Control surface roughness of mirror

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ABSTRACT

The relationship between statistical structure parameters of rough surface and associated correlation parameters of scattered field is based on the model of random phase object. We propose two technique for measuring surface roughness of mirror, which use measurement of a the contrast of the interference pattern in a field, as well as the devices implementing those techniques. One of them is based on measurement of a phase variance of the boundary object field while another of them is based on measurement of a transverse coherence function of a field. The sensitivity limit of the method in measuring the standard deviation of surface profile from base line is about 2 nm.

Keywords: rough surfaces, light scattering, mirror, transverse coherence function, phase variance, interferometry, contrast.

1. INTODUCTION

The diagnostics of slightly rough surfaces has been the subject of considerable interest recently. A great deal of progress has been made in this field[1]. A whole new class of optical diagnostics methods has been developed such as optical profiler total integrated scattering, angle-resolved scattering, speckle optics, interference and optical correlation techniques, etc[2].

A number of interference methods for measuring surface roughness are based on the model of random phase screen, which presumes[3,4]: i) infinitely extended object (all spatial frequency components of the radiation scattered by the object are present in registration zone); (ii) phase variance of the object is small; (iii) the correlation length of the inhomogeneity is larger than the wavelength.

A unique relationship is known to exist within this approach among the statistical parameters describing the object structure and associated correlation parameters of the scattered field[5].

We propose two techniques for measuring surface roughness of mirror, based on measurement of a the contrast of the interference pattern in a field, as well as the laboratory layouts implementing those techniques . One technique is based on measurement of a phase variance of the boundary object field while another - is based on measurement of a transverse coherence function of a field[6,7].

2. MEASUREMENT OF A PHASE VARIANCE OF THE BOUNDARY OBJECT FIELD

Consider two interfering coaxial waves, one of which is a plane wave and the other is an object wave modulated in phase by surface roughness. The result of interference can be written as

$$I_S(x,y) = A_0^2 + A^2(x,y) + 2A_0 A(x,y)\cos\varphi(x,y), \qquad (1)$$

where $I_S(x,y)$ is the resulting field intensity; $A(x,y)$ and A_0 are the amplitudes of the object and the reference waves, respectively, and $\varphi(x,y)$ is the phase difference of the reference and object waves. Assuming $\langle A(x,y)\rangle = A_0, \langle\varphi(x,y)\rangle = \varphi_0 + \pi$, and the phase fluctuations to be small, i.e., $\tilde{\varphi}(x,y) < 10^o$, relation (1), after area averaging and some manipulation, takes the form[5]

$$\frac{\langle I_S(x,y)\rangle}{I_0} = \sigma_\varphi^2 + \sigma_A^2 + m_{A\varphi}\,, \tag{2}$$

where σ_A^2 is the normalized amplitude dispersion,

$$m_{A\varphi} = \left\langle \frac{\tilde{A}(x,y)}{\langle A(x,y)\rangle} \cdot \tilde{\varphi}^2(x,y) \right\rangle \tag{3}$$

is the mixed third-order correlation moment of amplitude fluctuations and squared phase fluctuations, and $\sigma_\varphi^2 = \langle \tilde{\varphi}^2(x,y)\rangle$ is the phase variance. It follows from Eq. (2) that, since amplitude fluctuations in the boundary field are absent, then

$$\sigma_A^2 = m_{A\varphi} = 0.$$

This facilitates a direct interference measurement of the phase variance in the boundary field according to the relation that follows from Eq. (2):

$$\frac{\langle I_S(x,y)\rangle}{I_0} = \sigma_{\varphi 0}^2\,. \tag{4}$$

Using an interrelation among the height parameters of surface roughness and the phase parameters of the boundary object field, one obtains the following equation for an rms roughness:

$$rms = \frac{\lambda}{4\pi}\sqrt{\frac{\langle I_S(x,y)\rangle}{I_0}} \tag{5}$$

The arrangement used for the measurement is shown in Fig. 1[4]. A telescope consisting of two objective lenses transforms a light beam from a single-mode laser source into a plane wave, which then undergoes amplitude splitting into a reference and an object wave using a beamsplitter. The object wave reflected by the beamsplitter is focused by an objective lens onto the rough surface of a sample. The reflected radiation is used to form the surface image in the plane of a 2x2 position-sensitive photodetector array. The radiation reflected by the mirror interferes with the object wave forming an interference pattern with fringes localized at infinity.

The zeroth-order interference fringe is automatically kept within the 2x2 position-sensitive photodetector array by means of a transverse displacement of the micro-objective in the reference arm using two electric motors, and a longitudinal displacement of the mirror using a piezoceramic modulator, which simultaneously accomplishes amplitude modulation of the resulting light beam. The output signal from the 2x2 position-sensitive photodetector array is fed into the phase comparators which generate control signals for the motors and the piezoceramic modulator. The net signal is transformed then into a R_q value using the analogue processing unit, and is displayed on the indicator.

In general case, when the reference-to-object intensity ratio is not equal to unity, we use the following equation[4] derived from Eq.(5):

$$rms = \frac{\lambda}{4\pi}\sqrt{2 - \frac{I_{max} - I_{min}}{\sqrt{I_r}\,\sqrt{I_o}}}, \tag{6}$$

where I_{max} and I_{min} are the maximum and the minimum resulting intensities, respectively, and I_r and I_0 are the reference and the object beam intensities, respectively.

The distinguishing feature of both this and all of below discussed devices consists in the modulation data transducing. It relieves of the necessity to provide protection of the measuring device against vibrations. As a result, the sensitivity threshold for such devices approaches the level provided in heterodyne devices[1].

The arrangement shown in Fig. 1 can be custom-designed to meet specific requirements for measuring objects of different sizes under various conditions. The above arrangement permits measurements of low- reflectance surfaces since allowance has been made for the relative reflectance coefficient of the surface measured with respect to the reference mirror.

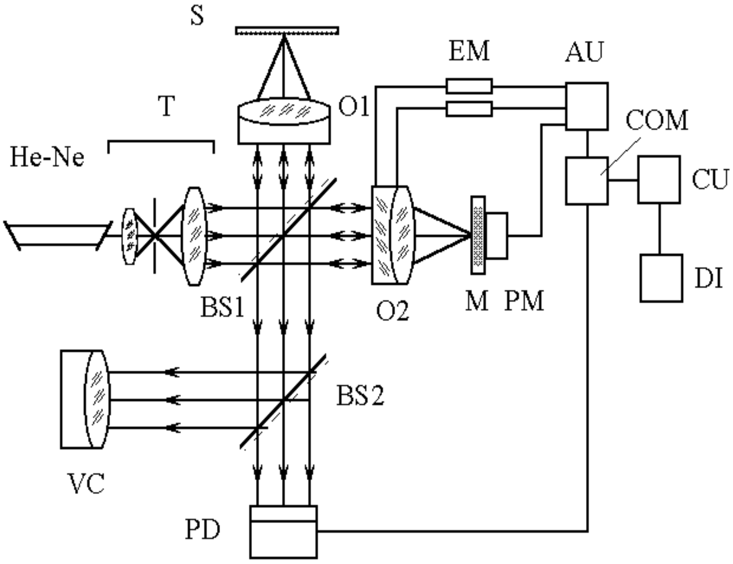

Fig. 1. Experimental arrangement for measuring the degree of low-reflectance surface roughness:
He-Ne - laser,
T - telescope,
BS1, BS2- beam-splitters,
O1,O2 - objective lenses,
S - sample, M - mirror,
PM - piezoceramic modulator,
PD-2x2 position-sensitive photodetector array,
VC- visualization channel,
EM - electric motors,
AU - automatic zero fringe adjustment unit,
COM - comparator,
CU - analogue R_q calculation unit,
DI - digital indicator.

Usage of this technique at various technological stages of making microelectronic devices includes the quality control of finishing of silicon plate's surfaces, control of the aluminium-evaporated plates and the photoresist-evaporated ones, as well as control of the etched plates, etc. The inclusion of a visual channel in the device considered permits choosing of the surface area of interest. Of course, usage of any contact profilometric technique for this purpose is prohibited.

It is interesting to note that moderate modification of the measuring technique permits to measure a height distribution function of surface microirregularities[8].

2. MEASUREMENT OF A FIELD'S TRANSVERSE COHERENCE FUNCTION

Another method for measuring the phase variance utilizes the relationship between the transverse coherence function $\Gamma_\perp(\rho)$ of the scattered field, on the one hand, and the statistical parameters of the object, on the other hand[5],

$$\Gamma_\perp(\rho) = \exp\left\{\sigma_{\varphi_0}^2 \left[K_{\varphi_0}(\rho) - 1\right]\right\}, \qquad (7)$$

where $K_{\varphi_0}(\rho)$ is the normalized phase correlation coefficient. In deriving the Eq. (7), Gaussian statistics of the object is assumed. An important point is that, for objects with $\sigma_{\varphi_0}^2 < 1$, the transverse coherence function $\Gamma_\perp(\rho)$ is given by the transverse coherence function of the boundary field $\Gamma(\rho)$ in any recording zone. It is seen from Eq. (7) that, by taking the logarithms of both sides, one can obtain an expression for the object phase variance .

By making the transverse displacement ρ of optically mixed components larger than the inhomogeneity correlation length l_{φ_0} when measuring the $\Gamma_\perp(\rho)$ function, one gets $K_{\varphi_0}(\rho)$=0, that immediately gives the $\sigma_{\varphi_0}^2$ value[5] .

The transverse coherence function $\Gamma_\perp(\rho)$ is known to be given by the boundary field coherence function $\Gamma_\nu(\rho)$, and can be defined as Eq. (7). Thus, by measuring $\Gamma_\perp(\rho)$ and making the relative displacement ρ of optically mixed components larger than the correlation length of the phase inhomogeneities l_{φ_0} , one can set $K_{\varphi_0}(\rho)$=0, and get

$$\Gamma_\perp(\rho > l_{\varphi 0}) = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \exp\left\{-\sigma_{\varphi 0}^2\right\}. \qquad (8)$$

This relation is commonly used in rough surface diagnostics.

The general schematic of the device that is intended for measuring the rms slightly rough surfaces is shown in Fig. 2[5].
A plane wave produced by the telescope T, consisting of a microscope objective, a pinhole and an objective lens, undergoes a total reflection in the polarizer cube PBS, and passes through the quarter-wave plate $\lambda/4$ after which it hits the surface S to be measured. The double-pass of the plane wave through the quarter-wave plate results in a 90^0 rotation of the plane of polarization. Thus, all the reflected light with polarization equal to the polarization of the incident light passes through the polarizer cube. The cube, together with the two calcite wedges W, one of which is stationary, the other movable, and the analyzer A, make up a scanning polarization interferometer. The relative displacement of the interferometer beams is determined by the separation between the wedges. Finally, the displacement of the movable wedge results in the net intensity minima $I_{\min}$ and maxima $I_{\max}$, which are recorded by the photodetector PD. The rms height deviation rms that follows from Eq. (8), can be found from the relation

$$rms = \frac{\lambda}{4\pi}\sqrt{-\ln\frac{I_{\max}-I_{\min}}{I_{\max}+I_{\min}}}. \qquad (9)$$

The information contained in the resulting interference pattern is extracted by transforming the optical signals into electric ones with subsequent processing in the analogue electronic unit CU.

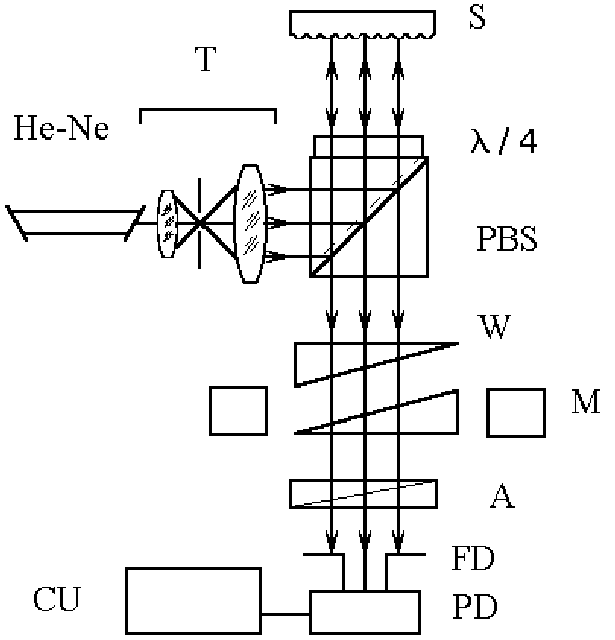

Fig. 2. Experimental arrangement for measuring the degree of arbitrary surface roughness:

He-Ne - laser,
T - telescope,
PBS- polarizing beamsplitter,
S - sample,
W- calcite wedges;
M - electromechanical modulator,
A - analyzer;
FD - field-of-view diaphragm;
PD - photodetector,
CU - analogue R_q calculation unit.

The device can be made either as a measuring head, or as a stationary instrument, depending on the size and the position of the object to be controlled. The advantages of the device over those currently in use are its speed, its high precision, and the non-contact nature of the measurement combined with the possibility of averaging over a large number of roughness elements.

Therefore, in a shearing interferometer, the object field interferes with itself, rather than with a reference field, thus making possible the measurements of arbitrarily shaped surfaces with radii of curvatures larger than 0.2 m. This is especially important, e.g. in the photochemical industry to monitor the quality of calender shafts, in the space industry to monitor the quality of mirrors fabricated by diamond micro-sharpening etc.

Being directly mounted at the polishing machine-tool, this device was used for surface quality control during processing. Calender shafts and spherical mirrors were monitored during fabrication by diamond micro-sharpening, and sensitivity of the rms height parameter down to 10Å was achieved.

4. CONCLUSIONS

The device can be made either as a portable measuring head, or as a stationary instrument, depending on the size and the position of the object to be measured. The advantages of the device over those currently in use are its fast acting (10 measurements per second), high precision (below 2 nm), non-contact nature of the measurement, and the possibility of averaging over a large number of roughness elements (throughout the analyzed area of the mirror).

Therefore, in a shearing interferometer, the object field interferes with itself, rather than with the reference field, thus making possible the measurements of arbitrarily shaped surfaces with the radius of curvature larger than 0.2 m. This is especially important e.g. in the photochemical industry to monitor the quality of calender shafts, in the space industry to monitor the quality of mirrors fabricated by diamond micro-shapening etc. Being directly mounted at the polishing machine tool, this device was used for the surface quality control during making of the detail.

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