Quantum Electronics **32** (10) 888 – 890 (2002)

PACS numbers: 42.30.Wb; 42.62.Be; 87.63.Lk
DOI: 10.1070/QE2002v032n10ABEH002311

Influence of light refraction on the image reconstruction in transmission optical tomography of scattering media

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Abstract. **A distorting influence of light refraction at the boundaries of scattering media on the results of tomographic reconstruction of images of radially symmetric objects is investigated. The methods for the correction of such refraction-caused distortions are described. The results of the image reconstruction for two model cylindrical objects are presented.**

Keywords: *optical tomography, scattering media, image reconstruction.*

The early diagnostics of various diseases by optical methods makes it possible to significantly develop practical medicine. Along with conventional types of tomography (X-ray, magnetic resonance, and radionuclide tomography), transmission optical tomography (TOT) currently attracts much attention because it offers a number of advantages, such as a noninvasive diagnostics, low cost, and compactness.

However, in TOT, it is necessary to take into account a much more complex interaction of optical radiation with a medium, in particular, light scattering, refraction, and reflection processes. This precludes the use of the mathematical apparatus applied in conventional tomography, which is based on the Radon transform. In addition, due to strong absorption of optical radiation, the recording of the initial data for the subsequent reconstruction of tomographic images is complicated.

The mathematical basis of TOT is the radiation transfer equation and its various approximations. In this work, we use a nonstationary axial model of radiation transfer [1, 2]. An object is reconstructed using an algorithm corresponding to the approximation of a proportional scattering medium, which allows one to pass from two unknown functions of a spatial variable (absorption and scattering coefficients) to a single function [3].

In the approximation of proportional media, it is assumed that

$$m_{\mathrm{s}}(\zeta) = \beta m(\zeta),$$

where ζ is the coordinate along the laser beam, $m(\zeta) = m_{\mathrm{a}}(\zeta) + m_{\mathrm{s}}(\zeta)$ is the extinction coefficient, $m_{\mathrm{a}}(\zeta)$ is the absorption coefficient, $m_{\mathrm{s}}(\zeta)$ is the scattering coefficient, and β is the proportionality factor. In this model, the expression for projections can be written in the form

$$p(\xi, \theta) = -\ln\left\{ \frac{I_+(\zeta_1)\left[1 + \left(1 - \beta^2\right)^{1/2}\right]}{\left(1 - \beta^2\right)^{1/2} + \left[1 - \beta^2 + \beta^2 I_+^2(\zeta_1)\right]^{1/2}} \right\},$$

where θ is the angle of rotation of the rotating coordinate system ξ, ζ with respect to a stationary coordinate system x, y; and $I_+(\zeta_1) = U_+(\zeta_1)/U_0$ is the ratio of the transmitted $U_+(\zeta_1)$ and incident U_0 radiation intensities. Then,

$$m(x, y) = \frac{1}{\left(1 - \beta^2\right)^{1/2}} \mathscr{R}^{-1}\{p(\xi, \theta)\},$$

where $\mathscr{R}^{-1}\{p(\xi, \theta)\}$ is the inverse Radon transform.

Consider the simplest problem of reconstructing the spatial distribution of the extinction coefficient in the cross section of a homogeneous cylinder:

$$m(x, y) = \begin{cases} \text{const}, & \left(x^2 + y^2\right)^{1/2} < R, \\ 0, & \left(x^2 + y^2\right)^{1/2} \geqslant R, \end{cases}$$

where R is the cylinder radius. The corresponding spatial distribution of the refractive index can be written in the form

$$n_{\mathrm{c}}(x, y) = \begin{cases} n_2, & \left(x^2 + y^2\right)^{1/2} < R, \\ n_1, & \left(x^2 + y^2\right)^{1/2} \geqslant R, \end{cases}$$

where n_1 and n_2 are the refractive indices of the environment and object, respectively. Because the reconstructed object is radially symmetric, the inverse Radon transform is reduced to the inverse Abel transform.

A tomographic reconstruction of even such a simple object is impeded by refraction and reflection effects. Figs 1a and 1b show the trajectories of rays with allowance for their refraction for a scheme with parallel scanning. The larger the difference between the relative refractive index $n = n_2/n_1$ and unity, the more significant the refraction effect. In the case of $n > 1$, regions inaccessible for scanning are formed (Fig. 1a), while for $n < 1$, all the points of the object can be scanned (Fig. 1b).

If the character of distortions in the object is known, we can change from curved rays to rectilinear ones, because the

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Received 24 June 2002
Kvantovaya Elektronika **32** (10) 888 – 890 (2002)
Translated by A.S. Seferov

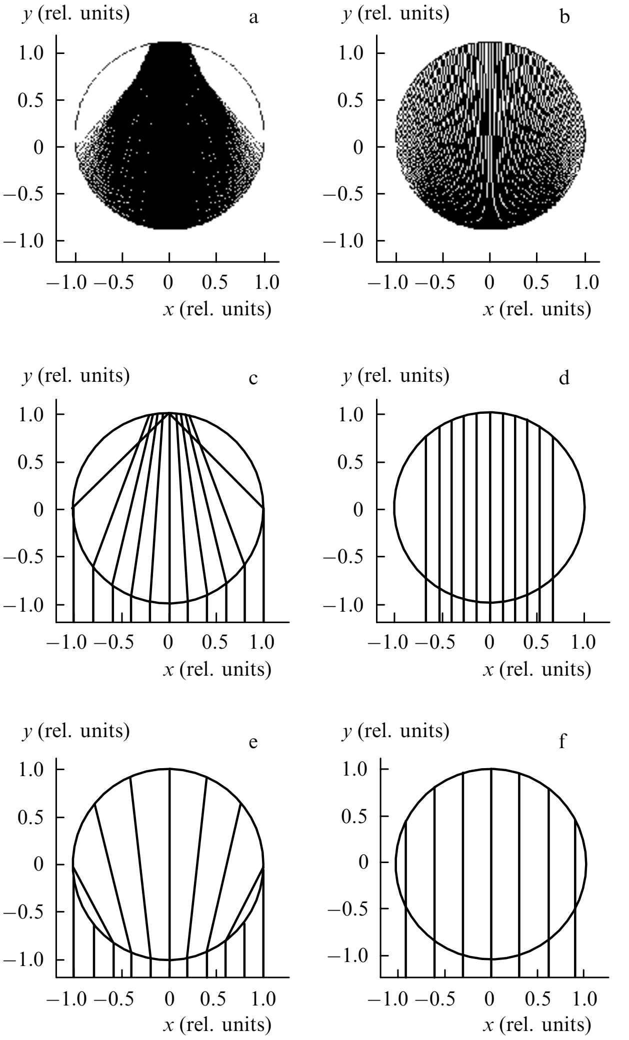

Figure 1. (a, b) Scanning of a cylindrical object and (c – f) a change to parallel rays for $n = 1.5$ (a, c, d) and 0.67 (b, e, f). Rays travel upwards.

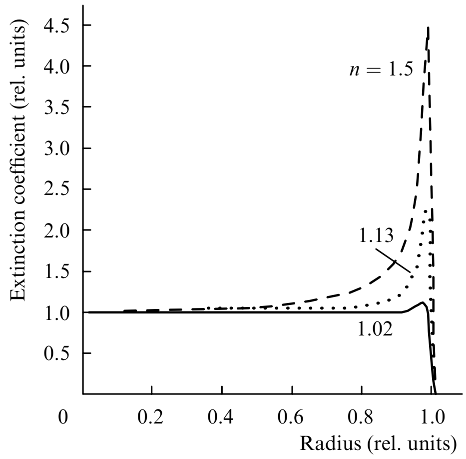

Figure 2. Central cross sections of the reconstruction of cylindrical objects without a refraction correction for various n.

path that a ray travels in a cylindrical object is determined only by the distance from the cylinder axis to the corresponding chord (Figs 1c – 1f). In this case, the initial scanning step $\Delta\xi$ becomes equal to $\Delta\xi/n$. Apart from the light refraction effect, additional difficulties are introduced by the regions of a sharp change in the transmittance, which is determined by an enhanced light reflection at a certain orientation of the scanning beam with respect to the interface between the media with different refractive indices.

Fig. 2 shows the results of reconstruction of a cylindrical object without a correction of the refraction effect, which show a sharp dependence of the appearing distortions on the relative refractive index.

Thus, the distorting effect of light refraction and reflection at the interfaces of two media is a serious problem, especially in tomographic measurements of objects with complex configurations of outer boundaries and, the more so, their interior structures with different refractive indices. The light reflection and refraction lead to the following negative consequences: the measurement geometry is disturbed; the beam path in the object changes (decreases or increases); regions that are inaccessible for scanning are formed; the detection of the transmitted radiation is hindered because of a beam deflection; and the signal is additionally attenuated due to reflection of a part of radiation.

If smooth outer boundaries of a perfect cylindrical strongly scattering object are known, a partial correction of the refraction is possible. It consists in the construction of a system of chords with the distances to the cylinder axis equal to those for actual trajectories; but, in this case, these chords are parallel to each other. In addition, the lacking data for the regions inaccessible for scanning can be obtained through interpolation. Although these methods reduce refraction-caused distortions, the latter cannot be fully removed. For objects with intricate shapes and unknown spatial distributions of the refractive index inside them, even such a partial correction is impossible.

A 1.06-μm, 20-mJ, 20-ns pulsed Nd : glass laser was used as a radiation source in experiments. We studied a paraffin cylinder 10 mm in diameter and 40 mm high and a more complex radially symmetric object. The latter was a mixture of glycerine ($n \approx 1.47$) with black ink (two drops per 20 mL of glycerine) filling a cylindrical cavity 28 mm in diameter in a polymethylmethacrylate ($n \approx 1.5$) parallelepiped with a length, width, and height of 60, 40, and 40 mm, respectively. A 10-mm-diameter glass column was coaxially inserted into the cavity. This complex object simulates a medium with nonuniform light absorption and scattering but with a homogeneously distributed refractive index, which corresponds to a several biological media [4]. Both objects under study were characterised by an intense light scattering.

A laser beam ~ 1 mm in diameter moved in the plane normal to the object axis with a step of 0.5 mm. The signal was measured with a silicon power meter. The results of the reconstruction of objects images are presented in Fig. 3. Fig. 3a shows that significant image distortions are observed without a refraction correction. The image is appreciably improved when this correction is applied (Fig. 3b).

Another possible method for reducing the distortions caused by light refraction is the placement of an object into an immersion medium. The corresponding results of the reconstruction of the complex object are shown in Fig. 3c. Note that, in the absence of an immersion medium, we failed to obtain an acceptable image of such an object.

Thus, our study has shown a strong effect of light refraction on the quality of tomographic reconstruction of strongly scattering objects. The methods for the correction

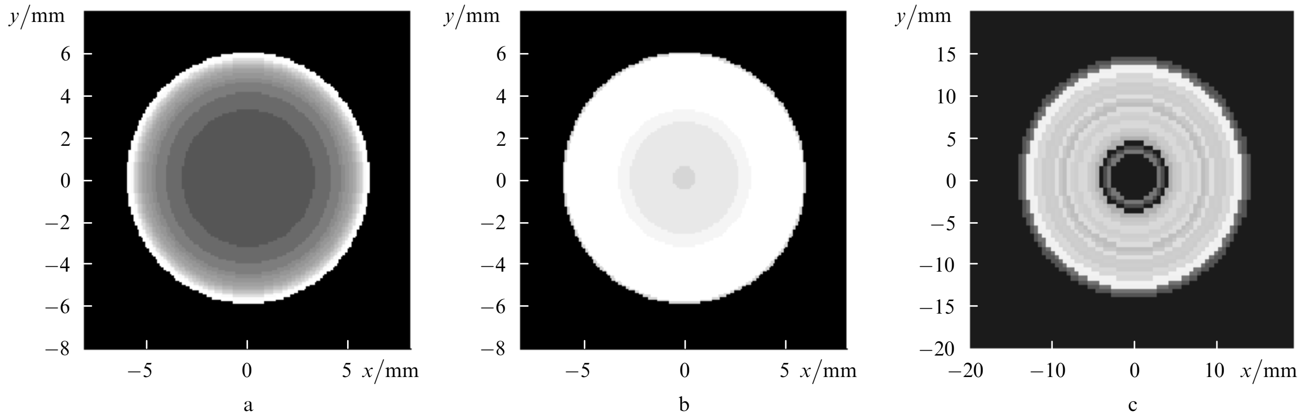

Figure 3. Reconstructions of images of a cylindrical paraffin object ($n = 1.5$) (a) without a refraction correction and (b) with a refraction correction together with an interpolation and (c) an image of a complex object in the immersion medium.

of distortions caused by light refraction have been described using an example of tomographic reconstruction of images of radially symmetric, strongly scattering objects.

Acknowledgements. This work was supported in part by the Russian Foundation for Basic Research (Grant Nos 00-02-16085 and 01-01-00065) and the Ministry of Education of the Russian Federation (Grant No. E00-1.0-188).

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