Low-cost Detection of Surface Defects on Ultra-smooth Optical Substrates

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Abstract. In order to better measure the surface processing quality of ultra-smooth optical substrates, an image acquisition system of laser scattering microscope is built based on the principle of microscopic dark-field scattering imaging, which can help acquire a substrate sample scattering image within 10 seconds. Various kinds of defects on the surface of the optical substrates can be observed, and in this way, the simple and qualitative analysis of the surface quality of the substrates is realized.

1. Introduction

With the rapid development of optical technology, various laser optical components have higher requirements for optical coating, and the realization of high-quality coating requires the support of ultra-precision optical polishing process [1-3]. Since this process may leave some defects on the surface of the optical substrate, such as spots, tracks, brush marks and uneven backing, which will directly affect the later coating process and normal use, it is essential to detect and screen the surface quality of the substrate.

Ultra-smooth surface measurement technology is a highly practical technology, and has developed into many branches. The stylus mechanical scanning method has a long history, but it has several disadvantages, the first is that the scratch of the needle is easy to damage the surface, the second is that the scanning speed is low and the scanning area is limited, and the third is that the peak-to-valley value can be provided but the root-mean-square value can not be given [4]. The optical probe method is a non-contact measurement method, which is simple in principle, fast in speed and high in accuracy, but the demands of accuracy and stability placed on the scanning mechanism are too high, so it is not easy to adjust [5, 6]. The vertical resolution of the white light interferometer is very high, but affected by the diffraction limit, the international top level of horizontal resolution can only reach about 0.34 μm. Some defects smaller than this level cannot be observed, so it cannot meet the needs of application [7, 8]. Differential interference contrast microscope (Nomarski microscope) is a two-beam interference microscope which works on the principle of polarization of light, with a resolution of 0.1nm, but because its interference fringes are localized at infinity, it is only used for qualitative observation of surface quality [9]. Atomic force microscope (AFM) has a high lateral resolution, which can reach atomic level (about 0.2nm), but its detection range is only sub-millimeter, and the test time is long, so it is not suitable for the workshop application [10]. In brief, there are many methods that can be applied to the field of ultra-smooth optical substrate surface measurement, and they reflect respective advantages and disadvantages during use. Compared with the above methods, this paper explores a low-cost solution. A laser scattering microscope system is set up to collect the scattering images of the substrate surface,
and then the images are analyzed and processed by various methods, so as to realize the rapid and reliable judgment of the defects and ensure the production quality of the optical substrates.

2. Experimental principle
In this paper, the detection of surface defects is achieved by collecting laser scattering images on the surface of ultra-smooth optical substrates, and the experimental process is based on the relevant theoretical knowledge of classical scattering.

2.1. Surface scattering distribution function
In the theory of surface scattering, there are two commonly used functions to describe the surface scattering distribution, namely the angle-resolved scattering function (ARS) and the bidirectional reflectance distribution function (BRDF). Although the names of the two are different, the defined objects are both the scattering loss in the unit projection solid angle in the given direction, that is, the ratio of the scattered irradiance to the incident irradiance in the given direction. This paper only introduces the angle-resolved scattering function (ARS) [11].

\[
\text{ARS} = \frac{\Delta P_{s}}{P_{0}d\Omega_{s}} = \frac{16\pi^{2}(n^{2} - 1)^{2}}{\lambda^{4}} \times \cos\theta_{i}\cos^{2}\theta_{s}S(f_{x}, f_{y})|q_{UV}|^{2}
\]

where
- \(\lambda\): the wavelength of the incident light
- \(n\): the refractive index of the substrate
- \(dP_{s}\): the power of the scattered light
- \(P_{0}\): the power of the incident light
- \(d\Omega_{s} = \sin\theta_{s}d\theta_{s}d\phi_{s}\): the size of the scattering solid angle
- \(S(f_{x}, f_{y})\): the spectral power density of the surface function \(s(x', y')\)
- \(f_{x}\): the spatial frequency along the \(x\) direction
- \(f_{y}\): the spatial frequency along the \(y\) direction

![Figure 1. Schematic diagram of ARS function definition.](image-url)
\( q_{uv} \): the scaling factor of the incident \( U \) polarized light and the scattered \( V \) polarized light, both \( U \) and \( V \) can be \( s \) and \( p \) respectively

\[
S(f_x, f_y) = \iint_A dA \exp \left\{ -\frac{2\pi}{\lambda} \left[ x' \left( \sin \theta_s \cos \varphi_s - \sin \theta_l \right) + y' \left( \sin \theta_s \sin \varphi_s \right) \right] \right\} s(x', y')
\]  

(2)

with

\[
\lambda f_x = \sin \theta_s \cos \varphi_s - \sin \theta_l, \quad \lambda f_y = \sin \theta_s \sin \varphi_s
\]

where

\( A \): the irradiation area of the incident light

\[
\begin{aligned}
q_{ss} &= \frac{\cos \varphi_s}{\cos \theta_i + (n^2 - \sin^2 \theta_l)^{1/2} [\cos \theta_s + (n^2 - \sin^2 \theta_s)^{1/2}]} \\
q_{sp} &= \frac{\cos \varphi_s}{-\left( n^2 - \sin^2 \theta_s \right)^{1/2} \sin \varphi_s} \\
q_{ps} &= \frac{-\left( n^2 - \sin^2 \theta_s \right)^{1/2} \sin \varphi_s}{\cos \theta_l + (n^2 - \sin^2 \theta_l)^{1/2} [\cos \theta_s + (n^2 - \sin^2 \theta_s)^{1/2}]} \\
q_{pp} &= \frac{-n^2 \sin \theta_l \sin \theta_s - \left( n^2 - \sin^2 \theta_l \right)^{1/2} \left( n^2 - \sin^2 \theta_s \right)^{1/2} \cos \varphi_s}{\left[ n^2 \cos \theta_l + (n^2 - \sin^2 \theta_l)^{1/2} [\cos \theta_s + (n^2 - \sin^2 \theta_s)^{1/2}] \right]}
\end{aligned}
\]

(3)

In general, we are more concerned about the case where the scattering plane lies in the incident plane \( (\varphi_s = 0) \). At this time, \( q_{sp} \) and \( q_{ps} \) in equation (3) are both zero, and there is no cross polarization, i.e., when the incident light is \( s \)-polarized light, the scattered light is only \( s \)-polarized light, and when the incident light is \( p \)-polarized light, the scattered light is only \( p \)-polarized light, then

\[
\begin{aligned}
q_{ss} &= \frac{1}{n^2 \sin \theta_l \sin \theta_s - \left( n^2 - \sin^2 \theta_l \right)^{1/2} \left( n^2 - \sin^2 \theta_s \right)^{1/2}} \\
q_{pp} &= \frac{1}{\left[ n^2 \cos \theta_l + (n^2 - \sin^2 \theta_l)^{1/2} [\cos \theta_s + (n^2 - \sin^2 \theta_s)^{1/2}] \right]}
\end{aligned}
\]

(4)

2.2. The principle of microscopic dark-field scattering imaging

The principle of microscopic dark-field scattering imaging is used during the image acquisition process and it is as follows. The figure 2 shows, the incident light is obliquely incident to the surface of the substrate at an incident angle \( \alpha \). When the irradiation area is smooth and free of defects, according to the law of reflection, the light is still emitted at an angle of \( \alpha \); when the irradiation area is defective, the defect can be considered as a scattering source, due to the irregular shape of the defect surface, the incident light will form scattered light within a certain range. Therefore, moving the laser irradiation area allows the microscope to receive only scattered light but not normal reflected light, and the CCD can detect the defect image at this time. Since only the scattered light enters the photosensitive surface of the CCD, the bright image on the CCD detector is presented in the dark background [12].
3. Experimental system

The image acquisition system of laser scattering microscope in this paper can be divided into two parts. The first part is the optical path, which mainly involves the relative position relationship between laser and microscope. Both of them are fixed on the work bench. The laser emits laser light to the surface of the substrate. Then the scattered light enters the microscope objective lens above the light spot and it is received by a CCD camera to realize the acquisition of scattered images. The second part is the mechanical structure, mainly the placement of components such as the microscope, the CCD camera, the image capture card and the image display. According to the requirement of the optical path part, the mechanical part should meet the requirement that the laser beam and the microscope spindle exactly intersect on the substrate surface. The overall design and workflow of the experimental system are shown in figure 3. The laser and the microscope are combined to build the laser scattering microscope system. The CCD camera is directly connected to the microscope, and it is connected to the computer through the image capture card. The optical substrate is placed on the X-Y translation stage, which is fixed on the work bench.
According to the principle of microscopic dark-field scattering imaging, normal defects can only be observed in the laser irradiation area, therefore, it is necessary to ensure that the laser beam spot can completely cover the region to be detected. Simply expanding the diameter of the laser beam is not desirable, because it will cause a reduction in the light intensity of the region, and under this condition, small defects cannot be captured. The scheme adopted in this paper is to collect the images by scanning first, and then splice them into a complete image. The scanning area is a large square of 4 mm × 4 mm on the surface of the substrate, which is divided into 16 small squares of 1 mm × 1 mm. In the process of substrate detection, since the laser beam is always fixed, the computer-controlled X-Y translation stage moves along a predetermined path to detect the region to be measured point by point. Each time it moves to a specified position to illuminate a specific area, a scattering image is collected. After one round of movement, the final laser scattering image of the substrate surface is achieved by cutting and splicing 16 small images obtained at different scanning positions.

The simulated laser scanning path is shown in figure 4. According to the sequence of serial number, the round laser beam spot sweeps through the entire large square area in turn, and each time it can ensure that the center of the spot covers a small square to be detected with the maximum intensity. The simple principle of image stitching is illustrated in figure 5. The small square areas of 16 small images, which are illuminated by the laser beam respectively, are cut and spliced together to form a complete laser scattering image of the substrate surface.

Figure 4. Simulated laser scanning path.
4. Experimental results and discussion
A set of laser scattering images were obtained by testing the optical substrate samples in the ultra-clean room. The bright dots, bright patches and bright bands on the dark background of the image correspond to the defects such as dots, tracks and brush marks on the surface of the substrate. The typical Substrate A and Substrate B are shown in figure 6.

Observing the laser scattering images of the substrate samples, it is not difficult to find that they have similar features, i.e., four bands with decreasing gradients of brightness values from left to right. After analysis, this is caused by volume scattering noise inside the optical substrate. Volume scattering refers to the scattering generated inside the medium, which is the total effective scattering generated after multi-path scattering. When the medium is inhomogeneous or mixed, volume scattering often occurs. The defects within the substrate and the inhomogeneity of the refractive index are the root causes of the volume scattering. The volume scattering is much higher than the surface scattering for substrates with good surface quality, even if the material is homogeneous. Therefore, volume scattering is an unavoidable issue that must be considered in substrate surface detection, and it directly affects the
accuracy and resolution of system detection. As shown in figure 7, in the measurement of the scattering of a smooth surface, the transmitted light entering the inside of the substrate sample is scattered as it travels through the sample. It is easy to see that within the scope of the microscope observation field, the number of particles illuminated by the transmitted light inside the substrate is different at different positions, and increases along a gradient from left to right. The greater the number of particles illuminated by light, the stronger the volume scattering that occurs, therefore, the volume scattering noise also increases along a gradient from left to right. Since the scanning path is divided into four columns in this paper, the volume scattering noise distribution of the laser scattering image on the surface of the optical substrate shown in figure 6 is in the form of four steps.

![Figure 7. Schematic diagram of volume scattering.](image)

In view of the noise characteristics, a corresponding model is constructed. Select the region without obvious defects as the raw data of volume scattering noise model, calculate the average gray value of each column of pixels, and divide the data into four groups (that is, four column scanning bands) for linear fitting. The data obtained by fitting is used as the gray value of each column, and the volume scattering noise model is established accordingly. Each image is processed to deduct the volume scattering noise model, and the three-dimensional images of the gray distribution corresponding to the post-processing images are made, as shown in figure 8. In the processed images, the surface is generally flatter and the defects are much more prominent than before. Substrate A has almost no defects, and its surface quality is relatively good. There are a large number of defects such as dots and tracks in Substrate B, and its surface quality is relatively poor.
5. Conclusion

In this paper, an image acquisition system of laser scattering microscope is set up based on the principle of microscopic dark-field scattering imaging, which can help acquire a substrate sample scattering image within 10 seconds through the cooperation of hardware and software. After relevant processing of the laser scattering images, we can observe and distinguish the defects on the substrate surface clearly and intuitively, and analyze the surface quality of the ultra-smooth optical substrates easily and qualitatively.

At the same time, the system also has two obvious shortcomings. One is that it cannot carry out the quantitative detection and give the quantitative size of the surface defects; the other is that it is impossible to judge the morphological features of the defects such as concave or convex and deep or shallow. These problems need to be solved in the follow-up research.

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