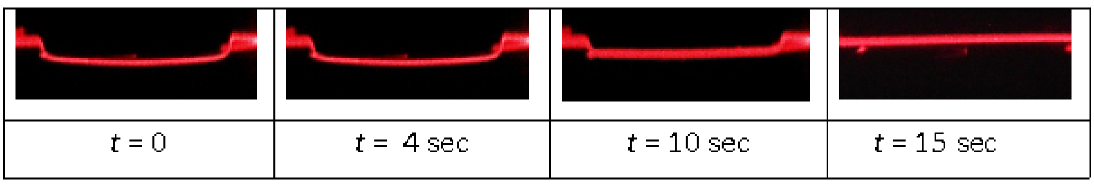

Figure 5: Refractive pattern for visualization of temperature distribution in different points in time.

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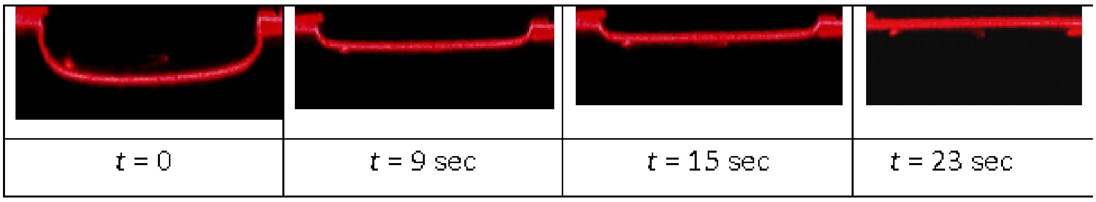

Figure 6: Refractive pattern for visualization of temperature distribution in different points in time.

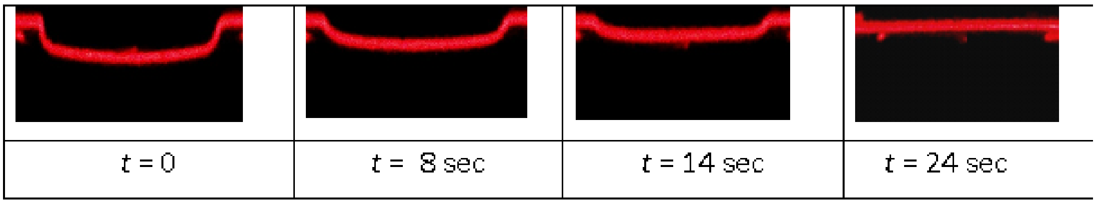

Figure 7: Refractive pattern for visualization of temperature distribution in different points in time.

In Fig. 8 shows the thermal elements around which investigated the refraction pattern.

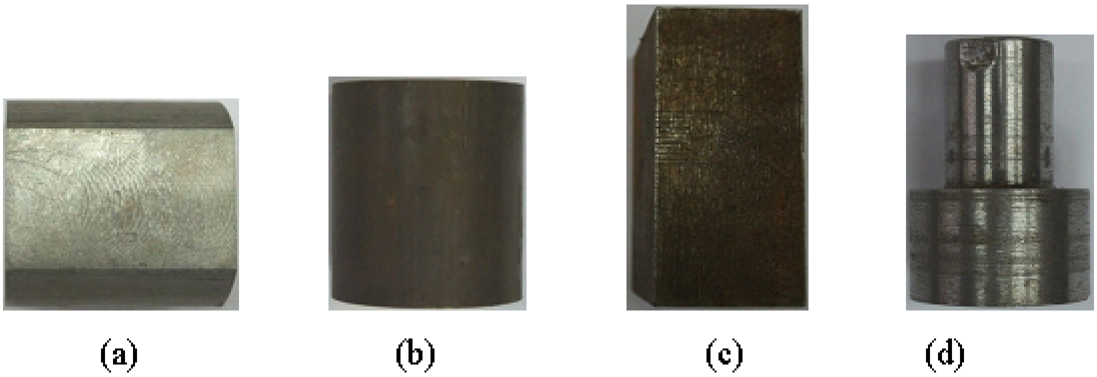

Figure 8: Heat elements: (a) horizontal cylinder, (b) vertical cylinder, (c) parallelepiped, (d) cylinder.

Fig. 9-12 shows the experimental refractograms flats optical beam obtained at the screen in 5 different points in time, which allows to determine the temporal process of cooling of heated bodies.

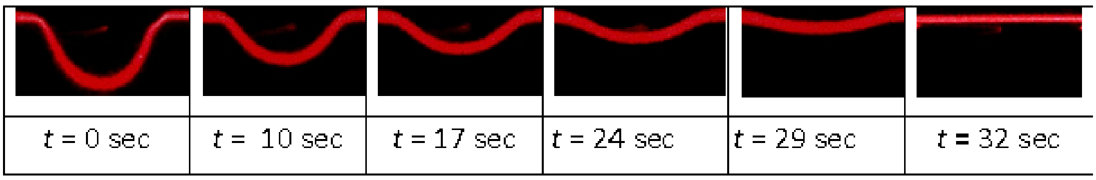

Figure 9: Refractive pattern for visualization of temperature distribution in different points in time of element (a).

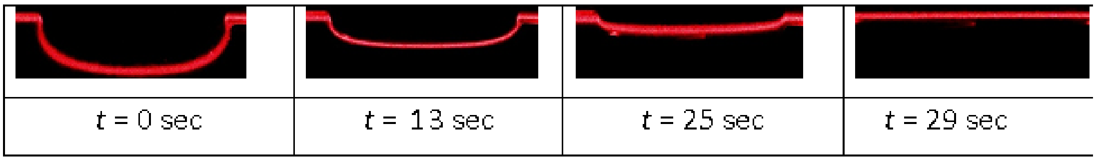

Figure 10: Refractive pattern for visualization of temperature distribution in different points in time of element (b).

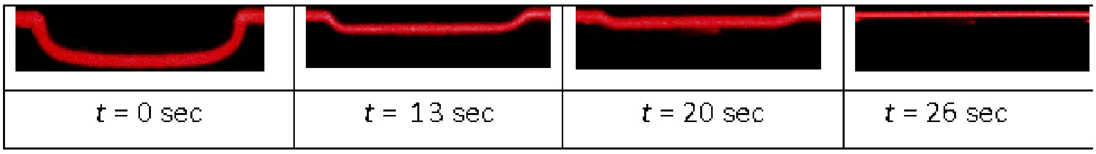

Figure 11: Refractive pattern for visualization of temperature distribution in different points in time of element (c).

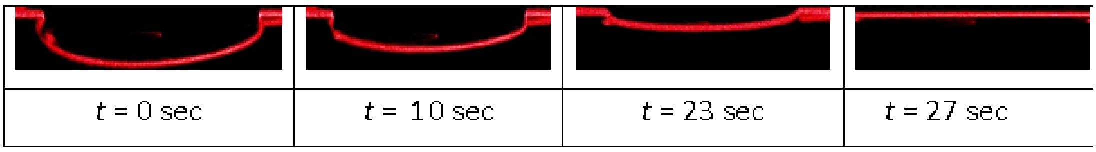

Figure 12: Refractive pattern for visualization of temperature distribution in different points in time of element (d).

6. Conclusion

Modern stage of optically inhomogeneous medium diagnostics refractive methods development is characterized by using of coherent light sources, new optical elements including DOEs. Laser refractography is oriented not only on inhomogeneity visualization, but also on getting quantitative information about optically inhomogeneous flows. Laser refractography can be used not only for stationary process diagnostics but also for fast nonstationary process diagnostics, including investigation of heat processes in liquids, gas and plasma, free convection in liquids near heated and cold bodies, processes of different liquids mixing in chemical technology devices.

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