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Optical Depth Measurement for Microgrooves: A Self-interferometry Method based on Near-field Polarization Analysis

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The subwavelength microgrooves have been widely applied to functional surfaces with microstructures. Inspection a nd measurement of microgroove depth are highly demanded to ensure the correct functions of microstructures. Tra ditional optical methods such as interferometry are non-invasive and have high throughput but are limited by the diffraction limit. It is hard to obtain depth-related information for microgroove which has a width smaller than th e diffraction limit.
In this research, we conducted numerical simulation by RCWA and found that the TM polarized light can retrieve the depth information under oblique illumination for diffraction-limited microgroove, while TE polarized light has less depth dependency. We propose a dark-field method to retrieve phase information on periodic microgrooves sur face by interfering TE and TM polarized light, naming as a self-interferometry method. The phase difference betwe en the two polarization states is almost linearly related to microgroove depth. In this method, interference light ha s the same optical path so that measurement is stable against environmental disturbances. Moreover, the dark-field method ensures that strong direct reflection on the top surface would not blur depth-related phase information. A n optical system was proposed to retrieve the phase difference between two polarization states.
Through numerical experiments, quantitative depth measurement is found available by the self-interferometry for pe riodic microgrooves that have width smaller than half of the wavelength. The depth measurement considered to be impossible in traditional interferometry has been achieved by the proposed self-interferometry.

1. Introduction

The microgroove is a fundamental structure for functional surfaces. Micro-optomechanical resonators [1], and Micro U-shape cavities for micro-structured optical sensors [2] are optical functional surfaces of which the shape decided its optical response and quality of functions.

Optical depth measurement is a fast and non-invasive method that is highly demanded in inspection and measurement. The measurement of microgroove depth would assure the correct functioning of the functional surfaces. The periodic structure of microgrooves is shown in figure 1. Traditional interferometry can get the phase difference between microgroove bottom and top surfaces for depth measurement. However, It is difficult to measure the microgroove which has its width smaller than the diffraction limit (which is also called the diffraction-limited microgroove) [3]. The reason is that the phase information of depth has been blurred because strong direct reflection on the top surface of microgrooves lowers the Signal to Noise ratio of bottom surface reflected light in diffraction limited microgrooves.

In previous research, the interaction of diffraction limited microgrooves (also called the subwavelength gratings) with polarized light has been studied and the polarization-dependent response has been observed [4]. Studies for light interaction with diffraction limited microgrooves have been conducted to study the reflected phase for depth measurement [5]. It was found that for diffraction-limited microgroove, the TM polarized light can retrieve the depth information even under oblique illumination. An almost linear relationship between TM phase and depth was obtained by numerical simulation for microgroove has width smaller than half of the wavelength because it reached the single-mode condition of the slab waveguide, while TE phase was independent with depth in this case because TE light cannot propagate to the bottom surface of microgroove due to the waveguide theory. This result suggested that the depth measurement of diffraction limited microgrooves was available under oblique illumination.

The previously mentioned problem of phase blur can be solved by dark-field observation: the reflection from the top surface of the microgroove is not collected by microscopy under oblique illumination, while the bottom reflection can propagate perpendicularly and be collected by microscopy. Therefore, a dark-field depth measurement method has been proposed that the phase of TM can measure the depth of the microgroove by taking the TE phase as a reference [6].

In this research, we firstly conducted Rigorous coupled-wave analysis (RCWA) to confirm the polarization characteristic of microgroove interaction with oblique incidence with shape variation of microgrooves. In the previous study, the Finite-difference time-domain (FDTD) has been applied for discrete shape variation [5]. Since RCWA is much faster, the phase-depth relation of diffraction limited microgrooves is comprehensively studied with continuous shape variation. Secondly, a dark-field system is proposed to retrieve phase information on periodic microgrooves surface by interfering with TE and TM polarized light, naming as a self-interferometry

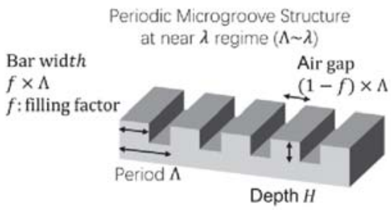

Fig. 1 Periodic microgroove structure is the fundamental element of function surfaces. The diffraction limited microgroove has its width smaller than the diffraction limit of the optical system for measurement.

method. Finally, far-field observation simulation is conducted to confirm the availability of depth measurement for diffraction-limited microgrooves using the proposed self-interferometry.

2. Near-field polarization analysis

2.1 RCWA simulation

Near-field phase analysis is conducted by RCWA. Parameters for simulation are summarized in table 1. A continuous parameter scan has been conducted for periodic microgrooves with different pitch sizes and depths under two polarization states. The microgrooves are sub-wavelength, and their width (half of the pitch size) is smaller than the diffraction limit. The phase variance of the reflected near-field electric field can be observed by setting the same phase reference plane when simulating microgrooves with different shapes. In a 2D parameter scan of pitch size and depth, the near-field phase shows depth dependency under TM illumination as shown in figure 2(a) while this dependency is weaker under TE illumination as shown in figure 2(b). Systematical results have been obtained in figure 2 compared to previous research based on FDTD.

2.2 Principle of near-field phase response

Results in figure 2 have shown TM polarization has a stronger depth dependency for almost all pitch size diffraction-limited microgrooves compared to the TE polarization case. To investigate how this result is consistent with previous research, a phase-depth relation is plotted in figure 3, taking pitch size 0.42 μm as an example. Theoretically, the reflected near-field phase increases linearly with depth and the phase-depth relation should almost follow perpendicular interferometry even under oblique incidence, for the TM case [5].

$$\phi = D/\lambda \times 4\pi \ \#(1)$$

Moreover, the slab waveguide theory indicates that the TE wave

Table 1. Parameters for numerical simulation

Parameters			Values
Source	Wavelength Incidence Angle Polarization		633 nm 50 degrees TM/TE
Materials	Background Microgroove		Air (n = 1.00) Silicon (n = 3.88 + 0.02i)
Shape	Fixed	Filling factor	0.5
	Variable	Pitch Depth	0.1 ~ 1 μm 0 ~ 1 μm
Imaging	Numerical Aperture Diffraction Limit		0.3 1055 nm

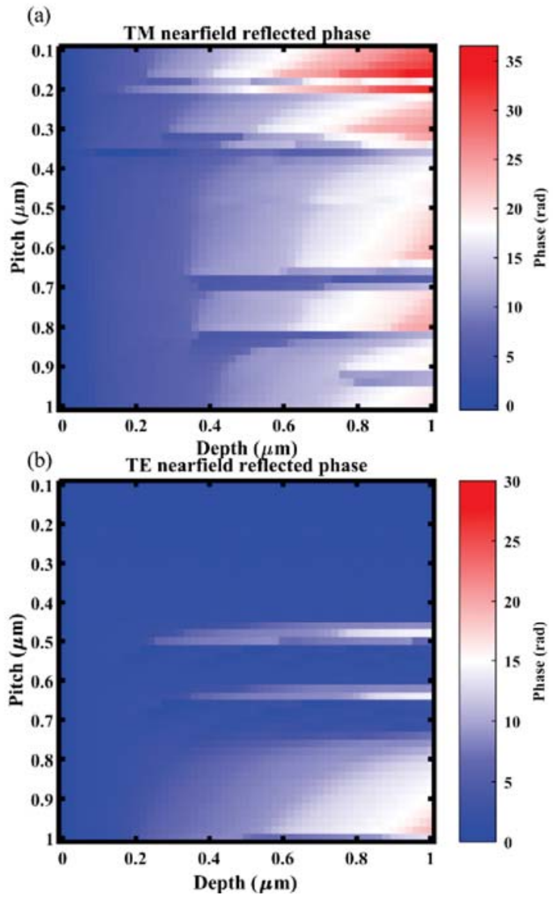

Fig. 2 RCWA 2D parameter scan for the near-field reflected electric field phase variation when changing the pitch and depth of periodic microgrooves, for (a) TM case and (b) TE case

has a cutoff condition that light can hardly go into the microgroove when the width is smaller than half of the wavelength. The theoretical cutoff condition is given by the following equation [6]. Therefore, the TE phase-depth relation has almost no dependency when the pitch size is smaller than the wavelength of 633 nm.

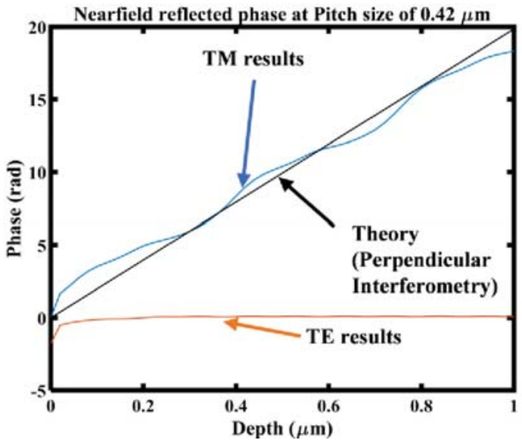

Fig. 3 Phase-depth relationship obtained from RCWA simulation for periodic microgrooves with pitch size of 0.42 μm. The result is consistent with previous found theory for TM and TE case [5] [6].

$$\lambda = 2 \times f \times \Lambda = \Lambda \#(2)$$

But the cutoff pitch size observed in figure 2(b) is smaller than the expected cutoff condition of 633 nm in waveguide theory. Further studies are needed on this phenomenon.

3. Proposal for self-interferometry method

To apply the polarization characteristic of microgrooves to metrology, special interferometry has been proposed. A dark-field system that interferes TE and TM polarized light is proposed to retrieve the phase difference between the two polarization states. This phase difference has depth dependency and can be utilized as a tool for depth measurement. Ideally, TM light brings the depth information following the equation (1), while the TE light has a stable phase that does not change with depth. The interference of TE and TM light can measure depth through their phase difference.

A self-interferometry method is illustrated in figure 4. The illumination light is polarized by an obliquely rotated linear polarizer so that both TE and TM polarization co-exist, and their intensity ratio can be modified by the polarizer angle. Then, the reflected light from the bottom surface of the periodic microgroove sample is collected by the objective lens. Before imaging onto a CCD camera, waveplates and a linear polarizer are located, applying the four-steps phase shift method to obtain the phase difference between two polarized reflections.

The detail of this four-step phase shift is discussed. Two waveplates are used to create combinations of phase shifts, and one linear polarizer rotated at 45 degrees interferes the phase-shifted TE and TM light just before the CCD camera. Two waveplates are one half-waveplate and one quarter-waveplate. The rotation of waveplates

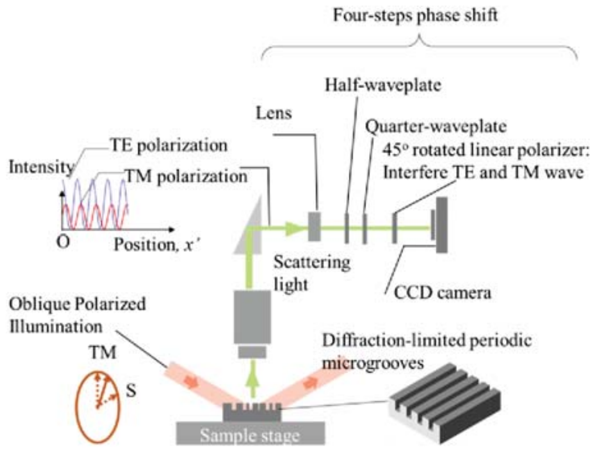

Fig. 4 Proposed dark-field self-interferometry. TE and TM polarized light reflected from diffraction-limited periodic microgrooves are imaged by CCD camera. Four-steps phase shift method is applied to get phase difference of two polarization state for depth measurement.

Table 2. Four-steps phase shift method to obtain TM and TE phase difference

Phase shift step	Waveplate rotation	Intensity
1	Half plate at 45° Quarter plate at 45°	$g_0(x) = \frac{1}{2}[a(x) + b(x)\cos(\phi(x))]$
2	Half plate at 45° Quarter plate at 0°	$g_1(x) = \frac{1}{2}\left[a(x) + b(x)\cos\left(\phi(x) + \frac{\pi}{2}\right)\right]$
3	Half plate at 45° Quarter plate at 90°	$g_2(x) = \frac{1}{2}[a(x) + b(x)\cos(\phi(x) + \pi)]$
4	Half plate at 0° Quarter plate at 45°	$g_3(x) = \frac{1}{2}\left[a(x) + b(x)\cos\left(\phi(x) + \frac{3\pi}{2}\right)\right]$

is calculated by the Jones matrix as shown in table 2. Then, the obtained intensity in four steps are g_0, g_1, g_2, and g_3. Finally, the phase difference can be calculated.

$$\phi = \arctan\left[\frac{g_3(x) - g_1(x)}{g_0(x) - g_2(x)}\right] \#(3)$$

4. Results of numerical experiments of self-interferometry

Far-field imaging simulation has been conducted based on near field complex electric field using the Fraunhofer approximation when the NA of the optical system is set to be 0.3. The 2D phase parameter scan has been obtained. Then, the phase difference between TE and TM polarization has been plotted in figure 5. It is found that the far-field phase difference has shown depth dependency for most microgrooves with small pitch sizes between 0.1 to 0.42 μm, except some discrete pitch size, while the diffraction limit is 1.055 μm.

Next, the far-field phase difference and depth relation are investigated compared to the perpendicular interferometry theory in equation (1). Results are plotted in figure 6, where the far-field reflected electric field phase difference between TE and TM light has an almost linear relationship for microgrooves having 0.1, 0.42, and 0.44 μm, for example. For pitch size of 0.1 and 0.42 μm, deviation of the phase difference and depth relationship has been observed compared to the theoretical value, but almost linear relationship has been obtained. It is the pitch size that mainly affects the deviation of the measured phase from theory. For 0.44 μm pitch size, the measurement becomes impossible since the phase difference and depth become independent, and the reason is that TE phase has depth dependent as shown in figure 2(b). This result suggests that the

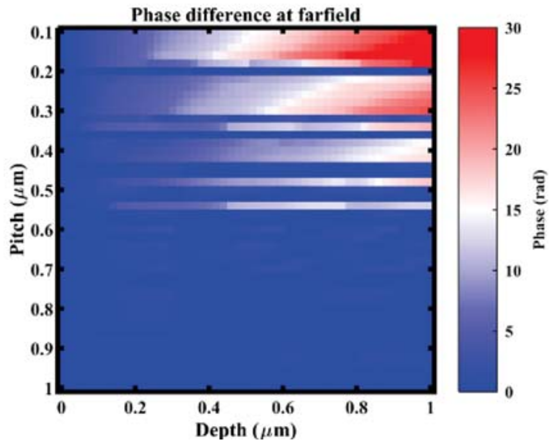

Fig 5. 2D parameter scan for the far-field reflected electric field phase difference between TE and TM light. The phase difference various when changing the pitch and depth of periodic microgrooves.

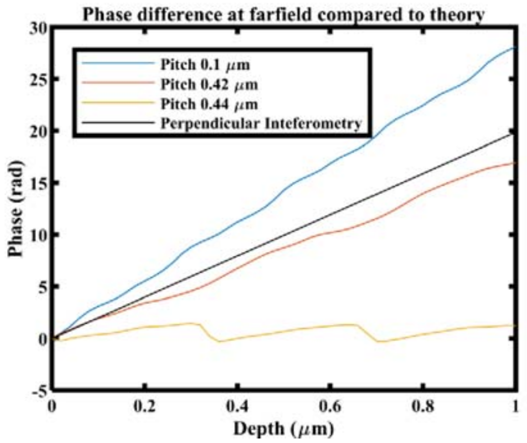

Fig 6. The far-field reflected electric field phase difference between TE and TM light has almost linear relationship, but deviation happens comparing to perpendicular interferometry.

proposed self-interferometry can determine the depth of microgrooves when the pitch size is predetermined, which is considered impossible due to the diffraction limit.

5. Conclusion

Firstly, RCWA analysis confirms the polarization characteristic of microgroove interaction with oblique incidence. The phase-depth relation of diffraction limited microgrooves is thoroughly studied with more shape variation of microgrooves. The pitch size and depth can also be divided by wavelength for dimensionless characterization. It is confirmed that TM light has phase response closely to the perpendicular interferometry even under oblique incidence, and TE light has nearly no depth dependency for microgroove with pitch size smaller than 0.46 μm.

Secondly, a dark-field system named self-interferometry is proposed to retrieve phase information on periodic microgrooves surfaces by interfering TE and TM polarized light. The advantage of this system is that its reference beam (TE light) has the same optical path with reflection containing the depth information (TM light). This system is stable against environmental disturbance. The four-steps phase shift method is introduced to retrieve the phase difference between two polarizations.

Finally, far-field observation simulation is conducted for diffraction-limited microgrooves using the proposed self-interferometry. It is found that the far-field phase difference changes almost linearly with depth for most microgrooves have pitch size in the range of 0.1 to 0.42 μm, which are much smaller than the diffraction limit of 1.055 μm,. The proposed self-interferometry can determine the depth of periodic microgrooves even they are diffract-limited and subwavelength. When the pitch size is predetermined by SEM or fabricated intentionally, the self-interferometry can be applied for the quantitative depth measurement.

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