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OPTICALLY TRAPPED MICROPROBE FOR NANO-PROFILE MEASUREMENT BASED ON INTERPOLATION METHOD OF STANDING WAVE SCALE USIGN CHROMATIC CONFOCAL SYSTEM

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Abstract – The improved nano-profile measurement technique by scanning an optically trapped microprobe is proposed, which is used as a sensor to read a standing wave scale (SWS) based on the interpolation method. An axial position of the optically trapped microprobe was measured using a chromatic confocal system to interpolate the SWS with high accuracy and high resolution. The length and the resolution of the interpolated SWS (iSWS) could be achieved 2.1 μm and 20 nm, respectively. In order to verify the validity of the proposed microprobe technique, the surface profile measurement of a glass small lens with accuracy higher than 50 nm was demonstrated.

Keywords: radiation pressure, microprobe, standing wave scale, chromatic confocal system, nano-profile

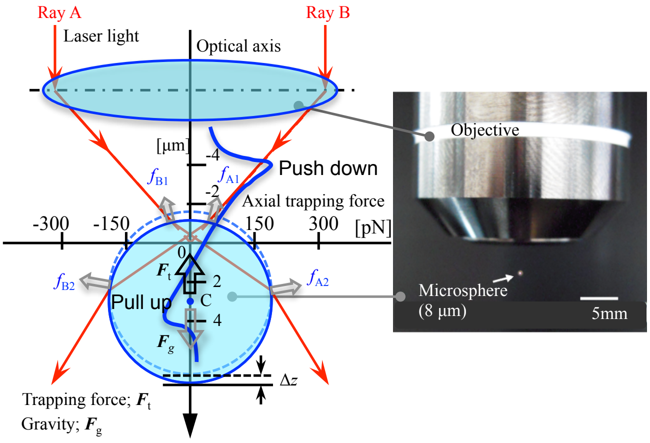
1. INTRODUCTION

Three-dimensional metrology is demanded to inspect the manufacturing performance of miniaturized products with nano/micro scale. To satisfy the specific requirements for coordinate metrology, we have developed the laser trapping probe, whose principle is based on single beam trap (SBT) of a microsphere in air [1, 2]. This technique is also applicable to scanning surface measurement based on SWS [3, 4]. The SWS is formed in accordance with interference of the laser, therefore highly reliable. However because of low resolution, high measuring resolution is required for nano-profile measurement of micro-components with free form surface. In order to improve the resolution of SWS with nanometer order, position measurement of a optically trapped microsphere with high accuracy and high resolution is needed for the interpolation of SWS. In this study, the improved nano-profile measurement technique based on the iSWS which could be read using a chromatic confocal system is discussed.

2. MIRCOPROBE BSED ON SWS SENSING

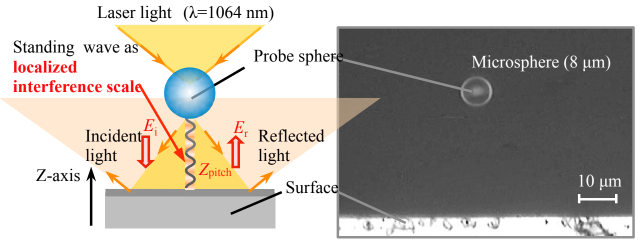
2.1. Microsphere trapped in standing wave potential

Using the SBT, a microsphere is trapped nearby the laser focus, so the microprobe can be moved to an arbitrary position by the movement of the laser focus. Figure 1 (a) shows dynamic properties of a dielectric microsphere that is optically trapped on an optical axis. The axial trapping force F_t is generated as the resultant of radiation forces such as f_{A1}, f_{A2} and f_{B1}, f_{B2}. Steep gradient of optical potential generated by the focused laser light confines the particle nearby the laser focus by the dynamical balance between the axial trapping force F_t and the forces of gravity F_g. The force curve for F_t along the optical axis is obtained as indicated in Fig. 1 (a). Based on the force curve, giving a shift of Δz along the optical axis, the microsphere is accelerated by the



(a) (b)

Fig. 1. Optically trapped microprobe; (a) Single-beam gradient-force optical trap of a microsphere, (b) Optically trapped microsphere using a single beam focused by using an objective (NA0.80, WD=3.4 mm) in air.



(a) (b)

Fig. 2. Formation of a standing wave pattern; (a) Schematic diagram of SWS and SWT force in the vicinity of the surface generated by interference of retro-reflected light and incident light through a microsphere, (b) Optically trapped microprobe approaching to a surface.

restoring force F_{SBT} and shifts Δz to the balance point along with the optical axis. F_{SBT} for a small Δz is given by

$$F_{SBT} = -k_{SBT}\Delta z \tag{1}$$

where k_{SBT} is the spring constant in the axial direction. As shown in Fig. 1 (b), we employ an optically trapped silica particle with the diameter of 8 μm as a probe. When the surface is laid on the optical axis shown in Fig. 2 (a), the incident light passing through an optically trapped microsphere and the retro-reflected light undergo interference and give rise to a standing wave along with the optical axis. Figure 2 (b) shows the microprobe approaching to a surface. The intensity of the standing wave field along optical axis $I(z)$ is obtained

$$I(z) = I_0\left[1+\alpha\cos(4\pi z/\lambda)\right] \tag{2}$$

where, I_o is the average intensity and λ is the wavelength of the incident laser and α is a value regarding to the reflective property of the surface. The standing wave pattern with a period of $\lambda/2$ in the vicinity of the surface performs as the fiduciary length scale. The origin of the scale is fixed on the surface precisely, and the optically trapped microsphere acts as a sensing probe that enables us to read the SWS.

Once an SBT microsphere is in a standing wave potential, it is acted upon by a weak force by the SWS. The microsphere is trapped at the position of maximum intensity of the standing wave field that is called standing wave trap (SWT). The displacement of the particle from the focus is assumed as Δz, then the restoring force F_{SBT} for a small Δz exerted on the particle is given by

$$F_{SWT} = F_{SWT(\max)}\sin(4\pi\Delta z/\lambda) \tag{3}$$

where $F_{SWT(\max)}$ is amplitude of the variable F_{SBT} depending on the reflective index of a surface and the laser power.

2.2. Principle of profile measurement using SWS

Sensing the SWS, the displacement of a measured surface is converted into a repetitive motion of a microprobe. It can measure the surface displacement along the optical axis by counting the divisions of the SWS as depicted in Fig. 3. An axial position of the microsphere is governed by the forces of F_{SBT} and F_{SWT}. When it is near to the focus, F_{SBT} is smaller than F_{SWT} due to the small Δz which indicates the distance between the focus and the center of the microsphere along optical axis. As the measured surface moves, F_{SBT} increases with increasing of Δz. When F_{SBT} grows over F_{SWT}, the microsphere is driven and abruptly changes the axial position from the position of maximum intensity of the standing wave field to the next one. Such the displacement of the microsphere is measured as the probe displacement signal. The period of the signal corresponds to the SWS pitch of $z_{\mathrm{pitch}} = \lambda/2$. A periodic, sawtooth-shaped signal is obtained by sensing the displacement of the microsphere as illustrated in Fig. 3.

2.3. Interpolation and self-calibration method of SWS

In the conventional method, the measurement resolution of the SWS is limited to half wavelength, so that small displacement such as the surface with a small curvature could not be measured. In addition, the probe displacement signal is not linearly related to surface displacement. Then the interpolation as well as self-calibration of the SWS is attempted. Since the position of the trapped microsphere can be well simulated by using the extended Mie-scattering theory [5], the self-calibration algorithm is developed based on a numerical model. Therefore accurate and precise position measurement of the trapped microsphere is crucial to the interpolation of the SWS.

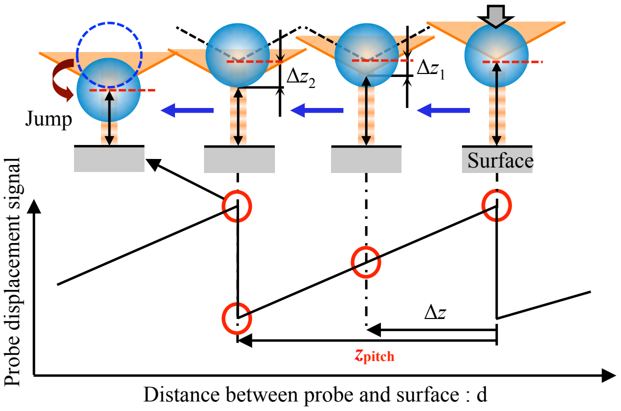


Fig. 3. Probe displacement signal by detecting the standing wave scale using the microprobe.

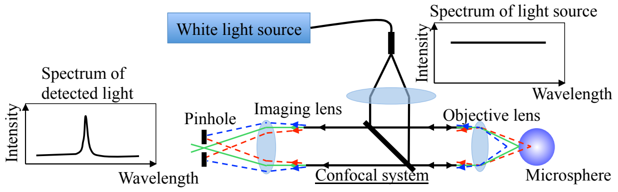


Fig. 4. Principle of chromatic confocal system for position measurement of the trapped microsphere.

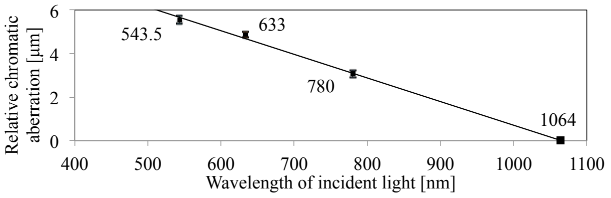


Fig. 5. Relative chromatic aberrations of the lasers with the wavelengths of 543.5nm, 633nm, 780nm, and 1064nm.

3. CHROMATIC CONFOCAL SYSTEM

3.1. Principle of position measurement of microsphere

To accomplish the resolution of more 10 times finer than the SWS, the position of the trapped microsphere should be measured with the resolution of better than 20 nm. Therefore the position measurement method of the trapped microsphere is needed the measuring range from -0.99 μm to 1.27 μm from the beam waist and the resolution of better than 20 nm. In order to meet our requirements the measurement using a chromatic confocal system [6] is achieved by using white light as the light source as shown in Fig. 4. In this method the position of a microsphere can be measured corresponding to the wavelength, and this method also has the advantage of less influence of stray light. It is needed to investigate the required wavelength range of the white light source. When the lasers with the wavelengths of 1064 nm (trapping laser), 543 nm, 633 nm, and 780 nm are collimated and incident an objective, chromatic aberrations from the relative focused position to the case of 1064 nm are indicated in Fig. 5. The result shows that the chromatic aberration changes linearly to wavelength, and the sensitivity is 11 nm/nm (chromatic aberration / wavelength). Considering the required measuring range and the distance from the beam waist of the focused laser, the required range of wavelength is determined from 570 to 785 nm.

3.2. Fundamental properties of chromatic confocal system

The measurement system integrating the chromatic confocal system into the laser trapping optical system was constructed as shown in Fig. 6. The white light is focused by an objective O_1 on the pinhole (25 µm), and after collimation the light is focused by an objective O_2 on the sample. Sample is driven by a piezo-electric stage in the direction of the optical axis. The reflected light from the sample passes O_2 and H_1, and is separated to observation part and detection part by beam splitter B_1. In the detection part, the light focused on the fiber with the core diameter of 50 µm to enter a spectroscopy. The stage was moved with step size of 200 nm, and the spectrums were acquired on each stage position. In each spectrum the wavelengths of 550 nm, 650 nm, 750 nm, and 850 nm were extracted, and the changes of intensity with each stage position were investigated as shown in Fig. 7. Each the full width half maximum (FWHM) of the intensity change for four wavelengths is 2.89 µm, 2.70 µm, 2.52 µm, and 2.43 µm respectively. Theoretically the FWHM (d) of the intensity change with the pinhole radius (a) is given by the following equation,

$$d = \frac{a\sqrt{2}}{M \times NA}$$

(4) where M is the magnification. In this case, the theoretical FWHM is calculated as 2.48 µm, which is good agreement with the FWHMs from the experiment.

To evaluate the measurement resolution of the iSWS, the displacement of a microsphere with the diameter of 8 µm on a glass substrate is measured, which was moved 200 nm with the step size of 10 nm using the stage. Fig. 8 indicates the relationship between the given displacement and the analyzed wavelength using the confocal system. Nevertheless some fluctuations, the measurement system is proved to measure the position of the microsphere using the iSWS with the resolution of 20 nm. Moreover, the measuring range of the iSWS was confirmed by moving the stage with the step size of 100 nm. Fig. 9 shows that the chromatic confocal system could measure the displacement of the microsphere with the measuring range of 2.1 µm.

4. NANO-PROFILE MEASUREMENT

4.1. Measurement method with scanning microprobe

A microprobe is scanned above a surface horizontally, as the distance between a microprobe and the surface is varied according to the surface topography. Fig. 10 shows the schematic diagram of the scanning measurement procedure. A distance between the probe position and the focusing-point position of z_p can be measured using an SBT microsphere. The interferogram is obtained by scanning the probe. The distance z_p is converted into the distance between the work surface and the focusing-point position of z_s based on the calibrated iSWS. Thus, the surface profile is reconstructed by the measured interferogram. In scanning mode, the profile of the work surface was measured by recording the X-coordinates where the microprobe detects

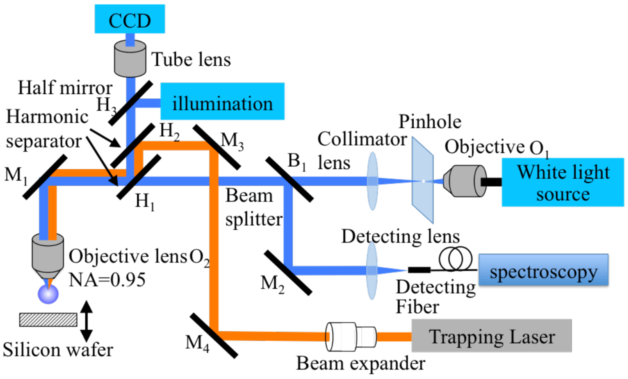


Fig. 6. The schematic of the chromatic confocal system combined with laser trapping..

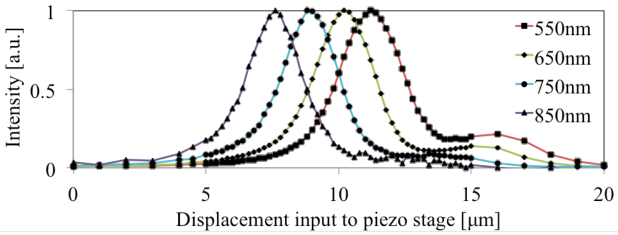


Fig. 7. Intensity distribution with displacement input to piezo stage.

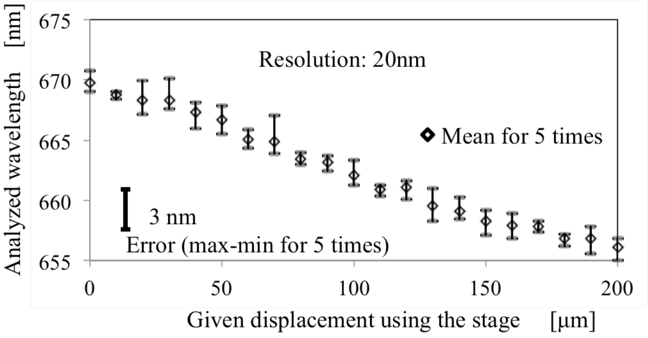


Fig. 8. The result of position measurement of the microsphere for inspecting the resolution.

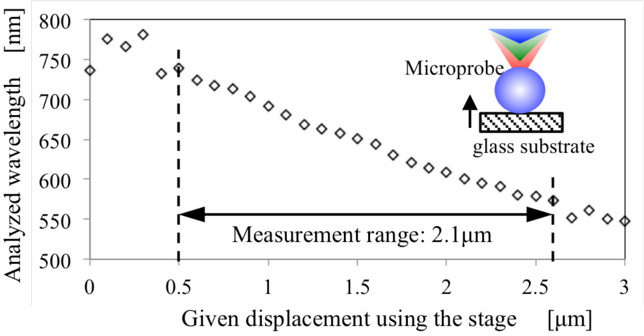


Fig. 9. The result of position measurement of the microsphere for inspecting the measurement range.

across the each division of the iSWS. Z-coordinates of the detected points were coordinated by transferred distance of the precise motion of the stage system.

4.2. Fundamental measurement of a tilted smooth surface

In order to verify the validity of the proposed scanning measurement procedure based on iSWS detected by the probe, the measurement property on the tilted smooth surface is investigated. Fig. 11 shows the measurement results of a tilted Si wafer surface. The microprobe is scanned at about 14 µm away from a silicon wafer surface tilted 9 degree at the scan length of 100 µm. As indicated in Fig. 11 (a), the interferogram could be obtained with the constantly increasing displacement. The measurement results of the displacement using both of SWS and iSWS are shown in Fig.11 (b). The measured displacements with SWS and iSWS are matched in the high precision. The standard deviation of 60nm is evaluated with the error distribution of the scanning measurement from linear approximation as shown in Fig. 11 (c).

4.3. Measurement of a glass small lens surface

In order to verify the validity of the chromatic confocal system for profile measurements with the iSWS, we conducted to measure a glass small lens with spherical surface by scanning a optically trapped microprobe. The glass small lens with the diameter of 2.0 mm and the curvature of 2.57 mm was used as the measurement work.

After trapping a microsphere (Φ 8 µm), the glass small lens was moved more than 500 µm along X-axis with the step size of 10 µm using the stage which is automatically controlled. The microprobe was relatively scanned above the surface of the glass small lens. The position of the microprobe over the measurement range of 2.1 µm was adjusted using the stage displacement in the z-direction.

The measured results are shown in Fig. 12. The measured points are fitted to a regression circle. The maximum deviation between a measured point and the regression circle was 719 nm. Beside the standard deviation for all measured points was 132 nm, the standard deviation was evaluated 54 nm for measured points around the top of the surface. Therefore, the nono-profile measurement of the glass small lens surface based on the iSWS was performed successfully by scanning an optically trapped microprobe which is improved with chromatic confocal measurement method as well as self-calibration of the SWS.

5. CONCLUSIONS

To improve the resolution of the profile measurement based on SWS by scanning an optically trapped microprobe, the interpolation method of the SWS was proposed. Accurate and precise displacement measurement of the microsphere was crucial to the iSWS. So the required specifications of displacement measurement of the optically trapped microsphere were confirmed. The chromatic confocal system was proposed as the appropriate measuring method of displacement. To inspect the specifications of the chromatic confocal system, position measurement was carried out. The measurement result shows the constructed system was confirmed to measure a microsphere on a glass

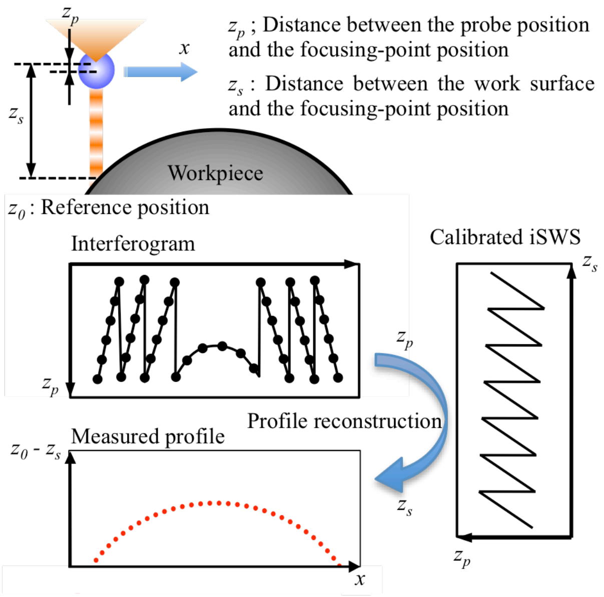


Fig. 10. The scanning measurement procedure and measured data interpretation based on the calibrated iSWS.

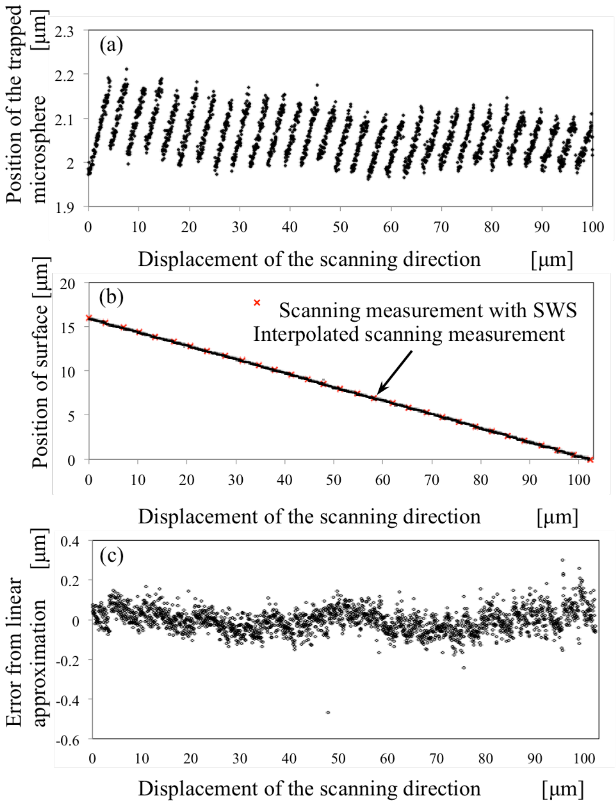


Fig. 11. The scanning measurement of the tilted Si wafer surface. (a) The result of the position measurement of the microprobe, (b) The results of the scanning measurement using both of SWS and iSWS, (c) Error distribution of the scanning measurement from linear approximation.

substrate with better than 10-nm resolution and larger than 5-μm range.

The feasibility of the proposed scanning measurement procedure based on iSWS is investigated by the fundamental measurement of the tilted smooth surface. The standard deviation of 60nm is evaluated with the error distribution of the scanning measurement from linear approximation. In order to verify the validity of the proposed method with the iSWS, the measurement of a glass small lens with spherical surface was conducted by scanning a optically trapped microprobe. These measurement results proved that the performance of the improved nano-profile measurement technique based on the iSWS meets the desired specifications.

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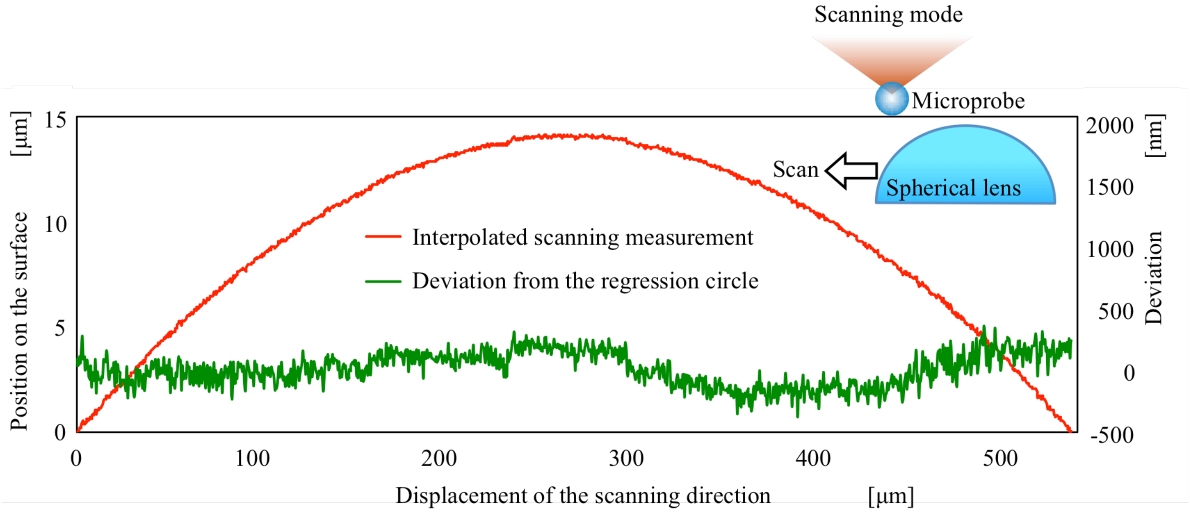

Figure 12. The scanning measurement of a small glass lens surface. (a) The measurement result of a surface profile using the interpolated SWS detected by the chromatic confocal system, (b) Deviation of the scanning measurement from the regression circle.