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Laser refractography of optically inhomogeneous media

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***Abstract*. The basic principles of laser refractography, a new method for diagnostics of optically inhomogeneous media and flows based on refraction of spatially structured laser radiation, are described. By using 2D- and 3D-refraction patterns, the medium under investigation can be visualised and the inhomogeneity profile can be diagnosed quantitatively. The method is modified for studying edge effects and thin boundary layers in liquids and gases. Due to nearly inertialess measurements, laser refractography can be used for diagnostics of fast and transient processes. The simultaneous diagnostics of processes in various regions is provided by an extended radiation source.**

Keywords: *refraction, refraction pattern, structured laser radiation, laser measurements, boundary layer, convection.*

1. Introduction

Due to their considerable advantages over other methods, laser techniques have been widely used in recent years for diagnostics of the fields of acoustic pressure, temperature, density, flow velocity in transparent media [1]. First of all, optical measurements do not distort the fields under study because the energy being absorbed by the medium is quite low in most cases. In addition, laser methods almost have no inertial errors, which makes it possible to perform precision measurements of fast processes. The possibility to perform remote measurements is an additional advantage of these methods. Laser methods can be used to study the refraction index field, which can be subsequently recalculated into the field of another physical quantity being sought.

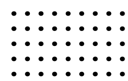
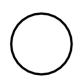
The modern stage of development of laser and computational techniques is characterised by the advent of visible semiconductor lasers, commercial production of diffraction optical elements [2], digital video and photo cameras with the number of pixels exceeding a million, computers with a speed exceeding 3 GHz and a memory exceeding 100 GB, and the development of new effective digital methods for optical image processing. All these factors have made it possible to work out optical diagnostic methods for inhomogeneous media at a qualitatively new scientific and technical level by developing methods for obtaining information on the medium or a flow in the chosen cross section (2D diagnostics) and in the bulk (3D diagnostics).

Refraction methods for diagnostics of flows have been revived in recent years due to the above-listed factors. Array photodetectors and computers have made it possible to work out new methods of laser gradient refractometry (speckle method, as well as computer-laser [3] and background oriented shlieren (BOS) methods [4]). High-quality laser beams of various shapes are produced by using simple optical systems. Scanning and multichannel refractometric systems with computer-assisted image processing have been developed [2, 4].

Laser refractography is a new method of laser diagnostic for optically inhomogeneous media such as liquid, gas and plasma flows. Laser refractgraphy is based on refraction of structured laser radiation in optically inhomogeneous media and digital recording of the refraction pattern. This method is a quantitative integral method used for studying transparent stationary and nonstationary media.

Structured laser radiation (SLR) is a spatially amplitude-modulated radiation obtained mainly with the help of diffraction optical elements. The main types of SLR sources are given in Table 1 and classified according to the shape of 3D geometrical figures formed by the beams from the sources of line-, plane- and cone-structured laser radiation. The two-dimensional figures shown in Table 1 are cross sections of the beams formed by a family of geometrical optics rays from the source. Combining the main types of sources, we can also create other sources adapted to the structure of inhomogeneities and to the shape of the surface of bodies near which the boundary layers are studied. For the diagnostics of spatial inhomogeneities, it is expedient to form measuring 'networks' of elementary sources.

Table 1. Main types of SLR.

Source type	SLR beam cross section
Line-structured	
Plane-structured	
Cone-structured	

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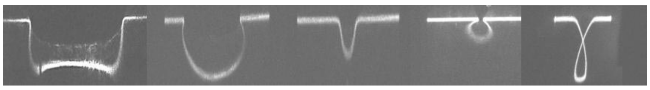
Obviously, the above approach is valid in the geometrical optics approximation. Hence, to determine the range of applicability of the method, the error associated with diffraction effects in actual measuring devices should be estimated. For example, plane-structured laser radiation, also known as the 'laser sheet' (LS), is actually an astigmatic laser beam with an elliptical cross section whose diffractional divergence is determined by using the familiar quasi-optical methods [5].

The structured laser radiation passing through a medium forms a 2D-refraction pattern on the screen, whose shape is determined by the type of SLR and the spatial distribution of the refractive index depending on temperature, pressure, density, salinity and other parameters of the medium.

A 2D-refraction pattern is the 2D-image of a source of spatially structured radiation formed by an optical system whose role is played by the medium under study. In this respect, the refractography technique is close to the BOS method in which images of the structured screen with randomly distributed points are studied in natural light passing through an optically inhomogeneous medium. The fundamental difference between laser refractography and the BOS method is the use of coherent laser radiation which allows a quantitative diagnostics of the medium and an analysis of interference effects carrying additional information. Moreover, observation of laser radiation scattered by small particles makes it possible to visualise the region under investigation.

2D-refraction patterns can be used for quick diagnostics of inhomogeneities even without subsequent computer processing. Figure 1 shows typical 2D-refraction patterns of the laser sheet used for diagnostics of the boundary layer and edge effects in the vicinity of heated or cooled bodies in a liquid. 2D-refraction patterns for other types of SLR are shown in [6]. The set of laser sheet projections in various cross sections forms a 3D refraction pattern of inhomogeneities.

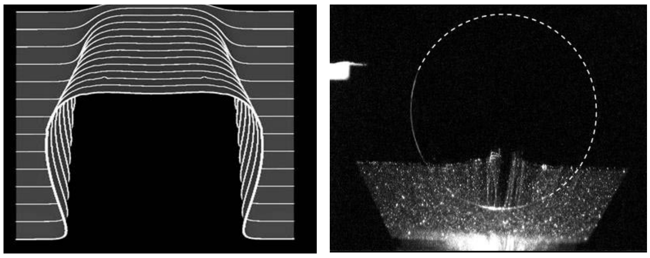


a b c d e

Figure 1. Typical 2D-refraction patterns of the LS, obtained for a boundary layer in the vicinity of heated (a – d) and cooled (e) bodies in a liquid: parallelepiped (a), cylinder with a flat bottom (b), sphere (c, e) and wedge tip (d).

A 3D-refraction pattern is a 3D image of the surface formed by the rays from SLR refracted in the medium (Fig. 2), and can be obtained from the entire body of experimental and theoretical 2D refraction patterns for various cross sections with the help of a special technique [7]. A 3D-refraction pattern can be visualised experimentally in scattered radiation (Fig. 2b).

2D- and 3D-refraction patterns are recorded with a digital video camera attached to the PC used for their processing. By comparing experimental and theoretical refraction patterns we can reconstruct the inhomogeneity profile and verify the numerical methods of computing the flow parameters with the help of application software packages.



a b

Figure 2. 3D-refraction patterns of the LS for a boundary layer under a hot (theoretical) (a) and cold (experimental) (b) sphere in water.

2. Laser plane refraction in a spherical inhomogeneity

For developing the method for constructing theoretical refraction patterns, LS refraction is studied [8] in a spherical layered medium with refractive index $n = n(r)$. Figure 3 illustrates the geometry of the problem. A laser beam in the form of LS (*1*) at right angles to the x axis propagates along the z axis. The origin of coordinates coincides with the centre of spherical inhomogeneity (*2*). The projection of the laser sheet is observed on screen (*3*) in a plane perpendicular to the z axis and located at a distance z_1 from the origin. The Cartesian and spherical coordinates are related by the expressions

$$x = r\sin\theta\cos\varphi, \quad y = r\sin\theta\sin\varphi, \quad z = r\cos\theta.$$

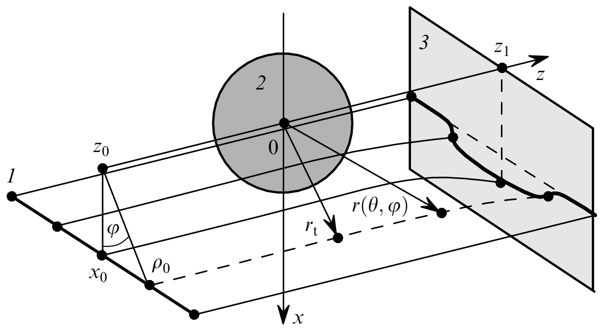


Figure 3. Geometrical parameters of the problem of constructing theoretical refraction patterns: (*1*) LS; (*2*) spherical inhomogeneity; (*3*) screen.

For $z = z_0$, the LS equation has the form $x = x_0$. The impact parameter ρ_0 of a beam lying in the LS is determined by angle φ (beam parameter)

$$\rho_0 = \frac{x_0}{\cos\varphi}. \tag{1}$$

In the case of spherical symmetry, this beam remains in the plane defined by parameter φ and its trajectory is described by the dependence $r(\theta, \varphi)$. The trajectories of beams are calculated using the relations describing their propagation in the spherical inhomogeneity [9]. The method for determining the trajectory of propagation of a beam in such a medium involves the splitting of the trajectory into two segments: from the point of entrance to the turning point and from the turning point to the plane of observation. In the case considered here, the turning point is determined by the minimal distance r_t from the beam trajectory to the origin (centre of the inhomogeneity) and can be determined from the equation

$$r_t n(r_t) = n_0 \rho_0, \qquad (2)$$

where n_0 is the unperturbed refractive index (for $z = z_0$).

The radial coordinate of the beam at the input to the medium (for $z = z_0$) is given by

$$r_0(\varphi) = \left(\frac{x_0^2}{\cos^2 \varphi} + z_0^2 \right)^{1/2}. \qquad (3)$$

The angle θ_0 characterises the direction of the beam entering the medium:

$$\theta_0(\varphi) = \frac{\pi}{2} + \arctan \frac{z_0 \cos \varphi}{x_0}. \qquad (4)$$

The angle corresponding to the turning point is given by

$$\theta_t(\varphi) = \theta_0(\varphi) + \int_{r_0(\varphi)}^{r_t(\varphi)} \frac{n_0 x_0 \mathrm{d}r}{r \cos \varphi \left[n^2(r) r^2 - \left(n_0^2 x_0^2 / \cos^2 \varphi \right) \right]^{1/2}}. \qquad (5)$$

The equation of the trajectory of the beam up to the turning point has the form

$$\theta(r, \varphi) = \theta_0(\varphi) + \int_{r_0(\varphi)}^{r} \frac{n_0 x_0 \mathrm{d}r}{r \cos \varphi \left[n^2(r) r^2 - \left(n_0^2 x_0^2 / \cos^2 \varphi \right) \right]^{1/2}}, \qquad (6)$$

while the equation for the trajectory beyond the turning point is

$$\theta(r, \varphi) = \theta_t(\varphi) + \int_{r}^{r_t(\varphi)} \frac{n_0 x_0 \mathrm{d}r}{r \cos \varphi \left[n^2(r) r^2 - \left(n_0^2 x_0^2 / \cos^2 \varphi \right) \right]^{1/2}}. \qquad (7)$$

Relations (6) and (7) form the basis for calculating refraction of the laser sheet in a spherical inhomogeneity. The angle φ is a parameter specifying an arbitrary beam in the LS, which allows us to describe the entire family of beams belonging to the laser sheet. The radial coordinate $r(z_1, \varphi)$ of the beam on the screen lying in plane $z = z_1$ can be determined from the relation

$$r \cos \theta(r, \varphi) = z_1, \qquad (8)$$

while the coordinates of laser sheet projection on the screen can be found from the equations

$$x(z_1, \varphi) = r(z_1, \varphi) \sin \theta(r(z_1, \varphi), \varphi) \cos \varphi,$$
$$y(z_1, \varphi) = r(z_1, \varphi) \sin \theta(r(z_1, \varphi), \varphi) \sin \varphi. \qquad (9)$$

These relations define the structure of refraction pattern for the given spherical inhomogeneity.

3. Theoretical laser sheet refraction patterns for a spherical thermal boundary layer

Note that all optical methods in fact describe the field of the refractive index, which can be subsequently transformed into the temperature field $T(x, y)$ or the field of some other parameter. Following [10], we shall analyse thermal processes assuming that for laser wavelength 0.6328 μm, the temperature dependence of the refractive index of water is determined by the approximate dependence

$$n(T) = 1.3328 - 0.000051T - 0.0000011T^2, \qquad (10)$$

where temperature T is measured in degrees Celsius.

The mathematical simulation of refraction of a LS in a spherically symmetric thermal boundary layer around a sphere of radius R is performed for the radial temperature dependence described by the expression

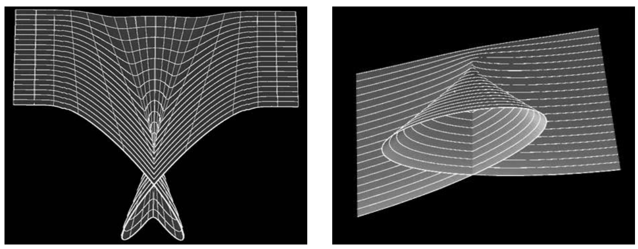
$$T(r) = T_0 + \Delta T \exp \left[-\frac{(r - R - \Delta R)^2}{a^2} \right], \qquad (11)$$

where T_0, ΔT, ΔR, and a are model parameters of the temperature field. The parameter T_0 is determined by the temperature of the walls of a cell filled with a liquid, temperature $T(R)$ is equal to the temperature T_s at the surface of the sphere, and the ratio $\Delta T/a$ corresponds to the temperature field gradient in a boundary layer of thickness a. For a hot sphere, $\Delta T > 0$, while for a cold sphere, we have $\Delta T < 0$.

The value of the temperature gradient for $r = R$ is determined by the shift ΔR, and $\mathrm{grad}[T(r)] \neq 0$ at the surface of the sphere if its thermal conductivity is not equal to that of the liquid. However, the possibility of this gradient assuming zero or a near-zero value in the boundary layer during measurements cannot be ruled out [11]. This determined the choice of the Gaussian model for the temperature field.

The refraction of a laser sheet in a liquid layer close to a hot sphere has been studied theoretically in detail in [8]. Here, we confine our analysis to the construction of refraction patterns for a boundary layer around a cold sphere.

Figure 4 shows 3D-refraction patterns for two models of temperature distribution in the vicinity of a cooled sphere in water: model 1 described by expression (11) with parameters $R = 20.5$ mm, $T_0 = 60\,°\mathrm{C}$, $\Delta T = -55\,°\mathrm{C}$, $\Delta R = -0.3$ mm, and $a = 2$ mm and model 2 in which the temperature in the inhomogeneity increases exponentially from 5 to 60 °C. A



a b

Figure 4. 3D-refraction pattern of a laser sheet for models 1 (a) and 2 (b) of the boundary layer of a liquid near a cold sphere (see text).

typical feature of the 'cold' spherical inhomogeneity in water is the formation of a loop on refraction patterns. For temperature gradients close to zero, a characteristic extremum is observed on the loop directly at the surface of the sphere, which is associated with a slight deviation of beams in this region. The temperature distribution in the layer in this case is nearly Gaussian (model 1). No extremum is formed for an exponential distribution.

Thus, visualisation of an inhomogeneity in the medium with the help of refraction patterns makes it possible to carry out quick diagnostics of the type of the inhomogeneity and draw conclusions about the temperature distribution in a thin boundary layer. The formation of a loop on the refraction pattern is directly linked with the presence of axial caustics [9] that can be visualised experimentally.

Figure 5 shows 2D-refraction patterns corresponding to the above 3D-refraction pattern (see Fig. 4a) for the parameters of model 1 and various distances z to the screen. The formation of the loop can be analysed in detail using the refraction pattern regions near the caustic in the figure (the observation plane is perpendicular to the z axis). The set of experimentally obtained 2D-refraction patterns allows a reconstruction of the corresponding 3D image and identification of the type of the inhomogeneity.

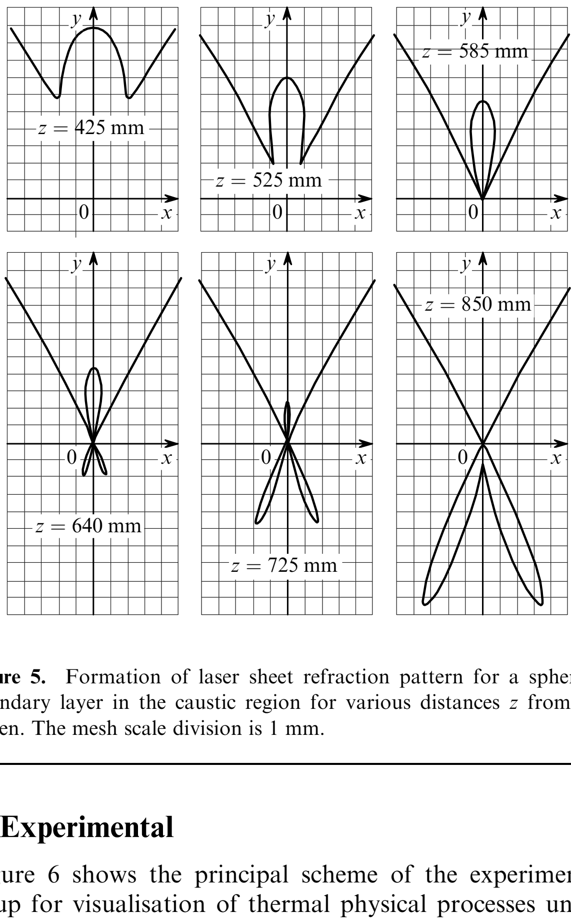


Figure 5. Formation of laser sheet refraction pattern for a spherical boundary layer in the caustic region for various distances z from the screen. The mesh scale division is 1 mm.

4. Experimental

Figure 6 shows the principal scheme of the experimental setup for visualisation of thermal physical processes under natural nonstationary convection in a liquid in the vicinity of heated (cooled) bodies with the help of SLR.

Laser radiation was directed to the region close to the surface of body (*5*) being heated by using an adjusting table and a device for rotating the diffraction optics elements. In the beginning of the experiment, the image of the refraction pattern was recorded on screen (*7*) with the help of digital video camera (*8*). This image was subsequently used for reference. The metal object was then heated to a temperature of 50–100 °C, or cooled to 9–10 °C and then immersed in a vessel filled with water. After this, video recording of the refraction pattern on screen (*7*) was performed for several minutes. The temperature of the body was measured with a thermocouple. The recorded image of the refraction pattern was loaded into a computer and processed with the help of a special application package. Figure 7 shows the experimental refraction patterns of the laser sheet obtained on the above device for a cooled sphere.

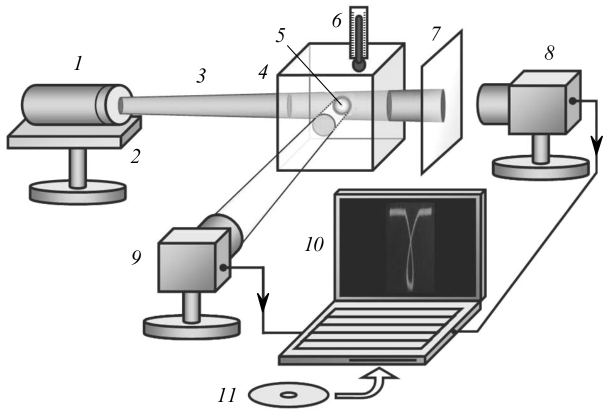


Figure 6. Scheme of the experimental setup for visualisation of natural convection: (*1*) semiconductor laser with diffraction optical elements; (*2*) adjusting table; (*3*) SLR; (*4*) transparent cell with water; (*5*) heated (cooled) object; (*6*) thermometer; (*7*) semitransparent screen; (*8*, *9*) digital video cameras; (*10*) PC; (*11*) special software package.

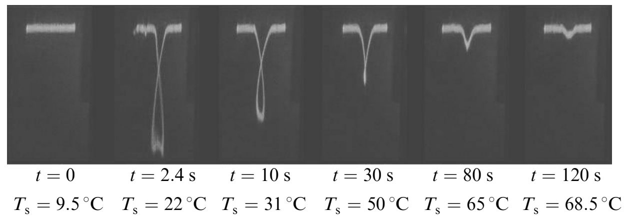


Figure 7. Experimental 2D-refraction patterns of the LS for the boundary layer around a cold sphere for an initial hot water temperature of 70 °C.

The measuring technique provides simultaneous diagnostics of the process in the region of passage of laser sheet in the boundary layer immediately over the sphere. Even a preliminary observation of the refraction patterns depicted in Fig. 7 makes it possible to draw qualitative conclusions concerning the evolution of the inhomogeneity in the layer using the library of typical refraction patterns (i.e., to carry out quick diagnostics of the process). For example, in the first seconds of observation (when the process is essentially nonstationary), the loop has a characteristic 'depression' whose presence indicates the existence of a water layer immediately at the surface of the sphere, in which the temperature gradient is close to zero (library refraction pattern for the Gaussian model of the temperature distribution in Fig. 4a). In subsequent moments of observation, the refraction patterns correspond to the exponential model of the temperature distribution in the spherical layer (library refraction pattern in Fig. 4b), which is in conformity with the results of numerical simulation of quasi-stationary convection [12].

Quantitative diagnostics of the temperature profile of the boundary layer is performed on the basis of the following technique. Special computer processing of the image of the 2D-refraction pattern minimising the diffraction effects is carried out [12]. The digitised experimental refraction pattern is compared with the set of library refraction patterns calculated for the given setup and for various parameters of the temperature layer for the given model. The criterion of minimisation of the mean square deviation is used for selecting the theoretical refraction pattern having the best coincidence with the experimental one. The temperature profile corresponding to the chosen theoretical refraction pattern is chosen as the measured profile.

Figure 8a shows the experimental and chosen theoretical refraction patterns obtained during an analysis of the convection process in water near the surface of a hot steel sphere of diameter 50.8 mm, observed after 40 s following the immersion of the sphere in water. Before immersion, the sphere was heated to a temperature of 90 °C. The centre of the laser sheet is situated at a distance of 0.1 mm from the lowest point on the sphere, the thickness of the laser sheet under the sphere in water is 37 μm at 1/e level. The refraction pattern was observed at a distance of 108 mm from the centre of the sphere. Figure 8b shows the temperature dependence in the boundary layer reconstructed by the technique described above. This dependence is then compared with the one obtained on the basis of the application package for calculating convection by the finite volume method. A comparison of these theoretical results with the experiment reveals a good agreement between them (the discrepancy between them does not exceed 10 % and may be due to an incomplete conformity of the model used for calculating on the basis of the applied package with the experiment).

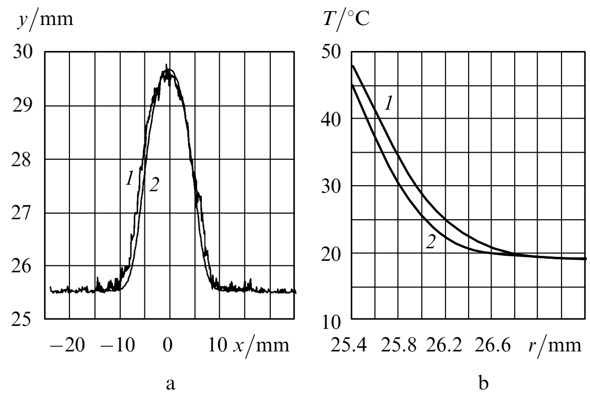


Figure 8. (a) Illustration of the method of reconstructing the radial temperature profile in a boundary layer; curves (*1*) and (*2*) correspond to the experimental and theoretical refraction patterns, respectively; (b) radial temperature dependences.

5. Conclusions

The method of laser refractography described in the paper uses SLR for obtaining 2D- and 3D-refraction patterns of transparent inhomogeneous media and liquid and gas flows. In a certain sense, a refraction pattern is a ‘portrait’ of the medium under study and can be compared with the set of elementary refraction patterns of typical inhomogeneities. This makes it possible perform a quick diagnostics of the medium right in the course of observations. The use of SLR also allows a 3D visualisation of the beam caustics and to trace their formation by analysing the evolution of 2D-refraction patterns.

Various combinations, orientation and arrangement of elementary sources of SLR make it possible to adapt the measuring setup to the structure of the inhomogeneity. In view of the extended nature of the radiation source, a simultaneous diagnostics of processes can be carried out in various regions. It follows from the above technique of measuring the temperature of boundary layers that the possibility of quantitative diagnostics of parameters of the medium (reconstruction of the inhomogeneity profile from a comparison of the experimental and theoretical refraction patterns) is a significant advantage of the laser refractography technique. The error of the method is mainly determined by diffraction effects and can be considerably decreased by using special methods for computer processing of images.

Because refraction measurements are virtually inertia-less, laser refractography can be used for diagnostics of stationary as well as rapid transient processes, including thermal processes in liquids, gases and plasma, natural convection in liquids in the vicinity of heated or cooled bodies, ultrasonic flows, and mixing of various liquids in apparatuses used in chemical technology.

Moreover, laser refractography technique can be adapted for diagnostics of boundary layers and edge effects, as well as for studying processes in micro- and nanochannels due to the possibility of formation of narrow probe beams.

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