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THE FDTD ANALYSIS FOR DARK FIELD IN-PROCESS DEPTH MEASUREMENTS OF FINE MICROGROOVES

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Abstract – Microstructures are widely used in the manufacture of functional surfaces. An optical-based in-process and non-invasive method is preferred for the depth measurement of the fine microgroove structure. A dark-field method is proposed using the features of polarization based on the waveguide theory. According to the numerical simulation based on the FDTD method and Fourier optics, the proposed method allows depth measurement for fine microgroove having an aperture size of less than several hundred nanometers with an aspect ratio (width/depth) of larger than one, even under the far-field measurement.

Keywords: Depth measurement, FDTD, Dark-field, Microgroove

1. INTRODUCTION

Recently, functional microstructured surfaces have increased industrial importance and expanded to new applications in the micromanufacturing field, such as micro-electro-mechanical systems, micro-opto-electro-mechanical systems, and so on [1]. A typical fundamental element is the microgroove structure. The microgroove having an aperture size of less than several hundred nanometers with an aspect ratio (width/depth) of larger than one is playing an essential role as the critical element in applications such as micro U-shape cavities for microstructured optical sensors [2], anti-reflection coating to further reduce the reflectance [3], and microfluidic systems for integration of biological detection and sample pre-preparation on one chip [4]. The inspection of manufactured microstructures is necessary for the correct functioning of the functional surfaces. Though it is more difficult to measure depth for in-process and non-invasive optical methods, precise depth measurement is indispensable [5].

In the in-process inspection process for microstructured surfaces, conventional depth measurement is shown in Fig. 1, which uses interferometry based on phase change. This method has nanometer resolution in the depth direction. However, it cannot be generally applied to the microgrooves, the width of which is less than about half of the wavelength due to low lateral resolution problems caused by the optical diffraction limit. The diffraction limit causes the near-field phase contrast to worsen in the far-field due to the point-spread function. Moreover, since the bottom reflection is always weaker than the surface, the obtained signal-to-noise ratio for depth measurement needs to be improved.

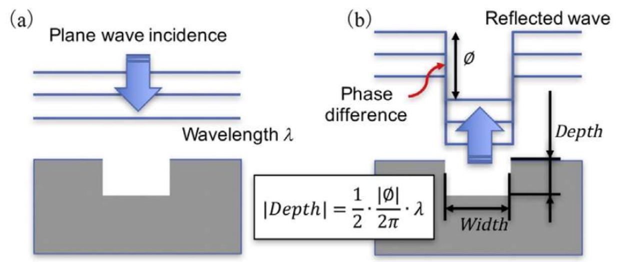

Fig. 1. Basic principle of conventional optical depth measurement based, on phase change. (a) Incident wave, (b) Reflected wave, phase of which is changed by surface profile.

Hence, the purpose of this research is to develop a novel optical depth measurement method, having the potential for an in-process depth evaluation of microgrooves, the width of which is less than half of the wavelength, with an aspect ratio larger than one. The dark-field method is selected since it has the potential to overcome the phase contrast worsen problem by enhancing the signal of bottom reflection. The Finite-Difference Time-Domain method (FDTD) is applied for theoretical analysis.

2. PROPOSAL OF DARK-FIELD DEPTH MEASUREMENT

A dark-field observation method is proposed to get a better signal-to-noise ratio from the bottom reflected light of the microgroove. The FDTD analysis is set for a single microgroove, and Fourier optics is used to simulate the dark-field observation in the near-field. Based on the near-field simulation results, the far-field imaging is calculated to simulate the dark-field observation. The polarization effects are discussed, and the physical mechanism is explained by waveguide theory. Based on the revealed facts, a novel depth measurement method is proposed.

2.1. Dark-field method

Figure 2 shows the dark-field observation method with an oblique incident light source. The lens is put above the microgroove to collect the diffracted light while the reflection

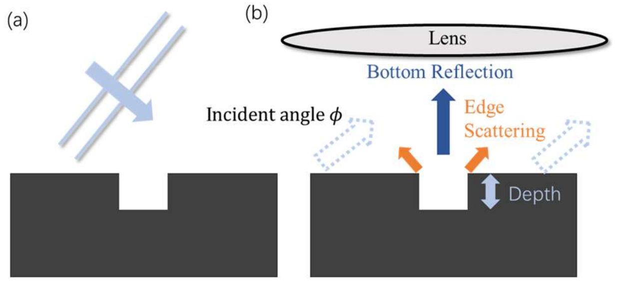

Fig. 2. Dark-field observation (a) Incident wave, (b) Bottom reflection and edge scattering can be isolated from incident light and direct reflection.

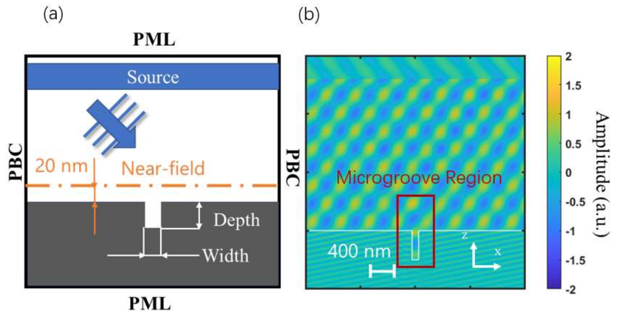

Fig. 3. (a) FDTD model of microgroove (b) Amplitude distribution.

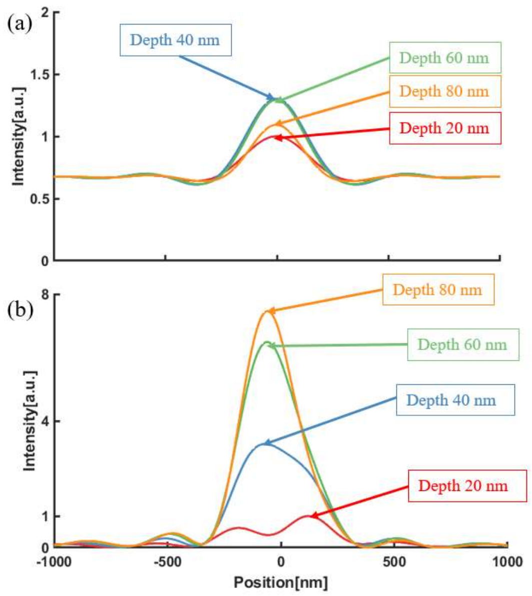

Fig. 4. The imaging intensity from simulation for (a) conventional interferometry and (b) dark-field observation. The intensity is normalized by dividing the peak intensity of 20 nm depth.

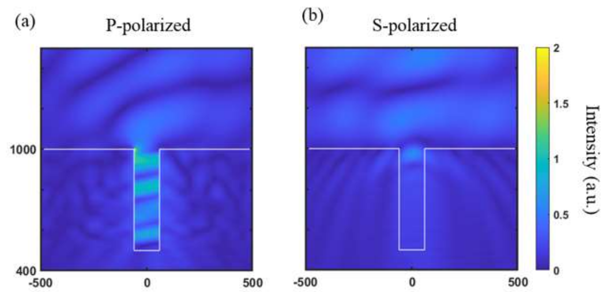

Fig. 5. Intensity distribution of microgroove region after applying the Fourier transform to cutoff the incident light and its reflection for (a) P-polarized case (b) S-polarized case.

of flat surfaces is not collected. The diffracted light includes reflection from the microgroove edge and bottom. This method can isolate these components from the incident light and its reflection.

2.2. Setup of FDTD analysis

The FDTD analysis is going to simulate the dark-field observation by setting the oblique incidence and its reflection on a single microgroove with its width smaller than half of the wavelength. The model is built with a microgroove set at the center with depth and width variance in Figure 3(a). The software used is Poynting developed by Fujitsu. The wavelength is set to be 400 nm, and Periodic Boundary Condition (PBC) is set in x-direction and y-direction, and Perfect Matched Layer (PML) absorption boundary condition is set in the z-direction. The light source is set beyond the microgroove while keeping enough spacing, and the incident angle is fixed to be 50 $degrees$. The simulation is conducted in two polarization, the P-polarized (amplitude in the x-direction) and S-polarized (amplitude in the y-direction) cases. The material of the microgroove is silicon. And the near-field is set to be 20 nm above the surface. One example of microgroove width 120 nm and depth 500 nm is shown for the P-polarized light component. The microgroove region is where the electric field distribution is affected by microgroove width and depth.

2.3. Optical response under dark-field observation

Since it is not applicable to simulate large regions due to the computational cost in FDTD, only the near-field region around the device can be modeled. In order to simulate the dark-field observation, Fourier optics is applied. The diffraction at the back focal plane after a lens is the same as Fraunhofer diffraction. The imaging process of a lens is similar to the convolution of the incident light intensity and the point spread function (PSF). In the frequency domain, the incident angle information is included. A special OTF can be used as a filter with unit value except frequency corresponds to incident angle to eliminate the light component with the same direction of incident light and the light component of reflected light with the same angle but reversive direction [6].

Then, an example for the far-field imaging intensity is plotted in Fig. 4. The microgroove width is 120 nm. The intensity above the microgroove region changes while the microgroove depth changes. The blurred distribution is due to the PSF. Then intensity change is normalized by dividing the peak intensity of 20 nm depth for two cases, respectively. It is found that the intensity change is more sensitive in dark-field observation than in conventional interferometry. The maximum change in intensity according to depth variation is about five times larger (taking 20 nm line peak intensity as 1, the depth 40 nm line peak has reached almost 1.5 for conventional interferometry, but the depth 80 nm line peak has reached almost 8 for dark-field observation) in the proposed method.

2.4. Effect of polarization

The polarization affects the interaction of light and microgroove. An example is shown in Fig. 5 after applying the Fourier transform to cutoff incident light and direct reflection. The width of the microgroove is $120\ nm$, smaller than half of the wavelength ($200\ nm$). When the depth is $500\ nm$, P-polarized light can touch the bottom of the microgroove while S-polarized light does not go into the microgroove. Only the edge region of the microgroove interacts with S-polarized light. The waveguide theory can explain the physical mechanism.

A planar waveguide consists of two cladding and one core material, where the core has a higher refractive index. Light or electromagnetic waves can propagate along the waveguide with slight loss due to total reflection inside the waveguide. And the propagation follows modes, which give unique distribution in the cross-section according to the wavelength and width of the waveguide. Though the microgroove is a waveguide with a core refractive index lower than its cladding, it follows the leaky mode, which is similar to the waveguide mode. [7] Then, according to the mode of TM and TE waves in a regular waveguide, which corresponds to the P-polarized and S-polarized cases, when the width of the waveguide is smaller than half of the wavelength, only TM mode (P-polarization) can propagate. The cutoff frequency for TE and TM is shown in equation 1.

$$f_c = \frac{m}{2d\sqrt{\mu\epsilon}} \tag{1}$$

where m is the mode number, d is the waveguide width, and μ and ϵ are electric constants.

The mode number $m = 0,1,2,3 \ldots$ is for TM mode, and $m = 1,2,3 \ldots$ is for TE mode. The TE mode has a minimum cutoff frequency so that the TE wave (S-polarization) can not propagate in a very thin waveguide.

Moreover, vertical standing-wave is confirmed in the P-polarized case, where light with direction different from the incident angle touch the bottom of microgroove and reflected to form this standing-wave. It is expected that this electric field can retrieve the depth information.

2.5. Depth measurement with the dark-field method

As summarized below, we have seen the advantages and features of dark-field observation.

1. The intensity retrieved from a single microgroove is more sensitive in this dark-field observation comparing to the conventional perpendicular interferometer.
2. The P and S polarized light shows different behavior when interacting with the microgroove, which has a width smaller than half of the wavelength. The P-polarized light can reach the bottom of the microgroove, while the S-polarized light only interacts with the edge of the microgroove.

Since the phase to depth calculation always needs a reference surface, which provides the reference phase, it is expected that the polarization characteristics can be used for depth measurement of a single microgroove. The S-polarized light would have a phase that does not change with depth, while the P-polarized light would have a phase that changes with depth. By utilizing this feature, subtraction of P-phase with S-phase would give a phase change that corresponds to the depth. What's more, this approach is experimentally available by introducing a circularly polarized light source and two kinds of polarizers putting above the microgroove.

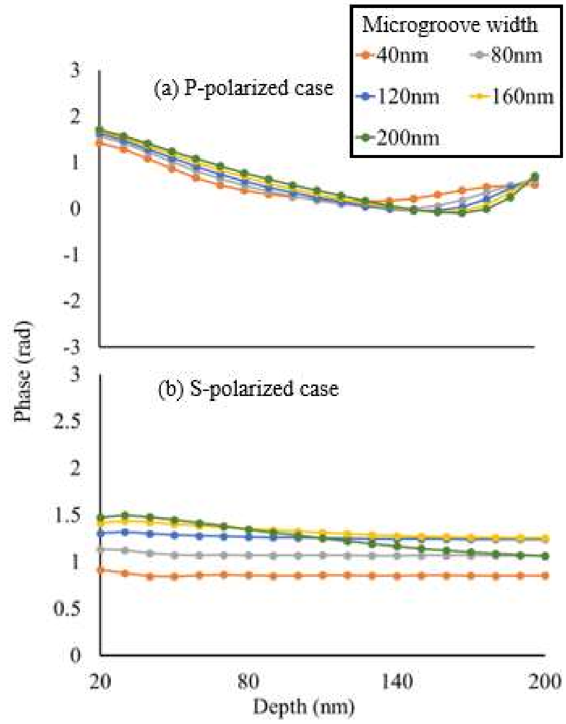

Fig. 6. Phase-depth relation in dark-field observation for (a) P-polarized light component (b) S-polarized light component.

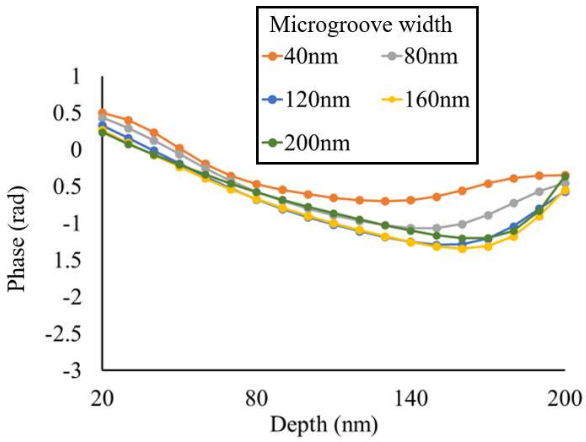

Fig. 7. The relative phase and depth relation by subtraction S-phase from P-phase.

3. NUMERICAL VERIFICATION

The phase is extracted from simulation along the near-field line, and the far-field phase is calculated by convolution with PSF, and the NA is set to be 0.9. The value of phase is sampled at the point above the center of the microgroove. The effect of polarization, microgroove width, and microgroove depth on the far-field phase is investigated.

3.1. Phase-depth relation for P-polarized case

According to the waveguide theory, the P-polarized light can go into the microgroove without limited by width. In the dark-observation simulation, the phase of P-polarized light and depth relation is plotted in Fig. 6 (a). A depth dependency of the P-phase is confirmed. However, this dependency deviates from linearity when the depth increases.

3.2. Phase-depth relation for S-polarized case

According to the waveguide theory, the S-polarized light can not go into the microgroove because its mode is limited by width. In the dark-observation simulation, the phase of S-polarized light and depth relation is plotted in Fig. 6 (b). The S-phase does not depend on the depth variation for width smaller than half of the wavelength, except for the case that width is the same as the wavelength ($200\ nm$). This result indicates that S-polarized light can be taken as the reference to determine the relative phase change for depth measurement.

3.3. Phase and Relative phase relation

Subtraction of P-phase value with S-phase value has shown an almost linear phase change that corresponds to the depth in Fig. 7. The best result of $40\ nm$ width line shows depth dependency upon $120\ nm$ depth, which reaches the aspect ratio of three. And the worst result of $200\ nm$ width shows depth dependency upon $170\ nm$ depth, which almost reaches the aspect ratio of one.

Under the premise of knowing the width of the microgroove, it is expected that this approach can measure the depth in a specific range corresponding to the width.

4. CONCLUSIONS

A dark-field observation method is proposed for nanometer-level depth measurement of the microgroove having an aperture size of less than half of the wavelength with an aspect ratio (width/depth) of larger than one.

The results obtained by FDTD analysis in this paper are summarized as follows:

1. The simulation confirms the waveguide theory that explains the interaction of the electromagnetic field with microgroove with its width smaller than half of the wavelength. This fact suggests that optical response can also propagate in the normal direction even under oblique incidence.
2. A dark-field method is proposed using the features of polarization based on the waveguide theory. S-polarized light mainly includes the edge reflection component, while P-polarized light mainly includes the bottom reflection of fine microgroove. Using S-phase as a reference, the phase change of P polarization can retrieve the depth information in the far-field with dark-field observation.
3. According to the numerical simulation based on the FDTD method and Fourier optics, the relative phase change obtained by the proposed method shows an almost linear depth dependency, which means that this method allows depth measurement for fine microgroove with width smaller than half of the wavelength even under the far-field measurement.

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