Determining the Geometric Parameters of Diffuse Scattering Objects

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Received January 21, 2008

Abstract—A spectral-correlation diagnostic method has been used for determining the linear dimensions of inhomogeneities with diffuse scattering surfaces in optical media. Experimental data are in good agreement with the results of numerical simulations and are consistent with theoretical notions. It is shown that the proposed method can be implemented on a simple technical basis and used in practice.

PACS numbers: 06.60.mr, 42.25.fx, 42.30.ms, 78.20.bh

DOI: 10.1134/S1063785008090101

For solving various applied problems, it is important to develop methods for the remote determination of the parameters of relief and geometric characteristics of optical objects possessing scattering surfaces. In many cases, the remote diagnostics of such objects encounters considerable difficulties.

A spectral-correlation diagnostic method described below is based on establishing correlations between the distributions of intensities \( I(x, y) \) (speckle patterns) of the radiation scattered from the object probed at various wavelengths [1]. The speckle patterns were monitored with a CCD matrix TV camera and then the corresponding mutual correlation functions (CCFs) were calculated using the following formula:

\[
CCF(\Delta \lambda_n, x_0, y_0) = \frac{N}{\pi} \int (I(\lambda_n, x, y) - \bar{I})(I(\lambda_n + \delta \lambda_n, x + x_0, y + y_0) - \bar{I})dx\,dy,
\]

where \( I(\lambda_n, x, y) \) is the distribution of intensities at a given probing radiation wavelength, \( I \) is the intensity averaged over the integration area, \( N \) is the normalization factor, and \((x, y)\) are coordinates in the observation plane. Using the dependence of the maximum value of the correlation functions on the probing wavelength, \( CCF_{\text{max}}(\lambda) \), it is possible to determine the interval \( \Delta \lambda_n \) of wavelength tuning at which the decorrelation of the speckle patterns takes place. Then, the object height can be evaluated using the following formula:

\[
\sigma \geq \lambda^2/2\Delta \lambda_n. \tag{1}
\]

It should be noted that an important advantage of this method is the ability of remote determination of the roughness heights exceeding the radiation wavelength (\( \sigma \gg \lambda \)). This possibility is not provided by other optical techniques [2].

We have numerically simulated the spatial distribution of intensities for a beam of coherent radiation scattered from a rough surface. The surface relief was formed using an approach described in [3]. Figure 1a shows a normalized correlation function \( \frac{CCF}{CCF_{\text{max}}}(\lambda) \) for the speckle patterns observed for the reflection of light with \( \lambda = 1.0 \, \mu m \) from the surfaces with different rms heights of roughnesses. Taking \( \Delta \lambda_n \) equal to the wavelength at which \( CCF_{\text{max}}(\lambda) \) exhibits a maximum (i.e., a sharp change in the derivative), we can determine the roughness height using formula (1). It should be noted that \( CCF_{\text{max}}(\lambda) \) also depends on the probability density distribution of the roughness heights. The measured values can be used to compare the results of measurements with other methods. We have also studied the case of radiation scattering from a plane-parallel transparent plate with a rough front surface. In these simulations, it was assumed that the speckle pattern structure is formed by two waves: the incident wave scattered from the front surface (first surface) and the wave transmitted through the plate, reflected from the rear (second) surface, and scattered from the first surface. In addition, we assumed that the diffuse scattering from the second surface could be ignored. The normalized correlation function \( \frac{CCF}{CCF_{\text{max}}}(\lambda) \) for a plate with thickness \( H = 100 \, \mu m \) exhibited a periodic character (Fig. 1b). The period of spectral beats \( \Delta \lambda_n \) of this function (for the normal incidence, \( \gamma = 0 \)) was related to the plate thickness as \( H = \frac{\lambda_0^2}{2\Delta \lambda_n} \). In the general case (\( \gamma \neq 0 \)), the relation is as follows:

\[
H = \frac{\lambda^2}{4}(1 - (\sin^2\gamma/n^2)^{1/2} / (2\Delta \lambda_n(n - (\sin^2\gamma)/n))). \tag{2}
\]

In order to verify the method described above, we measured the scattering from rough samples and from...
Fig. 1. Numerically simulated dependences of the normalized correlation function for speckle patterns on the interval Δλ of wavelength tuning: (a) for surfaces with rms roughnesses (1) 40 μm, (2) 78 μm, and (3) 190 μm; (b) for a glass plate with a thickness of H = 100 μm and diffuse-scattering front surface.

Fig. 2. Plots of the maximum values of the correlation function of measured speckle patterns versus probing radiation wavelength (a) for a rough surface and (b) for a glass plate with diffuse-scattering front surface.

transparent plates with diffuse-scattering surfaces. The probing radiation was generated by an injection laser with a central wavelength of λ = 1.05 μm and an output power of 20 mW. A collimator formed the beam of IR radiation of an elliptical shape with a 5 × 8 cm cross section and an angular divergence of 0.1°. The wavelength tuning was achieved by changing the temperature of a heterojunction laser in the interval from −15 to +25°C with the aid of a microcooler. For the accuracy of temperature variation about ΔT = 0.1°C, the maximum size of measured surface roughness was about 550 μm. Taking into account that the interval of wavelength tuning in the indicated temperature interval (ΔT = 30°C) was Δλ = 21 nm, it was only possible to detect relief inhomogeneities with dimensions exceeding 26 μm.

The samples with maximum surface roughnesses exceeding 30 μm were prepared by pressing aluminum foil against rough emery paper. The rms deviation of the height profile measured using a profilometer was about σ = 62 μm, which did not allow the microrelief to be adequately characterized because the probability density distribution of roughness heights had a multimodal character. Taking into account the density distribution of roughness heights, the most probable roughnesses were evaluated as σ_1 = 115 μm and σ_2 = 32 μm.

In order to determine the roughness height on the profiled foil surface using the proposed spectral-correlation method, we measured the distribution of intensity of the reflected laser radiation of variable wavelength, calculated the maximum values of the correlation function, and plotted them against the wavelength (Fig. 2a). As can be seen, these are two regions of weak dependence on the correlation function maximum CCF_max on the wavelength λ, which correspond to λ_n1 = 1044 nm (in a spectral interval of Δλ_1 = λ − λ_n1 = 4.8 nm and λ_n2 = 1033 nm (Δλ_2 = λ − λ_n2 = 16 nm). For these experimental data, formula (1) yields the following characteristic roughness heights: σ_n1 ≡ λ^2/2Δλ_1 = 114 μm and σ_n2 ≡ λ^2/2Δλ_2 = 34 μm. Differences between the roughness heights determined from the density of roughness height distribution, the results of profilometric measurements, and by the spectral-correlation method were about 10%.

An object for evaluation of the thickness of optical elements with a scattering surface represented a microscope cover glass with a diffuse-scattering coating applied on the front surface. The speckle structure of the scattered light was formed by the radiation reflected from both the front and rear surfaces of the glass plate. The plate thickness varied over its area within 170–200 μm. The constructed plot of CCF_max(λ) exhibited pronounced oscillations (Fig. 2b), which were caused by periodicity in the dynamics of variation of the speckle structure. The period of CCF_max(λ) variations observed with a CCD camera at an angle of ϕ = 15° relative to the normal was calculated using formula (2) and amounted to 195 μm. When the observation with the CCD camera was performed from the direction of