Quantum Electronics **45** (2) 143 – 144 (2015)

LIGHT SCATTERING

PACS numbers: 42.15.Fr; 42.25.Fx
DOI: 10.1070/QE2015v045n02ABEH015721

Wavefront analysis of the laser beam propagating through a turbid medium

I.V. Galaktionov, J.V. Sheldakova, A.V. Kudryashov

Abstract. **Laser beam propagation through a scattering suspension of polystyrene microspheres in distilled water is studied theoretically and experimentally. The dependence of wavefront aberrations on the particle concentration is investigated. The existence of symmetric wavefront aberrations of the laser beam passed through a turbid medium is shown.**

Keywords: *turbid medium, light scattering, wavefront sensor, adaptive optics.*

A medium is considered turbid or scattering if it possesses explicit optical inhomogeneity due to foreign particles with a distinct refractive index. Examples are fog, clouds, atmospheric haze, sea water, colloid solutions and biological tissues. In a turbid medium the energy of the initial beam is not lost but redistributed in space, forming a halo of scattered radiation. The diffusely scattered light makes shapes of viewed objects fuzzy and prevents radiation focusing, which becomes a serious problem in such fields as biological and medical investigations, laser therapy and oceanology [1, 2]. It is generally believed that there are three types of photons in scattered light [3]: ballistic, near-axial or 'snake' photons and off-axial or diffusive photons.

Ballistic photons propagate through a turbid medium along straight trajectories and do not interact with diffusers. This coherent component of scattered radiation is most valuable in problems of object image recognition. Near-axial photons undergo several collisions with diffusers and move along trajectories close to the initial beam direction. Near-axial photons become useful in a thicker scattering layer because the number of ballistic photons in this case falls exponentially. Off-axial photons are multiply scattered in all directions and form an incoherent component of scattered radiation. Ballistic photons carry undisturbed information about the object; however, as was already mentioned, the number of such photons falls exponentially with the layer thickness or the scattering coefficient of the turbid medium. Hence, the influence of near-axial and diffuse photons on the intensity distribution and on distortion of the wavefront of scattered radiation should be taken into account.

In the present work, scattering of laser radiation with a wavelength of 0.65 μm on polystyrene microspheres of 1 μm diameter suspended in distilled water is studied. The concentration of particles varied from 1.3×10^5 to10^6 mm^{-3}. The initial aperture of the laser beam was 4 mm, the refractive index of medium was 1.33 and the refractive index of polystyrene microspheres was 1.582 [4].

Propagation of radiation through a scattering medium was simulated by using the well-known Monte Carlo method based on a large number of realisations of random process at prescribed probability distributions of considered parameters [5]. At a particular instant, the laser beam was presented as a large number of photons (in the present work 2.5×10^{11}) uniformly distributed over the initial aperture (which is equivalent to the uniform intensity distribution). For each photon, the initial position was prescribed and the free path length l (the distance between two successive photon collisions with diffusers), the scattering angle θ and azimuthal angle φ were calculated. At the output from the medium all photons carried information about the covered optical path length and about the number of scattering events. The free path length l and the direction of propagation (θ, φ) of a photon after scattering on a particle were calculated by the formulae:

$$l = -\frac{1}{\mu_s}\ln\xi_l,$$

$$\cos\theta = \begin{cases} \dfrac{1}{2g}\left[1 + g^2 - \left(\dfrac{1-g^2}{1-g+2g\xi_\theta}\right)^2\right] \text{at } g > 0, \\ 2\xi_\theta - 1 \text{ at } g = 0, \end{cases}$$

$$\varphi = 2\pi\xi_\varphi.$$

Here, μ_s is the scattering coefficient of a medium; g is the factor of anisotropy; and ξ_l, ξ_θ and ξ_φ are random quantities uniformly distributed over the half-interval [0,1). Based on the free path length and new direction, a new position of the photon in space was calculated and the condition of crossing a medium boundary by a photon was verified.

The intensity and the phase surface of scattered radiation were calculated by the mathematical model with a square aperture having a side 4.8 mm on a grid with the step of 150 μm. The values of optical path lengths for photons fitting a particular sub-aperture of the grid were averaged, and the local phase value over the sub-aperture was calculated by the formula $\Phi = 2\pi n\sum_{i=1}^{m}(l_{s_i} - l)/(\lambda m)$, where n is the refractive index of the medium; m is the number of photons on the sub-aperture; l_{s_i} is the distance covered by ith photon in medium;

I.V. Galaktionov, J.V. Sheldakova, A.V. Kudryashov Moscow State University of Mechanical Engineering, ul. Bol'shaya Semenovskaya 38, 107023 Moscow, Russia; e-mail: ilya_galaktionov@activeoptics.ru, kud@activeoptics.ru, sheldakova@nightn.ru

Received 25 November 2014; revision received 12 December 2014
Kvantovaya Elektronika **45** (2) 143 – 144 (2015)
Translated by N.A. Raspopov

l is the distance that photon would cover in the absence of a scattering medium; and λ is the radiation wavelength.

An experimental setup schematically shown in Fig. 1 has been created in order to verify the theoretical model. The laser beam passed through a glass cell with a turbid medium and fell onto the Shack–Hartmann wavefront sensor (Active Optics NightN Ltd.) [6] which comprised a digital camera with lenslet array (the focal length was 6 mm, the distance between microlenses was 150 μm, the number of microlenses was 1350 and the detection area of sensor was 6.4×4.8 mm). The phase surface of scattered radiation was approximated by Zernike polynomials. In Fig. 2 one can see the dependences of the coefficients at the central-symmetric Zernike polynomials No. 3, No. 8, and No. 15 [7] on the particle concentration. The wavefront was analysed in a circle of diameter 4.8 mm with the centre coinciding with that of the sensor. The greater aperture as compared to the initial beam size was needed for making allowance for the contribution of near-axial photons into the radiation wavefront. One can see that enhanced defocusing (the coefficient at Zernike polynomial No. 3 increases to 0.9 μm) and spherical aberration (the coefficient at Zernike polynomial No. 8 increases to 0.59 μm) are observed at a higher particle concentration. The results obtained well agree with performed model investigations of light propagation through a turbid medium.

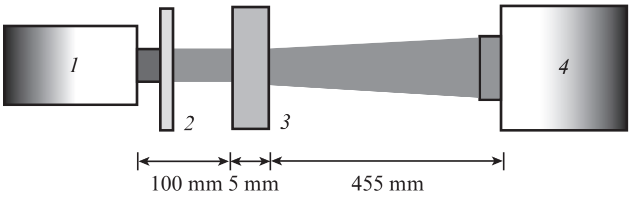

Figure 1. Experimental setup: (*1*) diode laser with the wavelength of 0.65 μm and output aperture of 4 mm; (*2*) optical filter; (*3*) glass cell with a turbid medium; (*4*) Shack–Hartmann wavefront sensor.

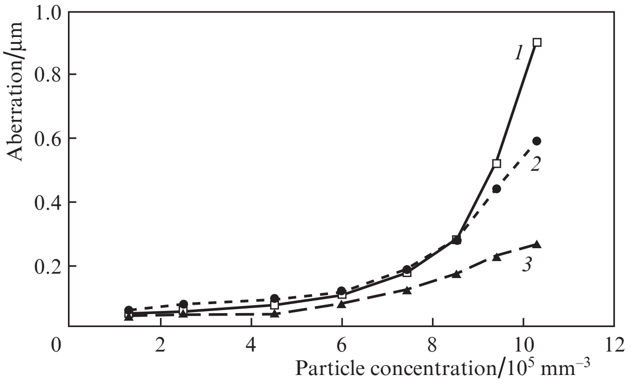

Figure 2. Wavefront aberrations vs. the concentration of particles in a turbid medium: (*1*) defocusing (Zernike polynomial No. 3); (*2*) low-order spherical aberration (Zernike polynomial No. 8); (*3*) high-order aberration (Zernike polynomial No. 15).

At a higher concentration of scatterers, the character of aberrations mainly remains the same. The analysis shows that low-order aberrations which are usually compensated by bimorph adaptive mirrors [8] prevail in the wavefront of radiation passed through a layer of a turbid medium with the concentration of scattering particles $1.3\times10^5 - 10^6$ mm^{-3}.

References

1. Mosk A.P., Lagendijk A., Lerosey G., Fink M. *Nature Photon.*, **6**, 283 (2012).
2. Vellekoop I.M., Mosk A.P. *Opt. Lett.*, **32**, 2309 (2007).
3. Ramachandran H. *Current Sci.*, **76**, 1334 (1999).
4. Ma X., Lu J., Brocks S., Jacob K., Yang P., Xin X.-H. *Phys. Med. Biol.*, **48**, 4165 (2003).
5. Wang L., Jacques S. *Comput. Progr. Methods Biomed.*, **47**, 131 (1995).
6. Aleksandrov A.G., Zavalova V.E., Kudryashov A.V., Rukosuev A.L., Sheldakova Yu.V., Samarkin V.V., Romanov P.N. *Kvantovaya Electron.*, **40** (4), 321 (2010) [*Quantum Electron.*, **40** (4), 321 (2010)].
7. Wyant J.C., Creath K., in *Applied Optics and Optical Engineering* (New York: Acad. Press Inc., 1992) Vol. XI, Ch. 1.
8. Samarkin V., Aleksandrov A., Kudryashov A. *High-Resolution Wavefront Control: Methods, Devices, and Applications III*. Ed. by J.D.Gonglewski, M.A.Vorontsov, M.T.Gruneisen (San Diego: CA, Proc. SPIE, 2002) pp 269–276.