定在波照明における微細開口の近接場光応答解析(第 2 報)

The FDTD Analysis of Near-field Response for Microgroove Structure with Standing Wave Illumination - The Relationship of Microgroove Depth and Near-field Phase Response

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1. Introduction

Microstructures fabricated among the surface of material provide specific functions such as antireflection coating [1] and microfluidic systems [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.

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 the frequency domain. 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.

Recently, the coherent SIM algorithm is under development. 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].

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 should 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.

2. Model and Methodology

Firstly, the model is shown in figure 2. FDTD analysis shows that the electric field of standing-wave illumination exists in both x and z-direction in figure 3. 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 incident angle is selected to be 50 degrees.

Secondly, the phase of optical response from flat silicon is illustrated in figure 4, and the simulation result is in 5(a), where the standing-wave characteristic of the phase is confirmed. The sampling point is selected at the center of the microgroove. A microgroove depth dependency is observed in figure 5(b), where phase changes monotonically with depth. The phase-depth relationship of oblique interferometry follows equation 1.

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

Where θ_n is the phase difference, k is an integer, and ϕ is the incident angle. Analysis indicates that the depth and relative phase change relationship becomes independent with the incident angle, as shown in figure 6.　This linear relationship is similar to the case with the perpendicular illumination interferometry when the incident angle is 0 in equation 1.

When the depth goes deeper, the phase response stops to show depth dependency. In the case of 50 degrees incidence, the detectable range is about 500 nm.

The waveguide theory can explain that the phase response of oblique incident angles of this microgroove should follow the perpendicular interferometry theory. 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 7(a), which has the bottom connected to the PML boudary. Time average of the electric field inside the microgroove model is plotted by setting a vertical observer line and a horizontal line. In figure 7(b), the vertical electric field amplitude decays exponentially same as the leaky mode. In figure 7(c), the horizontal electric field amplitude keeps almost a constant value at the region of the microgroove. The intensity distribution horizontally in 7(c) is similar to the TM0 mode in an ideal waveguide in figure 7(d). But the electric field in 7(c) leaked from the core region into the cladding region, which can be considered as the leaky mode. The leaked electric field is also the reason of the exponential decay in figure 7(b)

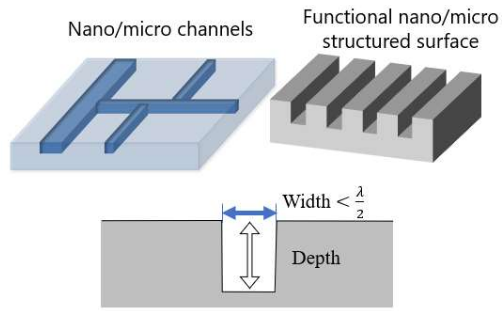
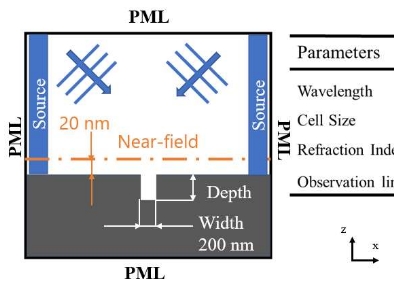


Figure 1: Functional surface with microgroove structure such as nanochannels, periodic structures, optical devices and so on.



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

Figure 2: Set up and parameters for FDTD analysis.

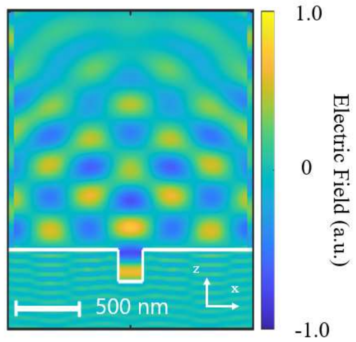


Figure 3: Electric field of microgroove model under standing-wave illumination.

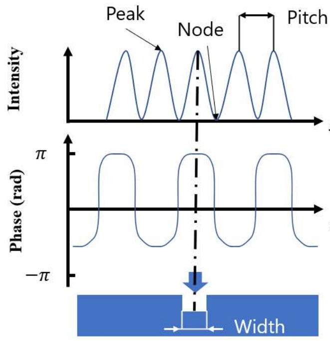


Figure 4: An illustration for the near-field intensity and phase of the standing-wave illumination against the microgroove

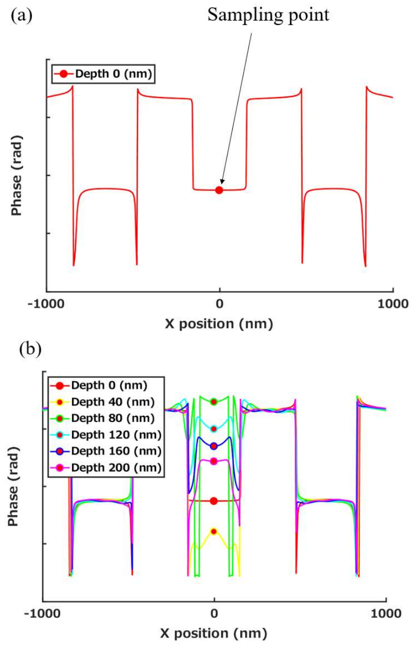


Figure 5: Near-field phase response obtained from FDTD when the incident angle is 50 degree, microgroove width is 200 nm, and the standing-wave peak is at the center above microgroove. (a) Response from a flat silicon surface, and the phase at 0 in x position is taken as standard phase to calculate the phase difference. (b) Phase varies with depth

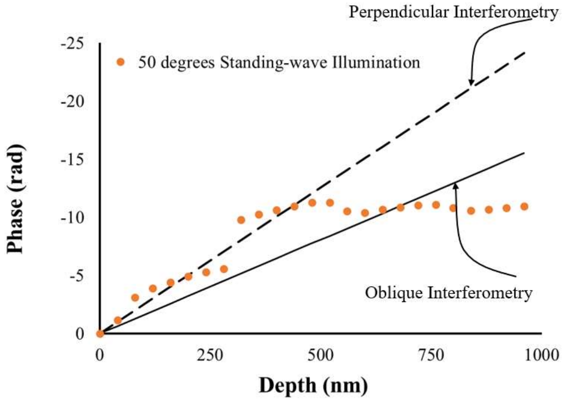


Figure 6: Near-field phase difference and depth relationship obtained from FDTD when the microgroove width is 200 nm and incident angle is 50 degrees. The dash line is theoretical value of perpendicular interferometer when incident angle is 0 and the solid line is theoretical value of oblique interferometer at 50 degrees

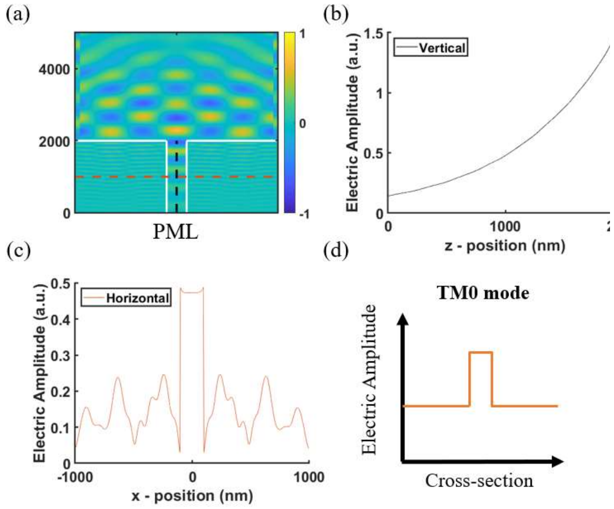


Figure 7: (a) Electric distribution of microgoove model with infinity depth touching the PML boundary at 50 degrees incidence. Observation line is set horizontally at $z = 1000\,nm$ and at center of microgroove vertically. (b) Vetical exponential decay of the electric amplitude is observed. (c) Horizontal electric amplitude indicates the time average of electric field is a certain value inside the microgroove (d) Ideal distribution of TM0 mode in a waveguide.

3. Conclusion

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, which has the potential for depth measurement.

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 leaky mode of waveguide dominates.

Thirdly, the detectable depth is about 500 nm at the incident angle of 50 degrees. One of the reasons is the vertical exponential decay inside the microgroove. The light observed at the near-field sampling point is a combination of reflection from the bottom surface of the microgroove and scattering light from the top surface. Further analysis and data processing will be investigated in future works.

Acknowledgment

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6. References

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