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Simulation approach for optical diagnostics of structure-inhomogeneous objects

Oleg ANGELSKY[a,b], Claudia ZENKOVA[a,b], Dmytro IVANSKYI[b,1], Vladyslav TKACHUK[b], Yulia URSULIAK[c]

[a]Research Institute of Zhejiang University-Taizhou, China
[b]Chernivtsi National University, Chernivtsi, Ukraine
[c]Municipal Enterprise Chernivtsi Regional Clinical Cardiological Center, Chernivtsi, Ukraine
[1]d.ivanskyi@chnu.edu.ua

INTRODUCTION

A new simulation approach for the optical diagnostics of a complex scalar optical field obtained by scattering and diffraction of radiation on a surface with roughness is suggested in this paper. The light-induced motion of nanoparticles suspended in an optical field allows for the detection and localization of intensity minima and phase singularities. Luminescence of carbon nanoparticles made it possible to register their coordinate position in time. The algorithm for the reconstruction of scalar optical field intensity distribution through the analysis of nanoparticle position is proposed. The optical speckle field's skeleton, with special attention given to the phase singularities is examined to restore the phase map.

MODELING THE SPECKLE FIELD OBTAINED FROM STRUCTURE-INHOMOGENEOUS OBJECT

1. Rough surface modeling

Modeling of a rough surface was carried out according to the appropriate algorithm [1]. Simulation took place in the *MATHEMATICA* software package. During the simulation, the points with a step of about of 5 µm are considered and the height of the inhomogeneity is randomly generated within the interval 0 - h_{max} (h_{max} = 2 µm). Intermediate values of heights are obtained using spline interpolation of the generated points. To obtain a complete picture of the simulated surface roughness, a Gaussian filter with a radius of 3 µm was used, with smoothing by 30 points, giving the possibility to reproduce the rough surface relief (Fig. 1).

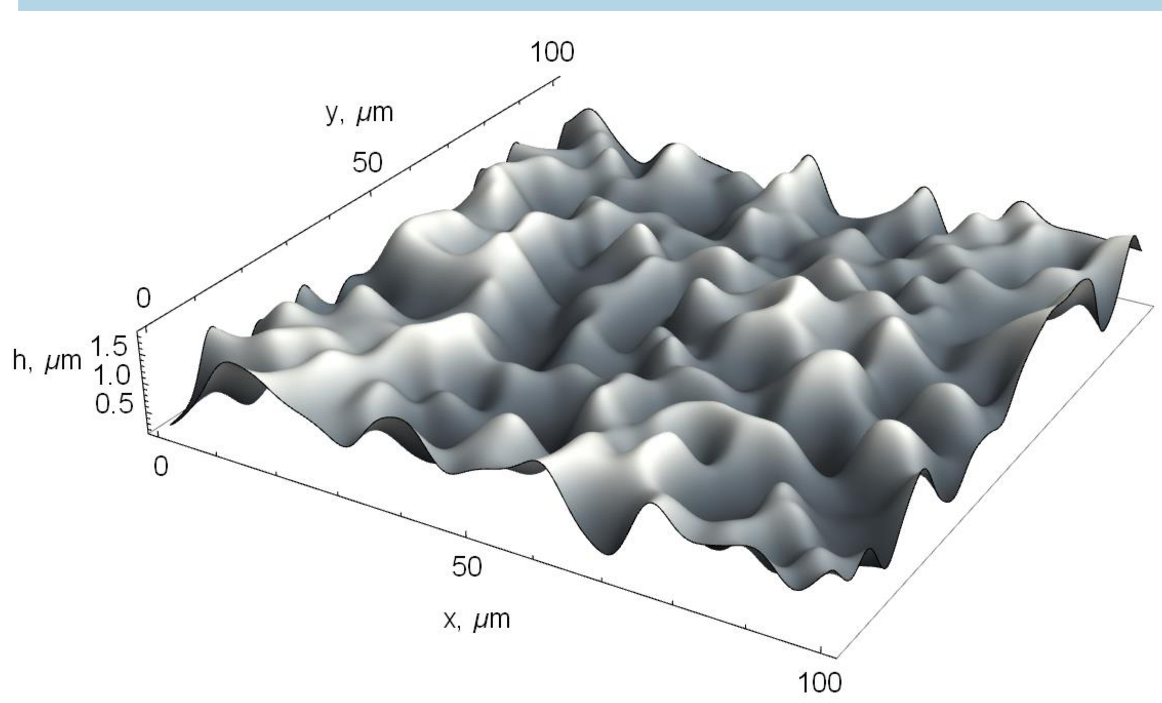


Fig. 1. Three-dimensional coordinate distributions of the surface inhomogeneities obtained in the modeling process

2. Speckle field modeling

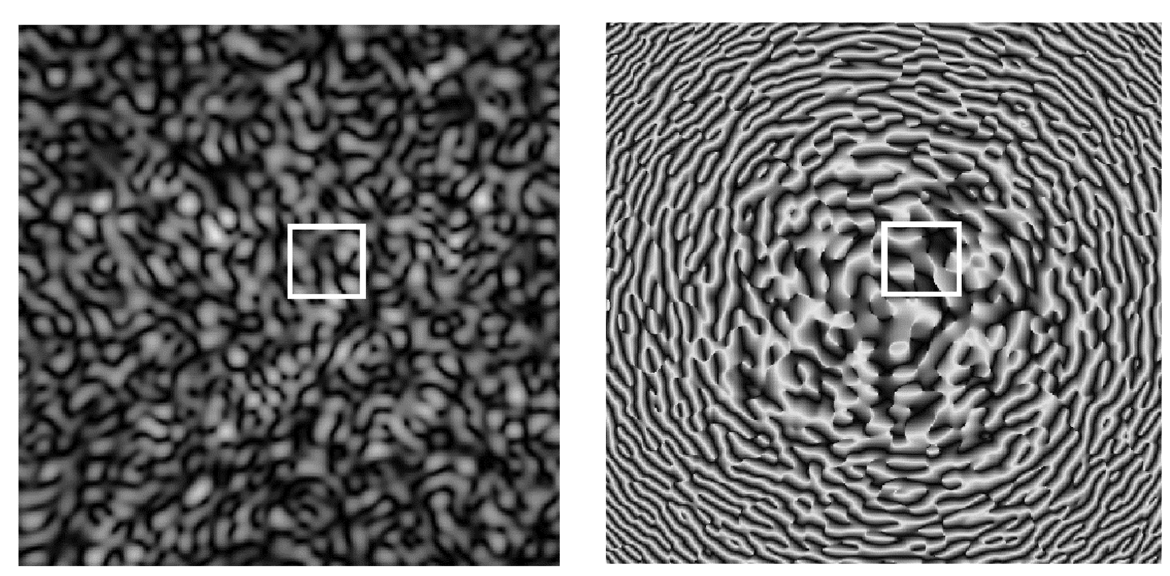
The analyzed complex optical field is obtained by the light scattering on the surface with roughness.

To simulate the diffraction image of a surface with a given roughness, the Rayleigh-Sommerfeld diffraction integral in the discrete approximation is used [1]:

$$U(\xi,\zeta)=\frac{z}{i\lambda}\sum_{x=1}^{X}\sum_{y=1}^{Y}\frac{F(x,y)}{R^2(x,y,z,\xi,\zeta)}\exp\{-ik[R(x,y,z,\xi,\zeta)+2h(x,y)]\},$$

Determining the real Re[U(ξ, ζ)] and imaginary Im[U(ξ, ζ)] parts of the calculated field makes it possible to evaluate the field amplitude modulus, intensity, and phase.

In the far field, a simulated diffraction pattern of 240 × 240 µm² (400 × 400 pixels) and the corresponding phase map are shown in Fig. 2.



(a) (b)

Fig. 2. Simulated diffraction pattern (a) and calculated phase map (b). The white square shows the part of the pattern of 30 × 30 µm² area undergoing further analysis

ALGORITHM FOR SPECKLE FIELD STRUCTURE DIAGNOSTICS

Cuvette with carbon nanoparticles in water solution, is placed in an optical field. Randomly suspended particles move in this field as a result of the internal optical flows action, and localize in regions of minimum intensity with and without singularities. It is possible to reconstruct the intensity distribution from tracks of nanoparticle motion. Motion of particles is visualized due to their bright luminescence at a wavelength of about 535 nm [1, 2].

Equation of motion of an i-particle (i=1..N, where N – total number of nanoparticles analyzed in the speckle field) under the action of optical force can be written as:

$$m_i\frac{d\vec{v}_i}{dt}=\vec{F}_{opt_i}+\vec{F}_{st_i}$$

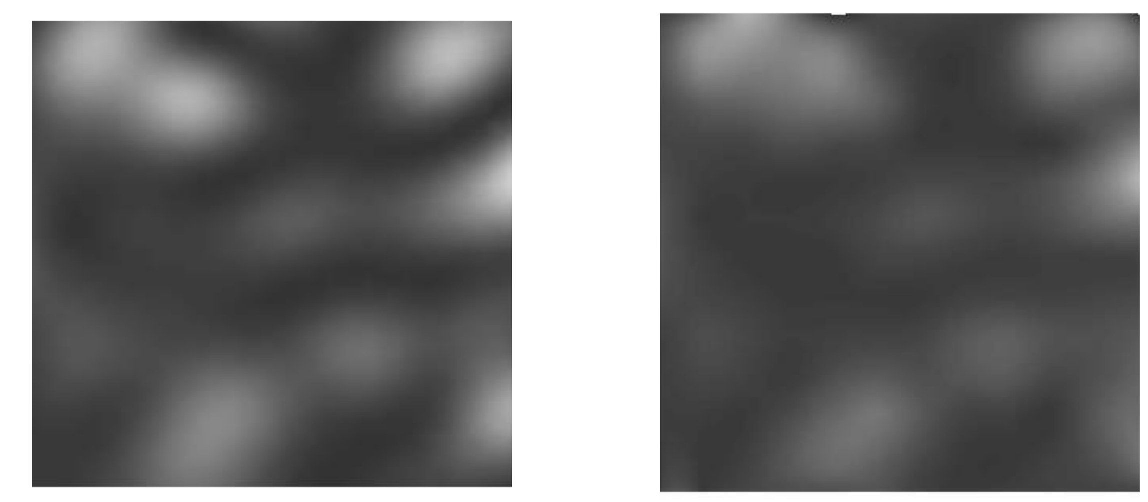
where $\vec{F}_{opt_i}$– the resulting optical force (components of which are gradient, scattering and absorbing components), $\vec{F}_{st_i}=6\pi r_i\eta\vec{v}_i$ – Stokes force, m_i– mass of carbon nanoparticle, r_i – particle radius,η – dynamic viscosity of the medium (water), $\vec{v}_i$ - velocity of particles motion.

The optical-force distribution can be restored with a high accuracy giving thus access to the detailed pattern of the field structural inhomogeneity [2]. For example, in the simplest case where the main optical-force contribution is the gradient force:

$$F_{opti}=\sqrt{F_{opt_{xi}}^2+F_{opt_{yi}}^2}\sim\frac{\Delta I_i}{\Delta s_i},\quad \Delta s_i(x,y)=\sqrt{\Delta {x_i}^2+\Delta {y_i}^2},$$

where ΔI_i is the increment of the light intensity at the i-th particle displacement Δs_i. Accordingly, $\Delta I_i\sim F_{opt_i}\Delta s_i(x,y)$, and the total intensity distribution can be recovered (Fig. 3):

$$I(x,y)\sim\sum_i F_{opt_i}\Delta s_i(x,y)$$

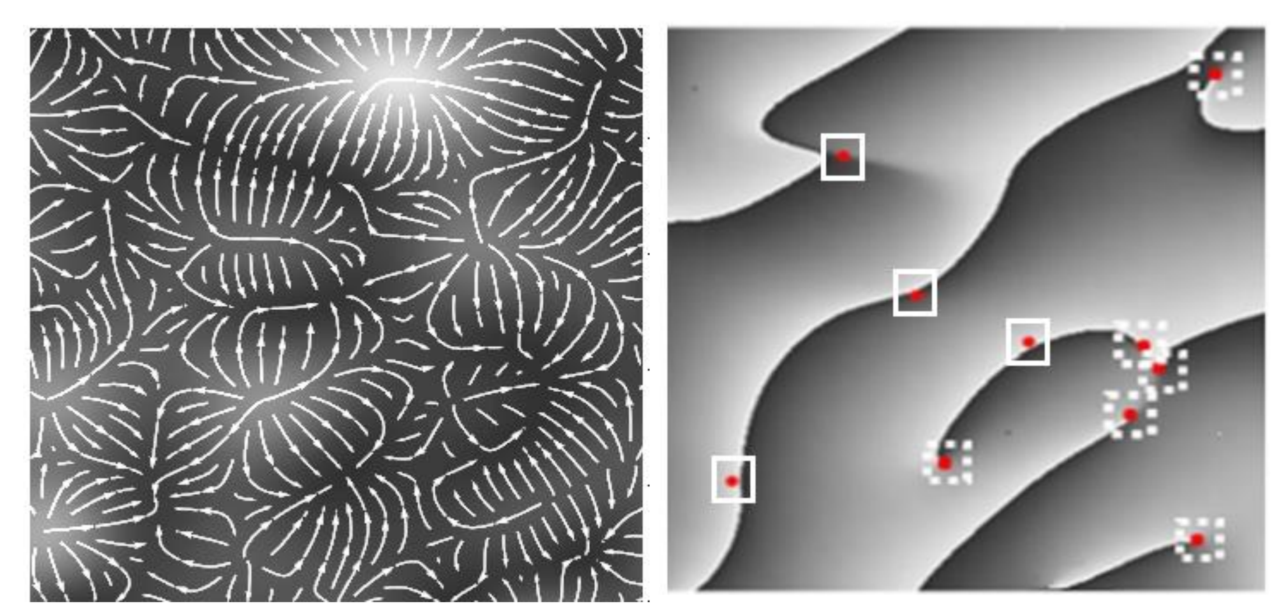


(a) (b)

Fig. 3. Original optical field (a) and corresponding reconstructed intensity distribution (b), through analyzing coordinate distribution of the 250 nanoparticle motion tracks.

SINGULARITY POINTS RESTORATION

Localization of particles in speckle field indicate points of intensity minima with phase singularities (Fig. 4), which can be used to increase the phase map restoration accuracy [3]



(a) (b)

Fig. 4 (a) The intensity distribution with the vector lines of the optical force acting on the nanoparticles (white lines with arrows) determine their resulting position
(b) Phase map with the predominant localization of nanoparticles (red points): dashed squares denote the phase singularities, solid squares denote the intensity minima without singularities.

CONCLUSIONS

New simulation approach of carbon nanoparticles using to study the optical field obtained as a result of random scattering from structure-inhomogeneous object is demonstrated. Motion tracks of nanoparticles in the optical field due to internal optical flows action, gives it possible to reconstruct the intensity distribution of analyzed optical field. Visualization of intensity minima with and without singularities due to final localization of nanoparticles, can be used in approaches of phase map reconstruction. The findings presented are expected to be valuable for sensitive probing in optical micro- and nanotechnologies and for reconstruction the surface inhomogeneity distribution of distant scattering objects.

REFERENCES

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