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DEVELOPMENT OF OPTICAL SURFACE PROFILING INSTRUMENTATION

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ABSTRACT

A novel non-contact optical profiler described in this paper is designed and made for measuring the surface characteristics of optical parts. Measurements are based on a combination of an optical heterodyne technique and a precise phase measurement procedure without the need of a reference surface. A Zeeman-split He-Ne laser is employed as the light source which offers two common-path polarized beams. The frequency difference between the beams is 1.8 MHz. A special optical head is designed and fashioned as a beam splitter which contains a birefringent lens and an objective. The whole optical system is completely common-path. This allows the optical common-mode rejection technique to be applied in the system for minimizing the environmental effects in measurements such as air turbulence, vibrations and temperature variations. To keep the sample surface focused to the ordinary rays in the optical head, an astigmatic autofocus system is employed. A stepping micro-stepping system can move the optical head in the range of 25 mm with 0.1 μm resolution. A data acquisition system is made to control the auto-focus system, data receiving and analyses. This makes the measurement automatically while the sample is being scanned. The characteristics of the surface can be displayed on the computer screen.

The theoretical and experimental analyses of the profiler are completed. The profiler measures samples with 1.1 Å height accuracy and 4 μm lateral resolution when a 40X objective is used in the optical head. The accuracy comparisons of the profiler with different objectives 5X, 10X, 20X and 40X are shown in a good agreement. The advantages of the present profiler are presented. Based on the autofocus system, the profiler optical system will be designed to mount on a large linear air-bearing slide, so that it is capable of scanning over a distance covering from 4 μm to 1 m.

1. INTRODUCTION

During recent years, several advanced techniques for determining the characteristics of optical surfaces have been developed such as mechanical probe instruments^[1], optical scattering^[2-3], multiple-beam interferometers^[4], optical profilers^[5-6], etc. Among these techniques, scientists are more and more interested in optical profilers because of their advantageous characteristics: non-contact measurement and reconstruction of surface profiles. Compared with mechanical probe instruments, optical profilers have major advantages insofar as they do not contact sample surfaces in measurement. The profilers do not require any surface preparation; coated surfaces can be tested as well as bare surfaces. This avoids the limitations of multiple-beam interferometers whose measurement and reference surfaces must be coated and pressed together. Optical profilers do not require any assumptions about the height distribution and autocorrelation function of a surface which is a requirement of the optical scattering techniques. Optical heterodyne interferometry is extensively treated among the profilers. Some heterodyne interferometers have been developed although they usually need very good experimental conditions^[7-9].

The novel optical heterodyne profiler described in this paper has a completely common-path optical system⁽¹⁰⁾. An optical common-mode technique is employed to minimize environmental effects. The height accuracy is achieved 1.1 Å and the lateral resolution is 4 μm when a 40X objective is employed. Measurements can be taken in ordinary experimental conditions.

2. PRINCIPLE OF OPERATION

The characteristics of the novel profiler are the applications of an optical heterodyne technique, a Zeeman-split He-Ne laser as the source, and a high precision phase measurement system. These qualities offer much convenience and make the profiler construction simple and easily understood. The completely common-path optical system arrangement and common-mode rejection technique employed are important in the profiler design. They introduce the advantage that the measured surface heights are directly related to the optical path-length differences between the measurement and reference signals. They also minimize the vibration-induced optical jitter in the system and the effects of air turbulence and temperature variations. Measurements are guaranteed to keep high accuracy during ordinary experimental conditions.

Fig. 1 Schematic diagram of the optical heterodyne profiler.

The optical path arrangement of the present profiler is depicted in Fig. 1. Two common-path beams produced by the Zeeman-split He-Ne laser are introduced to the optical system through a collimating lens. One beam is left circularly polarized, the other is right circularly polarized. Both beams have equal intensity and a highly stabilized frequency difference of 1.8 MHz. A part of each beam passes through a beam splitter (BS1) to a detector system comprised of a polarized (P1) and a photo-electric receiver (R1). Both beams are interfered at the P1, then received at the R1 where a beat-frequency signal is produced to serve as a reference signal. This signal incorporates information

of the initial phase difference between the two beams. The signal--after amplification--is displayed on an oscilloscope and is fed to a digital phase meter.

The two reflected beams from the BS1 become linear and orthogonal through a quarter wave plate (QWP). One beam polarization is parallel to the beam wave propagation plane, the other perpendicular. Both beams pass through the optical head to a sample surface. The optical head consists of a birefringent lens and a microscope objective. The crystal optical axis of the birefringent lens is arranged parallel to the beam wave propagation. The birefringent lens has two focal points, f_o and f_e ($f_o = 40.0735$ mm, $f_e = 87.8485$ mm), corresponding to its ordinary and extraordinary rays, respectively. One beam, working as the ordinary rays, becomes a focused beam; the other, working as the extraordinary rays, becomes a collimated beam. The surface is located in the ordinary-ray focal plane. The large collimated beam spot is overlapped on the small focused beam spot on the surface and used as a reference. The focused beam spot serves as a probe to measure the height in its spot area compared with its surrounding area. The large spot area is much greater than and concentric with that of the small one. The area ratio of the large spot (~ 143 μ m diameter) to small spot (~ 4 μ m) is 1250 when a 40X microscope objective is used.

Both reflected beams from the surface are combined and collimated through the optical head. They retain the characteristics of their orthogonal-linear polarizations but with a phase difference caused by the surface heights. A fraction of the beams is reflected by a beam splitter (BS2) to an auto-focus system. The reflected beam on the large spot is hindered by a polarizer (P3) whose polarization is set perpendicularly to that of the reflected beam. The focus system controls the focus of the optical head onto the surface according to the focus information from the other reflected beam. The two transmitted beams are interfered at a polarizer (P2) through the BS1. They are focused onto a photo-electric receiver (R2) where a beat-frequency signal is produced. This signal contains the information of the surface roughness and serves as a measurement signal. The digital phase meter compares with the phase values between the two incoming signals from the R1 and R2 with a high resolution, up to 0.01° . This permits the quantitative measurement of the optical path difference between the average surface levels of the focused and collimated beam spots to a high accuracy. The whole surface profile is created by scanning the optical head over the surface.

The optical common-mode rejection technique employed in the present profiler and the novel optical head design are critical in achievement of the high measurement accuracy. The birefringent lens is made of calcite crystal with the optical axis at 90° to a normal-incident beam. The two reflected beams from the BS1 are brought to the ordinary-ray and extraordinary-ray focal points, f_o and f_e , respectively. The f_e is at the back focal point of the microscope objective so that the extraordinary-ray beam becomes collimated after passing through the objective, and the ordinary-ray beam is focused onto the sample surface.

The reflected beams are combined after passing through the optical head. The phase, Φ , of the beam reflected on the small spot is determined by the surface height level, h ; the other phase, Φ_o , is determined by the average level integrated over the collimated beam spot which is viewed as a reference height level, h_o . When the beams scan across the surface, their phase difference follows surface irregularities. Both beams in travelling are always concentric to each other, so that the sample vibrations, air turbulence and temperature variations are introduced the same optical phase perturbations to each beam. The common-mode rejection, therefore, minimizes the perturbations in the optical heterodyne phase measurement. The measured surface profile is simply described by the relationship between $(h-h_o)$ and $(\Phi-\Phi_o)$.

The phase difference between the measurement and reference signals from the receivers, R1 and R2, carries the information of the surface profile. It is also affected by the system characteristics such as mechanical instabilities, thermal drifts, laser cavity detuning, etc. The influence of these characteristics is examined and presented below.

The sum of amplitudes of the two polarized beam fields at either detector can be expressed as below:

$$V = V_+ + V_- = \exp[i(k_+ z_+ - w_+ t)] + \exp[i(k_- z_- - w_- t + \varphi_0)] \quad (1)$$

where w is the angular optical frequency, k is the wave number associated with w , z is the distance traveled, φ_0 is the initial arbitrary phase, and subscripts "+" and "-" correspond to the beams of up-shifted and down-shifted frequencies, respectively. The signal, S , from each receiver is proportional to the intensity, $S \sim I = |V|^2$. The signal from the reference receiver can be expressed,

$$\begin{aligned} S_r &= |\exp[i(k_+ z_r - w_+ t + \phi_{1r})] + \exp[i(k_- z_r - w_- t + \phi_{1r} + \varphi_0)]|^2 \\ &= 2[1 + \cos[(k_+ - k_-)z_r - \Delta w t - \varphi_0]] \end{aligned} \quad (2)$$

where $z_+ = z_- = z_r$ is the common-path length traveled by the reference beams, $\Delta w = w_+ - w_-$ is the angular Zeeman frequency, and ϕ_{1r} is the noise effect of environmental conditions such as temperature variations. The signal from the measurement receiver can be expressed,

$$\begin{aligned} S_m &= |\exp[i(k_+(z_m + z/2) - w_+ t + \phi_{2m})] + \exp[i(k_-(z_m - z/2) - w_- t + \phi_{2m} + \varphi_0)]|^2 \\ &= 2[1 + \cos[(k_+ - k_-)z_m + (k_+ + k_-)z/2 - \Delta w t - \varphi_0]] \end{aligned} \quad (3)$$

where $z_+ = z_m + z/2$ and $z_- = z_m - z/2$ are the path lengths traveled by the two polarized measurement beams, respectively, z_m is the average path length and z is the difference between the two path lengths, ϕ_{2m} is the noise effect of environmental conditions such as surface vibrations, temperature variations and air turbulence. The noise effect does not appear in the AC and DC component of the S_m .

The phase difference, Φ , between the measurement and reference signals is,

$$\Phi = (k_+ - k_-)(z_m - z_r) + (k_+ + k_-)z/2 \quad (4)$$

where the wave numbers, k_+ and k_- , can be expressed as,

$$k_+ = (2\pi/c)(f_0 + \Delta f) \quad k_- = (2\pi/c)(f_0 - \Delta f) \quad (5)$$

where f_0 is the center frequency of the He-Ne laser, and Δf is the Zeeman-split frequency. Substituting Eq. 5 into Eq. 4 gives,

$$\Phi = (2\pi/c)[\Delta f(z_m - z_r) + f_0 z] = (2\pi/c)(\Delta f z' + f_0 z) \quad (6)$$

where $z' = z_m - z_r$ is the average path difference between the measurement and reference beams. Eq. 6 represents the phase difference as a function of the optical system parameters.

As the sample surface is scanned, the variation of the surface heights alters the z and yields a related phase change. The phase change is also influenced by the other system characteristics and experimental conditions such as temperature variations, laser cavity tuning and drift of the beat frequency. The phase change, $\delta\Phi$, is studied by differentiating Eq. 6,

$$\delta\Phi = (2\pi/c) (z' \delta(\Delta f) + \Delta f \delta z' + z \delta f_0 + f_0 \delta z) \quad (7)$$

Table 1 Comparison of the effect magnitude of each term in Eq. 7.

Parameter	Value	Variation
z'	1 m	1 mm
Δf	1.8 MHz	1 Hz
z	1 μ m	0.1 nm
f_0	500 THz	10 MHz

Phase Contribution	Value (rad)
$(2\pi/c) (z' \delta(\Delta f))$	2 E-8
$(2\pi/c) (\Delta f \delta z')$	4 E-5
$(2\pi/c) (z \delta f_0)$	2 E-7
$(2\pi/c) (f_0 \delta z)$	1 E-3

In the expression above the terms represent the instabilities of the system characteristics. The first term is introduced by the drift of the Zeeman-split frequency, the second and last terms are related to the mechanical drifts and the surface heights. The third term is related to the laser detuning. The amplitudes of these terms are listed in table 1. The values used in the table are from the specifications of the employed equipment parts. The table shows that the effects of the system instabilities are much less than those of the angstrom-level surface height variations. The contribution to the phase change is largely dependent on the surface profile. The other contributions can be neglected. In fact, the actual measurement sensitivity is limited by that of the phase detection system. The term, $(2\pi/c)(\Delta f \delta z')$, is the largest among the other three terms. It produces the phase effect of 2.3E-3 degrees. This effect is smaller than 0.01° sensitivity of the used phase detector system to the input signals of 1.8 MHz, and cannot be measured. Hence, Eq. 7 is simply expressed as,

$$\delta\Phi = (2\pi/c) (f_0 \delta z) = (2\pi/\lambda) \delta z \quad (8)$$

where the relationship, $\lambda = c/f_0$ is used, λ is the center wavelength of the laser. The relationship between the optical path change and the surface height is,

$$\delta z = 2 \delta h' \quad (9)$$

where h' is equal to the height difference, $h - h_0$, at the focused and collimated beam spots on the sample surface. The surface height change is expressed in the term of the measured phase change:

$$\delta(h-h_0) = (\lambda/4\pi) \delta\Phi \quad (10)$$

The phase changes are only related to the surface height variations. The phase measurement is insensitive to the signal intensity variations, sample vibrations and the other system instabilities. Measurement, therefore, can be made in ordinary experimental conditions.

The application of the birefringent lens is very important for the profiler to minimize the effects of environmental conditions in measurements. The collimated beam incident to the center of the optical head has two orthogonally polarized components, P and S, which align with the ordinary and extraordinary ray axes of the birefringent lens, respectively. The P is deviated more than the S. The P and S focal points are exact at the central optical axis of the lens and at different distances from the lens. The difference of the focal powers between the components is small. The objective lens provides a relatively powerful focusing effect to the ordinary rays. It is combined with the birefringent lens to work as a collimator to the extraordinary rays. A fine focus screw, 83 threads/in, is set on the housing of the optical head. This is for the axial-scanning adjustment to alter the objective position so that its back focal point is overlapped on the extraordinary-ray focal point. The objective is adjusted to scan along its optical axis. The scanning is precisely linear along the axis without transverse component and tilt. The microscope objective mounted on the optical head is changeable. It is available with 5X, 10X, 20X and 40X. A 40X objective is the one we specify for the system.

Measurements are taken only if the sample surface is in focus. An astigmatic autofocus system^[10-11] is employed to move the optical head so that the ordinary-ray beam is focused on the surface. This is sensitive to the degree of the collimation of the reflected ordinary-ray beam after passing through the optical head. The two foci of the system are set horizontally and vertically. For a collimated beam entering the system, a quadrature detector is set between the two foci so that the beam image on it is circular. If the incident beam is convergent or divergent, the beam image on the detector is elliptical.

$$PES = [(A+B)-(C+D)]/(A+B+C+D)$$

A, B, C and D represent the intensity signals on the four quad cells of the detector.

Fig. 2 Optical spot pattern on the quadrature detector when the sample surface position is : (a) too far, (b) in focus, (c) too close.

The optical information of the reflected ordinary-ray beam is converted into an electrical signal through the detector. This is presented in Fig. 2. The beam image becomes elliptical when the beam is convergent or divergent (the sample is too far or too close from the optical head). The major and minor axis of the image switch if the unfocused surface moves across the focal position from either side. The focus position error signal (PES) is contributed by the intensity signals on the four quad cells of the detector. This determines the sample unfocused value and the adjustment direction of the optical head. A 0.1 μm resolution, 25 mm range stepping motor system is controlled according to the PES to move the optical head up or down until the surface is in focus.

3. EXPERIMENTAL MEASUREMENTS

The experimental results of surface profiles are tested with the measurement accuracy of the profiler. The accuracy represents the total system noise level caused by laser stability, electronics, optical and mechanical parts, and environmental conditions. It is a statistical parameter--the root mean square value of the noise over certain number of tests:

$$\text{Accuracy}(n) = \{ (1/n) \sum_{i=1}^n N_i^2 \}^{1/2} \quad (11)$$

where N_i is the tested value of the system noise and n is the number of tests.

Fig. 3 Measurement accuracy of the profiler.

The source employed is a HP5518A Zeeman-split He-Ne laser. The Zeeman-split frequency is 1.8 MHz. The phase test system is a universal time interval counter, SR620, from Stanford Research Systems. This has a 0.01° resolution to phase tests of 1.8 MHz input signals. A data acquisition system is made to control the autofocus system, data receiving and analyses. The system accuracy is measured when the sample surface is statically set in the focus of

Fig. 4 Comparison of measurement accuracies with different objective (5X, 10X, 20X and 40X) attached to the optical head.

the ordinary rays in the optical head. Each test of the system is at the same sample point. The objective is 40X. Actual accuracy is measured 1.1 Å, as shown in Fig. 3, and average noise level is very small. This means that the vibrations,

electronic and thermal effects cause very little drifting in the measurements. Comparison of the measurement accuracies with different objectives, 5X, 10X, 20X and 40X, are shown in Fig. 4. This displays that the system noises with different objectives are in a good agreement.

Fig. 5 Measured surface profile along scanning line 1.

The surface profile measurements are shown in Fig. 5 and 6. They are taken automatically with the data acquisition system while the surface is scanned. The objective attached to the optical head is 40X. The measurement data is taken only if the sample surface is maintained in good focus. The profiler sends one piece of data to the computer analysis system, then scans another sampling point. The measured surface profile along scanning line 1 is shown in Fig. 5. The surface roughness (RMS) is 6.2 Å. The profile shows that the sample surface has very fine

Fig. 6 Measured surface profile along scanning line 2.

roughness and flatness. Fig. 6 is obtained along scanning line 2 which is close to line 1 on the surface. The surface roughness is 7.4 Å. The comparison of both measurements demonstrates that different areas on the surface have different roughness levels. Although these differences are very small, they are described in the measurements of the our profiler.

4. CONCLUSIONS

The new optical heterodyne profiler has been developed without the need of an extra reference surface and the results displayed. It has shown itself to be a useful instrument for describing the characteristics of optical surfaces. When a 40X objective is employed, the lateral resolution is 4 μm and actual height accuracy is 1.1 Å. Measurements are made during ordinary experimental conditions. The lateral resolution can be improved with a more powerful objective, while the height accuracy can be improved with better electronics and by reducing the input signal frequency of the phase detection. Additionally, 0.1 μm resolution, 25 mm range allows the profiler to characterize large optics such as synchrotron radiation mirrors if the optical system of the profiler will be mounted on a long air-bearing slide.

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