Angle-deviation optical profilometer

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Received July 1, 2010; accepted August 16, 2010; posted online January 1, 2011

We propose a new optical profilometer for three-dimensional (3D) surface profile measurement in real time. The deviation angle is based on geometrical optics and is proportional to the apex angle of a test plate. Measuring the reflectivity of a parallelogram prism allows detection of the deviation angle when the beam is incident at the nearby critical angle. The reflectivity is inversely proportional to the deviation angle and proportional to the apex angle and surface height. We use a charge-coupled device (CCD) camera at the image plane to capture the reflectivity profile and obtain the 3D surface profile directly.

OCIS codes: 120.6660, 120.0120, 080.2468, 100.2000.

doi: 10.3788/COL201109.011201.

Surface profile measurement can be separated into contact[1,2] and non-contact methods[3−16]. The lateral resolution of the traditional contact method for measuring surface roughness that requires passing a stylus probe across the surface and monitoring its movement so that a surface microprofile can be traced is limited by its probe size. More recent techniques for imaging surface profiles of a plate, such as atomic force microscopy (AFM) and scanning electron microscopy (SEM), perform high-resolution imaging at the nanometer scale. However, these methods do not permit real-time evaluation and lack the ability to perform wide-range scanning. Furthermore, these techniques face intrinsic limitations, including special preparation of the sample and environmental shielding. In contrast, optical methods offer many advantages. They are non-contact, non-destructive, sensitive, highly stable, and can perform real-time, high-resolution, and wide-range imaging without special preparation of sample and environmental shielding. For these reasons, such methods have become increasingly popular.

Many of the optical techniques proposed for imaging or measuring surface profiles of materials, such as laser profilometry, require expensive, bulky equipment, and pose difficulties in implementation for on-line measurement of surface roughness. A number of optical methods, such as speckle[3,4], interference fringe patterns[5], heterodyne interferometry[6], laser scattering probe[7,8], microdeflectometry[9], slit-beam-profile reflectometer[10], fringe projection[11], phase-shifting[12−14], longitudinal light profile microscopy[15], and transmission-type angle deviation microscopy[16] are applicable to surface-roughness measurement. Except for Refs. [13,16], the direct measurement of a laser beam as it passes through a transparent object, such as a thin film, glass, grating, or living cell, has been barely explored.

Our research focuses on a laser beam passing through a transparent object (grating) and is based on a linear transform from angular deviation to light intensity (or reflectivity) of a parallelogram prism in critical angle theorem. The proportionality of the surface height difference to the deviation angle, as well as the function of the reflectivity of a parallelogram prism as the light is incident at the nearby critical angle, allows a three-dimensional (3D) surface profile to be obtained rapidly using a charge-coupled device (CCD) camera to record reflectance of each point and substitute it into the transfer function. Our method has several advantages, including a simple and inexpensive configuration, and on-line and high-speed measurement. However, its greatest advantage is in obtaining the overall 3D surface profile of the transparent specimen in real time.

From Fig. 1, when a light is normally incident into a transparent plate with a refractive index n and a small apex angle α, if α is sufficiently small, the angular deviation may be written as

$$\beta = (n-1)\alpha, \tag{1}$$

and the surface height difference between two adjacent lights with a distance departure Δx is given as

$$\Delta h = \alpha \Delta x = \frac{\beta \Delta x}{n-1}. \tag{2}$$

Thus, the surface height difference is proportional to the apex angle α and the deviation angle β. From Fresnel's equations, in the critical angle case, the reflectivity slope of the p-polarization is higher than that of the s-polarization. It is thus more sensitive to the deviation angle detection in p-polarization. If the light is reflected twice at the same angle in a parallelogram prism, the total reflectivity is written as $R_{\mathrm{p2}} = \left| r_{\mathrm{p}}^2 \right|^2$, where r_{p} is the reflective coefficient of the p-polarization. Assume that

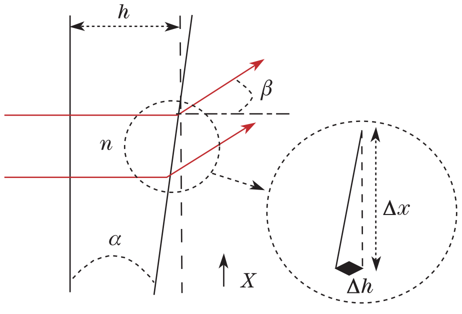

Fig. 1. Relation between surface height Δh and deviation angle β.

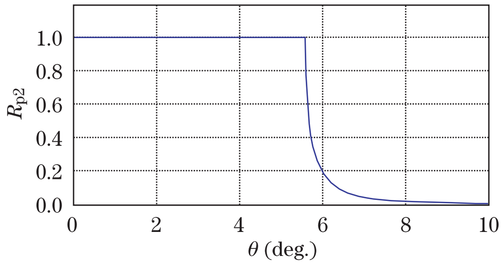

Fig. 2. Simulation curve of R_{p2} versus incident angle θ.

the refractive indices of the prism and air are n_1=1.51509 and n_2=1.0003, respectively, and the incident angle θ at the first surface of the prism is in the region of 0°−10°. Figure 2 shows the curve of reflectivity of R_{p2} versus the incident angle at the critical angle nearby. Thus, the reflectivity is inversely proportional to the angle θ. From the curve, the best angular sensitivity is at the critical angle; however, the measurable range of height is limited and smaller than at the other angles. For 1−100 nm surface height measurement, let the point $\theta \approx 5.72°$ be a reference point. Then, to measure reflectivity of the prism, one merely has to obtain the incident angle θ.

The variation $\Delta\theta$ is equal to the deviation angle β and is also proportional to the apex angle α; m is negative. Hence, the surface height difference between two points is inversely proportional to the reflectivity and may be given as

$$\Delta h = A\Delta R_{p2} = \frac{\Delta x}{m\,(n-1)}\Delta R_{p2}, \tag{3}$$

where A can be a constant value if the test surface is sufficiently smooth, and may be given as

$$A = \frac{\Delta x}{m\,(n-1)}. \tag{4}$$

From Eq. (4), let m be the average slope of R_{p2} at the setting angle $\theta \approx 5.72°$. Thus, the surface height profile $h(x)$ on the test surface can be obtained and written as

$$h(x) = A[R_{p2}(x) - C], \tag{5}$$

where C is a threshold value and $R_{p2}(x)$ is the reflectivity profile corresponding to the coordinates on the test surface.

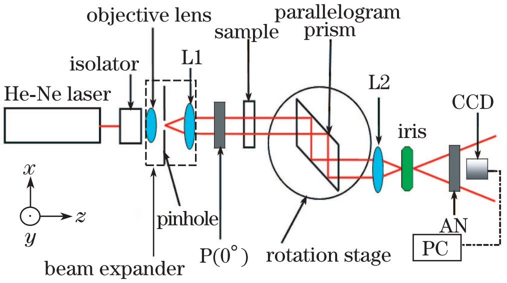

Fig. 3. Experimental setup.

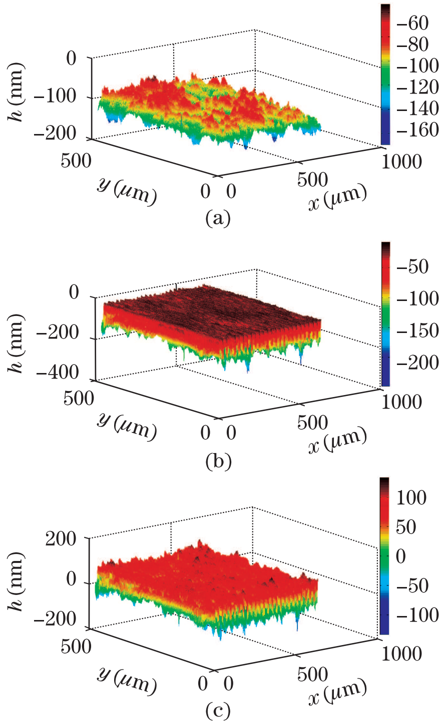

Fig. 4. Experimental results of 3D surface profilers. (a) System error profile (without sample); (b) surface height profile with system error; (c) actual surface height profile.

Figure 3 depicts the proposed experimental setup. A beam from a He-Ne laser was incident into an isolator to prevent the reflected light from returning to the laser. The isolator was composed of a polarizer and a $\lambda/4$ wave-plate. An expanded beam with p-polarization was formed by allowing the laser beam to enter a beam expander and pass through a polarizer P(0°), where the expander was composed of an objective lens, spatial filter, and lens (L1). The expanded beam was then normally incident into the specimen and passed through a parallelogram prism. Next, we rotated a rotation stage to meet the totally internal reflection (TIR) condition and find the TIR intensity profile. The rotation stage was then rotated to adjust the incident angle at the setting point ($\theta \approx 5.72°$). To generate the reflectivity profile $R_{p2}(x)$, a CCD recorded two image patterns from TIR angle to the setting angle ($\theta \approx 5.72°$). Owing to the angle shift, the CCD must be translated laterally for two totally overlapping images. The intensity ratio of the setting angle to TIR angle was the reflectivity. The output beam intensity from the prism was adjusted by rotating an analyzer (AN) to prevent CCD saturation, and the surface image of the specimen was magnified using lens L2. The CCD was located at the image plane. In our setup, the optical magnification was −8.467. The pixel size of the CCD was 8.4×9.8 (μm) and the corresponding point size on the test plane was 0.992×1.157 (μm). Therefore, the best lateral resolution may be close to 1 μm and the recorded area was 634.88×555.36 (μm) for a CCD array of 640×480 (pixel). To reduce errors due to intensity variation in the light source and environmental vibrations, at each angle (at TIR or setting angle), we averaged each pixel data from a sequence of profiles recorded successively within a short period. Finally, we substituted the reflectivity profile $R_{p2}(x)$ into Eq. (5) using a personal computer (PC) for 3D surface profile calculation.

To demonstrate the feasibility of this method, we used a 1000-lines/inch grating as specimen, and a Dektak-600

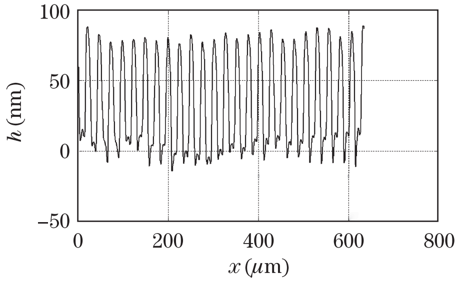

Fig. 5. 2D images of the average surface profile of 1000-lines/inch grating.

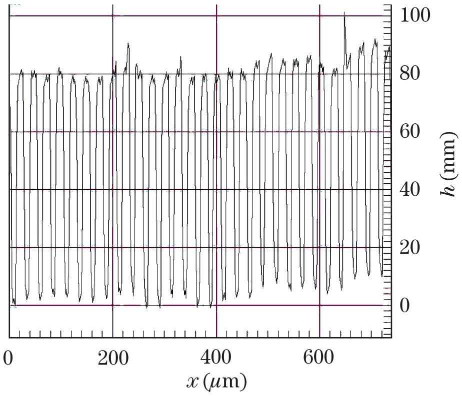

Fig. 6. 2D image of surface profile of 1000-lines/inch grating from Dektak 600.

Surface Profiler to measure the same area. As mentioned above, the refractive index of the gratings was 1.51, $\triangle x$=0.992 μm, m=−15.99 change/rad and the value of A was −121.6 nm·rad. We calculated the surface height $h(x)$ by substituting the reflectivity profile $R_{\mathrm{p2}}(x)$ into Eq. (5).

The 3D profile results are shown Fig. 4. The system error profile due to the surface roughness of the parallelogram prism and other components was measured using the same steps, and is shown in Figs. 4(a)–(c) show the 3D profile with and without the system errors, respectively, where the actual surface height profile of Fig. 4(c) is equal to the result of Fig. 4(b) minus Fig. 4(a). Thus, the threshold value C was canceled so that the surface profile was a relative height profile. The average two-dimensional (2D) surface profile is shown in Fig. 5, where the average surface height is 79.1 nm.

Figure 6 shows the 2D profile results of the 1000 lines/inch grating from the Dektak-600 Surface Profiler. The average surface height was approximately 80 nm. A comparison of our results with those of the Dektak-600 Surface Profiler shown in Fig. 6 indicates good agreement and the feasibility of the proposed method was demonstrated. The axial sensitivity of our method was 8.22×10^{-3} change/nm for 8-bit analog-to-digital (A/D) converter. The axial resolution was 0.5 nm.

The surface image was obtained directly from the reflectivity profile, which allowed the test surface and effective error of the optical system to be obtained. The method can also be used to compare the difference between the test and stander surfaces. This transfer function was implemented using the high-reflectivity slope characteristic of p-polarization light at the critical angle nearby. Using a CCD to record the reflectivity profiles, the 3D and 2D surface profiles were obtained simultaneously. Adjusting the optical magnification made it easier to determine the measurement ranges of the surface height and surface area. To enhance its performance, the optical magnification, number of reflections in the prism, and bit number of the A/D converter should all be increased, while the CCD pixel size should decreased, or a high-sensitivity angle of incidence should be chosen.

In conclusion, we propose a new method for 3D profile measurement that is based on the transformation from surface height to reflectivity. The best axial and lateral resolutions are of 0.5 nm and 1 μm, respectively. In addition, this method enables real-time analysis of roughness or defect measurement. This method has the advantages of simple, easy operation and set up, on-line detection, low cost, high sensitivity, high resolution, and large range measurement without scanning.

This work was supported in part by the National Science Council under Grant No. NSC98-2221-E-150-035.

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