# 定在波照明における微細開口の近接場光応答解析
# The FDTD Analysis of Near-field Response for Microgroove Structure with Standing Wave Illumination

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## 1. Introduction

The precise optical measurement method is desirable for industry and researchers in semi-conductors. Its fast response and non-invasion advantages surpass most existing measurement methods. In previous research, two methods are proposed to measure the width and depth of diffraction-limited microgrooves. The FNRDM (Far-Field based Near-field Reconstruction Depth Measurement) calculates near-field response with plane-wave illumination to get depth information and SIM (Structured Illumination Microscopy) introduces phase shift with standing-wave illumination to obtain the lateral information [1] [2]. A combination of those two methods may achieve a new method that is available for three-dimensional super-resolution.

The first step to investigate this proposal is to observe the near-field response of microgrooves with standing-wave illumination. However, the blend of light components in FDTD (Finite-Difference Time-Domain) simulation prohibits direct observation. To solve this problem, two techniques, the polarization separation, and the Fourier Filtering method are proposed in this research to distinguish the direct reflection light and the scattering light in simulation.

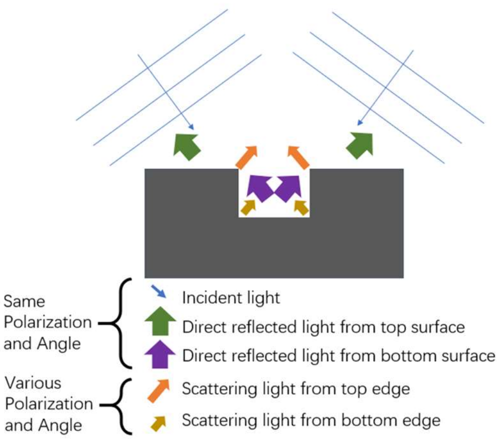


Fig. 1 The light component in the case of standing wave illumination.

## 2. Model and Methodology

Firstly, the polarization separation method is explained. The microgroove is placed oblique in the vertical view of the silicon surface. The incident light is polarized in the direction of y, which is s polarization in the front view. On the flat surface, the incident and reflection light would keep the same polarization. But on the edge position, the scattering may introduce differently polarized reflected light, which can be extracted by observing the light component with polarization in the x-direction, which is the p polarization in the front view.

The second method is called Fourier Filtering. 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) as shown in equation 1. Where the subtitle 'i' indicates an image plane and the 'o' indicates objective plane

$$I_i\,(X,Y) = I_o\,(x,y) \otimes psf \qquad (1)$$

Since the Fourier transform of PSF is optical transfer function (OTF) of the lens, so in another form, equation 2 gives

$$I_i\,(X,Y) = F^{-1}\,\{F[I_o\,(x,y)] * OTF\} \qquad (2)$$

And with coherent illumination, instead of using intensity, the complex electric field is used in equation 3.

$$E_i\,(X,Y) = F^{-1}\,\{F[E_o\,(x,y)] * OTF\} \qquad (3)$$

In the case of lens imaging, the incident angle is included in the multiplication of the Fourier transform of electric field and OTF, and the multiplication's distribution in Fourier space is related to the incident angle. In the simulation, we apply a special OTF as a filter with unit value except special frequency 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.

$$OTF = \begin{cases} 0 & (incident\ angle) \\ 1 & (other\ angles) \end{cases} \qquad (4)$$

The models of those two methods are described in figure 2. The software used is Poynting developed by Fujitsu. The calculation uses $10\,nm \times 10\,nm \times 10\,nm$ grid size and the simulation area is $4000\,nm \times 1000\,nm \times 4000\,nm$. The periodic boundary is set in x and y-direction. The PML boundary is set in the z-direction, in which the light source input above the silicon surface. The microgroove size used is $300\,nm \times 300\,nm$ in its front view.

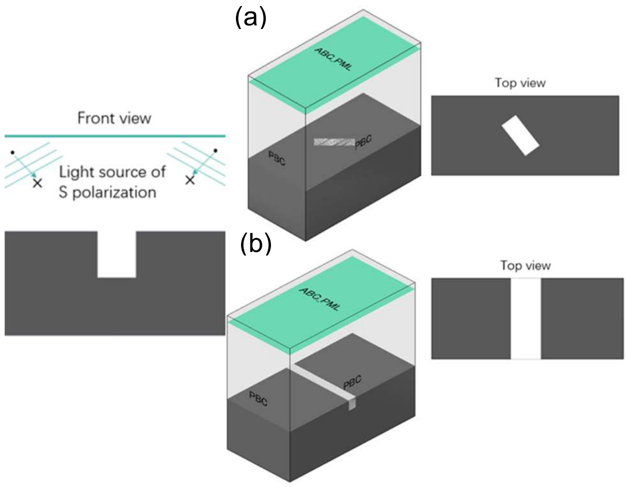


Fig. 2 The model of (a) polarization separation observation with oblique microgroove (b) Fourier Filtering

## 3. Results

In the case of polarization separation, the observation of the x-direction polarization component in figure 3 illustrates the ability to obtain the response of the electric field of scattering light with standing wave illumination. To confirm that, the observed scattering light should not be considered as noise. A model with a flat plane is built, and the noise level is confirmed to be much smaller than the scattering light.

Next, the result of Fourier Filtering is shown. Because the filter is in the Fourier space, its relationship with incident angle is confirmed by using only one oblique incident light with incident angle swept from 75 degrees to -75 degrees in the step of 10 degrees. The relationship between peak location and incident angle has been plotted in figure 4 and the two-dimensional observation result with 75 degrees incident is shown in figure 5. The elimination of light components is the light with the same angle and the reflection light of it. Then, it is confirmed that the peak has a linearity relation with the incident angle. Moreover, it is difficult to differentiate large incident angles, 65 degrees, and 75 degrees for example, which have the same peak location in the Fourier space.

Secondly, the Fourier Filtering is applied with standing-wave illumination and the result is shown in figure 6.

## 4. Discussion

Firstly, both methods give a distribution pattern of the scattering light of micro-groove under a standing wave illumination.

Secondly, a trial to apply the polarization separation method in plane-wave illumination, similar to in the first step of FNRDM, is failed to

calculate the depth accurately because the scattering light-induced at the bottom edges and top edges of the micro-groove includes the light reflected in a different direction. The phase difference of those scattering light should not be considered as the phase difference from the bottom surface and the top surface under a plane wave illumination. Therefore, a new algorithm is necessary to be developed. Moreover, the scattering light with x-polarization (~100 mV/m) is weaker than the incident light with y-polarization (~1000 mV/m). In the experiment, the information of those light in far-field would be weaker than the incident light.
Thirdly, because the microgroove is not continuous in the polarization separation method, the size will affect the result. The relationship between the size and the near-field response should be further investigated.
Fourthly, a demonstration of Fourier filtering is applied to the simplest model of an oblique incident with a flat plane. It is verified by applying different incident angle and the relationship of incident angle and the frequency distribution is studied for future filter design. However, the distribution function in Fourier space is not a single delta function, so that the filter size is going to be investigated.
Fifthly, a larger incident angle corresponds to a larger distribution in Fourier space. More girds should be applied to make better filtering.
Sixthly, the two darkfield observations are complicated and further comparison and evaluation are necessary before the investigation of size measurement.

## 5. Conclusion

The Finite-difference time-domain method (FDTD) simulation is applied to observe the electric and magnetic field of microgroove structure with standing wave illumination. The method using Fourier Filtering is proposed and analyzed to distinguish the light component reflected from the structure. The analysis is essential to the proposal of a new super-resolution and non-destruction depth measurement method.

## 6. References


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2. Ye, Shiwei, et al. "Non-Destructive Optical Depth Inspection of Sub-Diffraction Limit Fine Holes (The Sixth report)." Proceedings of JSPE Semestrial Meeting 2019 JSPE Autumn Conference. The Japan Society for Precision Engineering, 2019.


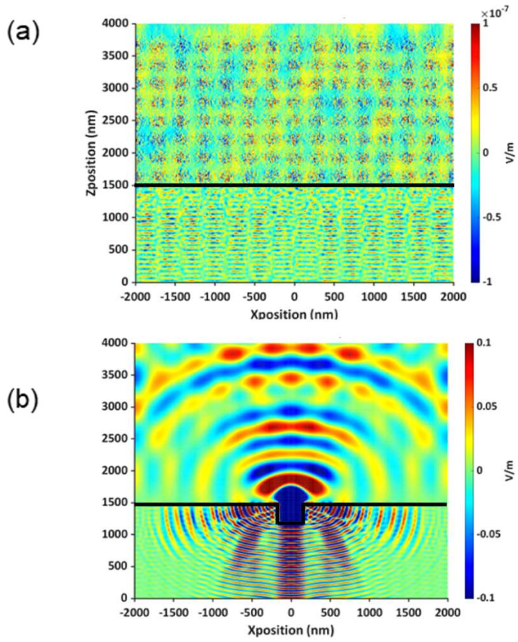


Fig3. Polarization separation result by observation of x-polarization component (p polarization) of standing wave illumination with y polarization illumination (s polarization) for the (a) flat surface to confirm the noise level and (b) micro-groove structure

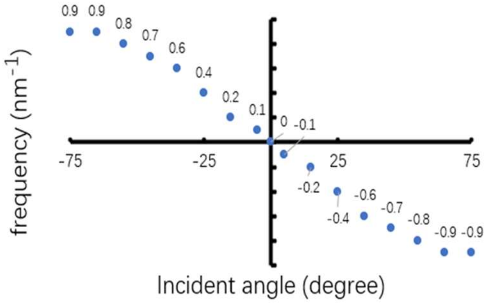


Fig4. The angle is related to the frequency domain and by filtering, the light component with special incident angle can be eliminated

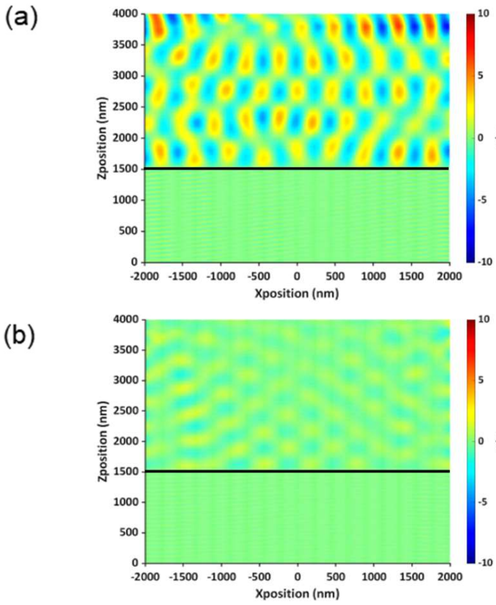


Fig5. Flat surface model with one oblique incident of 75 degrees (a) before and (b) after Fourier Filtering applied. The incident component has been removed.

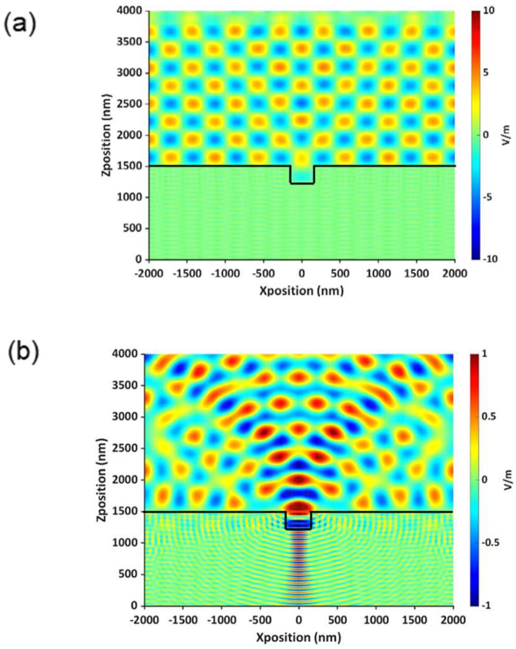


Fig6. Microgroove response with standing wave illumination (a) before and (b) after filtering