THE FDTD ANALYSIS FOR DIFFRACTION LIMITED MICROGROOVE STRUCTURE WITH STANDING WAVE ILLUMINATION FOR THE REALIZATION OF COHERENT STRUCTURED ILLUMINATION MICROSCOPY*

Yizhao Guan[a], Masahiro Kume[a], Shotaro Kadoya[b] , Masaki Michihata[a] , Satoru Takahashi*[b]
[a]Department of Precision Engineering, The University of Tokyo, 7 Chome-3-1 Hongo, Bunkyo City, Tokyo, 113-8654, Japan
[b]RCAST, The University of Tokyo, 7 Chome-3-1 Hongo, Bunkyo City, Tokyo, 113-8654, Japan

Abstract

The optical-based super-resolution, non-invasive method is preferred for the inspection of surfaces with massive microstructures widely applied in functional surfaces. The Structured Illumination Microscopy (SIM) uses standing-wave illumination to reach optical super-resolution. Recently, coherent SIM is being studied. It can obtain both the super-resolved intensity distribution and the phase and amplitude distribution from the sample surface. By analysis of the phase-depth dependency, the depth measurement for microgroove structures with coherent SIM is expected. FDTD analysis is applied for observing the near-field response of microgroove narrower than the diffraction limit under the standing-wave illumination. The near-field phase shows depth dependency in this analysis.

Keywords: FDTD, Structured Illumination Microscopy, Depth Measurement

I Introduction

Microstructures fabricated among the surface of material provide specific functions such as antireflection coating and microfluidic systems. Subwavelength textured structures for antireflection coating reduces reflectance by providing the equivalent effect of infinite layers of antireflective thin films [1], while those structures can also construct microfluidic systems that have applications ranging from biology to energy [2]. Functional surfaces are constructed by arrangements of nanochannels, and the typical fundamental element is a microgroove, as shown in figure 1. The width and depth are minimizing to the scale of the nanometer so that the inspection requires measurement of both the width and depth of the microgroove structure. In optical super-resolution researches, many methods have been proposed for breaking the Rayleigh limit, and some are capable of the width measurement on the level of ~ 100 nm. The super-resolution for depth measurement at the same time is desirable but not available at this time. This study focuses on depth measurement with optical super-resolution methods.

The optical methods have the advantage of high throughput and non-invasiveness comparing to other methods such as Atomic Force Microscopy (AFM) and cross-section Scanning Electron Microscopy (SEM).

Structured illumination microscopy (SIM) is one of the developed optical super-resolution methods. SIM utilizes a structured light pattern. Typical illumination is the standing-wave illumination formed by two oblique monochrome incidences in opposite directions to form a Moiré pattern. The optical resolution is limited by the Numerical Aperture (NA). In the frequency domain that NA creates a cutoff area in the observable frequency region. It is mathematically possible to compute the unknown frequency content around the cutoff area through the SIM reconstruction algorithm [3]. Three times phase shifts (two more figures beside the original one) are necessary. The phase shift of incident light leads to the peak shift of the standing-wave in real space, and it provides more information near the initial cutoff area in

* takahashi@nanolab.t.u-tokyo.ac.jp; phone +81-3-5452-5187

the frequency domain. The illustration is in figure 2. As a result, the SIM can obtain a two-dimensional optical super-resolution. However, for super-resolution of both width and depth, an improvement should be developed for the SIM reconstruction algorithm to achieve three-dimensional super-resolution.

Moreover, the coherent SIM algorithm is under development recently, as shown in figure 3. Not only the intensity of response but also the phase and amplitude will be obtained with this new algorithm, compared to the previous incoherent SIM algorithm [4]. The principle of coherent SIM is explained. Since the coherent information can not be obtained directly from the Charge-Coupled Device (CCD), a reference light is introduced into SIM's illumination system to interfere with the scattering light from the sample. The images obtained with interference can calculate the phase of scattering light.

On the other hand, the interferometer utilizes the phase change of the reflected light from the sample surface to measure its depth. A similar principle may also be available in the case of standing-wave illumination based on coherent SIM. Therefore, it becomes indispensable to study the phase and microgroove depth relationship under standing-wave illumination. Finite-Difference Time-Domain method (FDTD) is applied.

II MODEL AND METHODOLOGY

The model is built with a microgroove set at the center with depth variance in figure 4. The software used is Poynting developed by Fujitsu. Periodic Boundary Condition (PBC) is set in the y-direction, and Perfect Matched Layer (PML) absorption boundary condition is set in the z-direction. The light source is set vertically to eliminate the boundary effects. Enough spacing above the microgroove let two oblique incident light form the standing-wave illumination continuously among the surface of the microgroove. It is found that when the microgroove width is smaller than the wavelength, the TE wave can not reach the bottom of the microgroove while TM wave can. Figure 5(a) shows that the electric wave goes into the microgroove. The reason can be explained by using the waveguide theory, and a model with infinity depth is built and analyzed in figure 5(b) for confirmation. The polarization of the light source is set in the x-direction. The material of the microgroove is silicon.

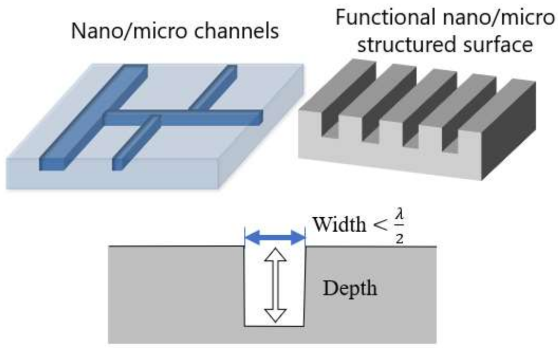


Figure 1: Functional surface with microgroove structure such as nanochannels, periodic structures, optical devices and so on.

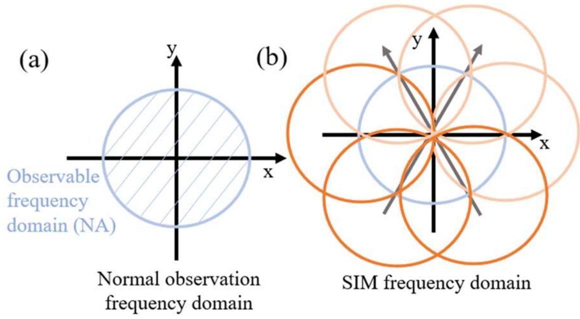


Figure 2: SIM enlarges the observable region (from (a) to (b)) in frequency domain to reach super-resolution by phase shift three times along one axis. For a two-dimensional super-resolution, shifts are done in three axes rotated $\frac{\pi}{3}$ rad here.

The phase is obtained at near-field by setting an observer line 20 nm above the surface. The endeavor should be made in further research to reconstruct near-field phase information from far-field phase and amplitude in practical application. According to the perpendicular illumination interferometer, Ye. etc., has established far-field based near-field reconstruction depth measurement (FNRDM) [5].

A typical phase and intensity for standing-wave obtained from the observer in the x-direction are shown in figure 6. The microgroove is illuminated by light with this unique characteristic, and its phase change introduced by depth change is the key to the development of optical nanoscale depth measurement. Phase-depth dependency has been investigated.

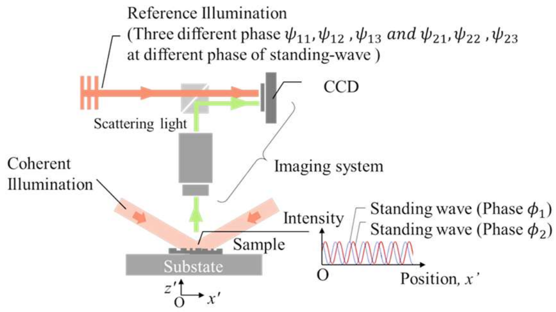
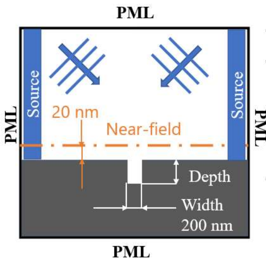


Figure 3: Concept of coherent SIM with standing-wave illumination shift [4].



Parameters	
Wavelength	500 nm
Cell Size	5 nm $(x) \times 5nm$ $(y) \times 5$ nm (z)
Refraction Index	$5.4376 + 0.0079i$
Observation line	$y = 0, z = 1020$ nm

Figure 4: Set up and parameters for FDTD analysis.

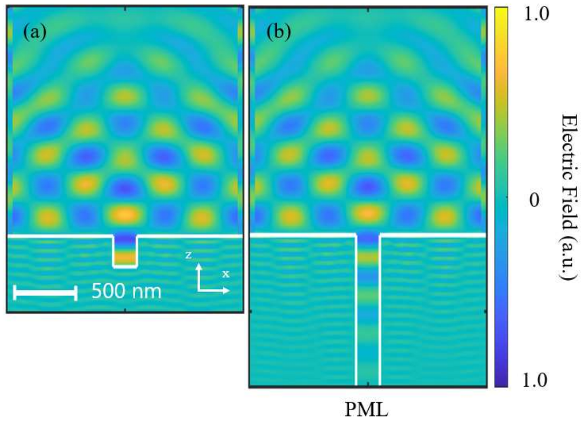


Figure 5: Electric field of (a) microgroove model under standing-wave illumination. (b) infinity depth microgroove model using perfectly matched layer boundary condition.

III Results and Discussion

Firstly, the electric field distribution shows that the standing-wave exists in both x and z-direction. It is the x-components of two oblique incidences form the standing-wave in the x-direction. The incidence and reflection propagate in opposite directions forming the standing-wave in the z-direction. The constructive interference forms peaks while the destructive interference forms nodes.

Secondly, the phase of optical response from flat silicon is plotted in figure 7(a), where the standing-wave like behaviors of the phase is confirmed. The sampling point is selected at the center of the microgroove. A microgroove depth dependency is observed in figure 7(b), where phase changes monotonically with depth.

Thirdly, the incident angle has been swept for standing-wave. Analysis indicates that the depth and relative phase change relationship becomes independent with the incident angle, as shown in figure 8. This linear relationship is similar to the case with the perpendicular illumination interferometry, which follows equation 1.

$$\text{Depth} = \frac{\lambda}{2} \times \left(\frac{\theta_n}{2\pi} + k\right) \tag{1}$$

Where θ_n is the phase difference, and k is an integer.

When the depth goes deeper, the phase response stops to show depth dependency. In the case of incidence of 70 degrees, the detectable range is 200 nm depth, in the case of incidence of 50 degrees, the detectable range is 480 nm, and in the case of incidence of 30 degrees, the detectable range is 760 nm.

The waveguide theory can explain that the phase response of different incident angles follows the same theory as the perpendicular interferometry. Light is confined between two vertical walls. In slab waveguide, TM mode has no cutoff frequency, while TE mode has. Only TM0 mode can exist in slab width smaller than half of the wavelength, while TM1 and TE1 mode can only exist when slab width is more than half of the wavelength.

In a waveguide, the core refractive index is always larger than the refractive index of cladding so that the total reflection happens. However, in this microgroove, the condition is reversed so that the electric field leaked away, which is called a leaky mode. The intensity decreases exponentially along the propagation direction [6].

FDTD analysis is applied for infinity depth microgroove, as shown in figure 5(b), which has the bottom connected to the PML region. Figure 9 shows the time average of the electric field inside the microgroove model by setting a horizontal observer line at z=1000 nm, which is 1000 nm far from the top surface. The intensity distribution is considered as the TM0 mode, where the electric field amplitude is constant at the region of the microgroove.

Finally, the intensity at the observation line reflected from the bottom of the microgroove and the intensity reflected from the model without the bottom part is compared, and the ratio of intensity is shown in figure 10. The result is fitted by an exponential function. The relative intensity may explain the detectable depth obtained in figure 8.

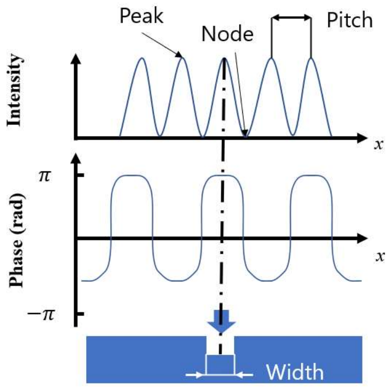


Figure 6: An illustration for the near-field intensity and phase of the standing-wave illumination against the microgroove

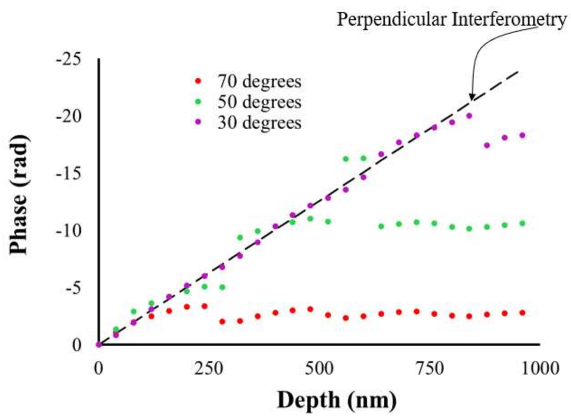


Figure 8: Near-field phase difference and depth relationship obtained from FDTD when the microgroove width is 200 nm. The solid line is theoretical value of perpendicular interferometer when incident angle is 0.

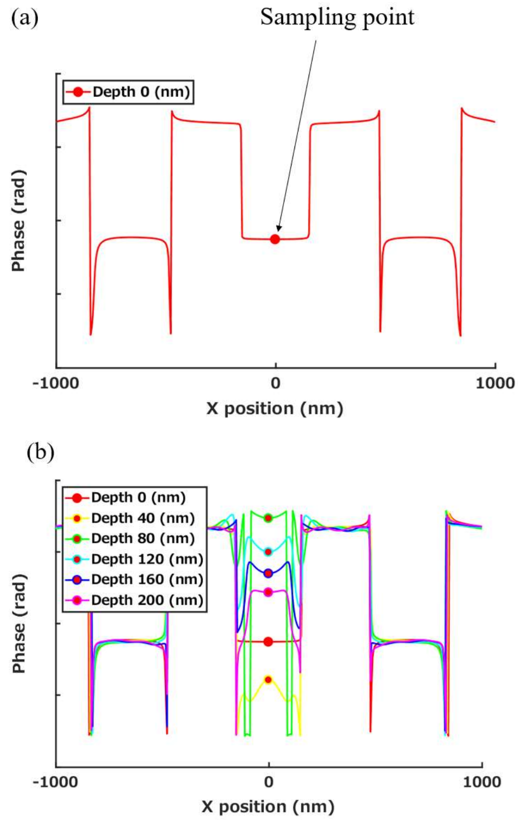


Figure 7: Near-field phase response obtained from FDTD when the incident angle is $50\,degree$, microgroove width is $200\,nm$, and the standing-wave peak is at the center above microgroove. (a) Response from a flat silicon surface, and the phase at 0 in x position is taken as standard phase to calculate the phase difference. (b) Phase varies with depth

IV Conclusions

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

Firstly, the near-field phase varies with the depth of microgroove under standing-wave illumination.

Secondly, The perpendicular illuminating interferometer theory may explain this phase-depth relationship even under sanding-wave illumination generated by oblique incidence. The reason behind this can be considered as the waveguide-like behavior dominates.

Thirdly, the detectable depth is smaller at a larger incident angle. This can be explained by the relative intensity of reflection obtained from the bottom of microgroove and the intensity of top surface reflection. The reflection of bottom of microgroove is 50% weaker than the reflection from the top surface when depth is about 240 nm at 70 degrees incidence, 390 nm at 50 degrees incidence, and 1000 nm at 30 degrees. These values correspond to the detectable depth of 200 nm at 70 degrees, 480 nm at 50 degrees, and 760 nm at 30 degrees.

Acknowledgment

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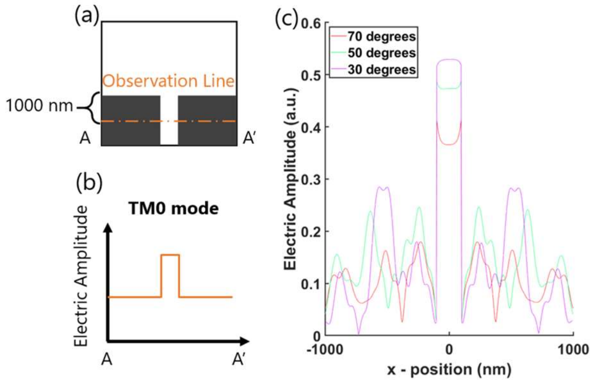

Figure 9: Time average of electric field inside the microgroove model. (a) Observation line is set horizontally to z=1000 nm. (b) Ideal distribution of TM0 mode in waveguide (c) FDTD results with variation of incident angle obtained from model oin figure 5(b).

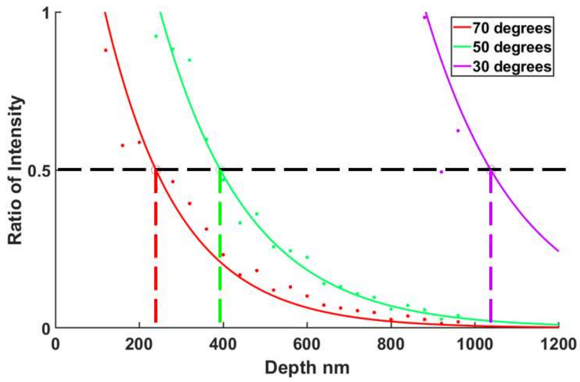

Figure 10: Ratio of intensity which is obtained by dividing the bottom reflected intensity with the intensity reflected from infinity depth model without bottom, at near-field observation line. The intersection with 50% intensity line is plotted.

References

[1] Kim, Kyunghwan, Yunwon Song, and Jungwoo Oh. "Nano/micro dual-textured antireflective subwavelength structures in anisotropically etched GaAs." Optics letters 42.16 (2017): 3105-3108.

[2] Matschuk, Maria, Henrik Bruus, and Niels B. Larsen. "Nanostructures for all-polymer microfluidic systems." Microelectronic Engineering 87.5-8 (2010): 1379-1382.

[3] Lal, Amit, Chunyan Shan, and Peng Xi. "Structured illumination microscopy image reconstruction algorithm." IEEE Journal of Selected Topics in Quantum Electronics 22.4 (2016): 50-63.

[4] H. Kume, M. Michihata, K. Takamasu, S. Takahashi. Numerical analysis on high resolution optical measurement method with long working distance objective for in-line inspection of micro-structured surface, Precision Engineering. (2020)

[5] Ye, Shiwei, et al. "Modified Linnik microscopic interferometry for quantitative depth evaluation of diffraction-limited microgroove." Measurement Science and Technology 29.5 (2018): 054011.

[6] Hu, J., & Menyuk, C. R. (2009). Understanding leaky modes: slab waveguide revisited. Advances in Optics and Photonics, 1(1), 58-106.