

DETECTION OF SUBWAVELENGTH STRUCTURE PROFILE BY DECOMPOSITION OF MUELLER MATRIX

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Abstract – Recently, the surface profiles of subwavelength structure have been reduced in size in order to develop microfabrication techniques. In particular, feature sizes of a few tens of nanometres are common in the semiconductor industry. This study uses a Mueller matrix polarimeter, which is based on a scatterometry technique, to evaluate the surface profiles of subwavelength structure. In this technique, a profile of the structure is determined from the Mueller matrix which expresses all the polarization properties of the sample by experimental measurements and calculated values. Furthermore, the Mueller matrix is decomposed for more precise detection. In this paper, the experimental results after decomposition agree well with the values obtained by numerical analysis. We measured the characteristic of non-diagonal elements in the Mueller matrix by varying the incidence azimuth of the subwavelength structure.

Keywords: subwavelength structure, scatterometry, Mueller matrix

1. INTRODUCTION

A nanostructure can be easily fabricated on a flat surface by lithography. There are many methods available to evaluate its surface profile. Optical microscopy is a powerful tool for investigating the surface profiles of objects, but it is difficult to image surface profile structures that are smaller than the wavelength of light using optical microscopes. Electron microscopy and atomic force microscopy are more effective methods for measuring the surface profiles of nanostructures. However, these techniques encounter many problems for practical applications that require measuring small areas of the order of hundreds of micrometers and short measurement times.

Scattered light, such as reflection, diffraction and polarization has some information about a surface condition of reflected plane. Reflectance Difference Spectra (RDS) method which bases on reflection depends on a surface condition or the surface molecule such as dielectric constant is useful for measurement of surface condition for a flat semiconductor or crystal surface [1]. However the RDS method can not be detected a surface profile of nanostructure. Scatterometry has been attracting increasing attention as a rapid, non-contact method for measuring the surface profiles of nanostructures. The reflected light from a

binary grating is diffracted and there are high order diffraction. The reflectivity or a rate of high order diffraction depends on the surface condition of grating. However in the case of the structure reducing, there is no diffraction because the high order diffraction becomes evanescent wave. For detecting nanostructure, it achieves this by comparing experimentally measured values of the optical parameters with values calculated numerically. Especially, polarization states of the reflected beam depend on the surface profile of the sample. A method for evaluating the surface profile has been proposed that uses the phase Δ and the complex reflection amplitude ϕ of the reflected beam as optical parameters [2].

The purpose of this study is to evaluate the surface profile of a nanostructure by using the elements of a Mueller matrix, which is 4 x 4 matrix that fully defines the polarization characteristics of an object. We compare the results obtained by applying rigorous coupled-wave analysis (RCWA) [3] to a sample with nanostructure with measurements made using the Mueller matrix polarimeter proposed by Azzam [4]. There have been proposed the evaluation method using scatterometry based on the Mueller matrix [5]. However, in contrast to techniques based on shape variation, it proved to be difficult to interpret the highly sensitive parameters of polarization properties, since the Mueller matrix contains information all the polarization properties. In addition, we decompose the Mueller matrix to obtain specific polarization properties. The relationship between these evaluated polarization properties and the surface profile of the nanostructures is examined. In the experiment, we measured the Mueller matrix of subwavelength structure using a dual-rotating-retarder polarimeter, and we also calculated the structure by RCWA. We found that the experimental values and the calculated values exhibited the same tendency.

2. MUELLER MATRIX OF SUBWAVELENGTH STRUCTURE

Polarization properties of reflected light from a periodically nanostructure, such as grating, is included structural information. Because a width or height is less than the wavelength, it is considered the structure as an optical alignment material. Optical properties of reflected light from the periodically nanostructure, such as linear polarity, circular polarity and diattenuation, are expressed by the

Mueller matrix \mathbf{M} which consists of 4 x 4 elements. Figure 1 shows a schematic illustration of induced into a nanostructure. Period, width and height of the nanostructure are about wavelength and a manufacturing error is less than 0.1λ .

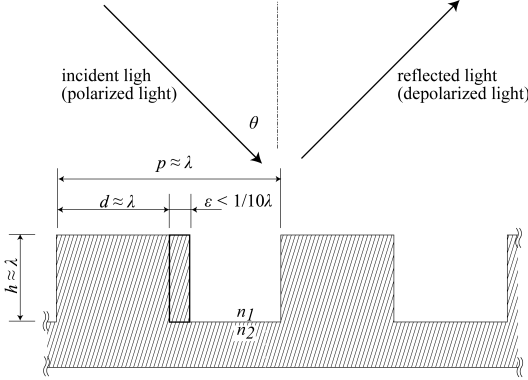


Fig. 1. Definition of nanostructure and its manufacturing error ε .

However there are some errors ε about structure from manufacturing shown in Fig.1. In the case of polarized light inducing into the nanostructure with error ε , a reflected light is depolarization and some polarized states are mixed. Especially, the depolarization is caused by fluctuation of the structure less than 0.1λ . Then it is necessary to decompose the Mueller matrix for analyzing the polarized light.

The Muller matrix decomposition has been proposed by R.A. Chipman [7]. The algorithm is useful for defined optical properties for scattered light from the structure. A polarized Muller matrix is determined by

$$\mathbf{M} = \mathbf{M}_\Delta \mathbf{M}_R \mathbf{M}_D, \quad (1)$$

where \mathbf{M}_Δ is a depolarization, \mathbf{M}_R is retardance and \mathbf{M}_D is diattenuation of the Muller matrix. The diattenuation \mathbf{M}_D can be expressed by

$$\mathbf{M}_D = \begin{pmatrix} 1 & \mathbf{D} \\ \mathbf{D} & \mathbf{m}_D \end{pmatrix}, \quad (2)$$

where \mathbf{D} is the diattenuation vector of \mathbf{M} is given by

$$\mathbf{D} = \frac{1}{m_{00}} [m_{01} \quad m_{02} \quad 0]^T. \quad (3)$$

Where \mathbf{m}_D is the following parameters:

$$\mathbf{m}_D = \sqrt{1 - \mathbf{D}^2} \mathbf{I} + (1 - \sqrt{1 - \mathbf{D}^2}) \frac{\mathbf{D}}{|\mathbf{D}|} \left(\frac{\mathbf{D}}{|\mathbf{D}|} \right)^T, \quad (4)$$

Where \mathbf{I} is the unit matrix.

Then the matrix \mathbf{M}' excluded the diattenuation \mathbf{M}_D from the Muller matrix \mathbf{M} can be given by

$$\mathbf{M}' = \mathbf{M} \mathbf{M}_D^{-1} = \mathbf{M}_\Delta \mathbf{M}_R, \quad (5)$$

each matrices are

$$\mathbf{M}' = \begin{bmatrix} 1 & 0 \\ \mathbf{P}_\Delta & \mathbf{m}' \end{bmatrix}, \quad (6)$$

$$\mathbf{M}_R = \begin{bmatrix} 1 & 0 \\ 0 & \mathbf{m}_R \end{bmatrix}, \quad (7)$$

$$\mathbf{M}_\Delta = \begin{bmatrix} 1 & 0 \\ \mathbf{P}_\Delta & \mathbf{m}_\Delta \end{bmatrix}, \quad (8)$$

where \mathbf{m}' is a sub matrix of \mathbf{M}' . \mathbf{P}_Δ can be given by

$$\mathbf{P}_\Delta = \frac{\mathbf{P} - \mathbf{m}_D \mathbf{D}}{1 - \mathbf{D}^2}, \quad (9)$$

$$\mathbf{P} = \frac{1}{m_{00}} [m_{10} \quad m_{20} \quad m_{30}]^T. \quad (10)$$

Then a sub matrix \mathbf{m}_D is shown

$$\mathbf{m}_D = \pm [\mathbf{m}(\mathbf{m})^T + (\sqrt{\lambda_1 \lambda_2} + \sqrt{\lambda_2 \lambda_3} + \sqrt{\lambda_3 \lambda_1}) \mathbf{I}]^{-1} \times [(\sqrt{\lambda_1} + \sqrt{\lambda_2} + \sqrt{\lambda_3}) \mathbf{m}(\mathbf{m}')^T + \sqrt{\lambda_1 \lambda_2 \lambda_3} \mathbf{I}] \quad (11)$$

where $\lambda_1, \lambda_2, \lambda_3$ are eigenvalues of \mathbf{m}' . Retardation matrix as \mathbf{M}_R is derived from eq.(5), (6), (7) and (8).

The optical setup for measurement of the Mueller matrix of subwavelength structure shown in Fig. 2 consists of a light source (He-Ne laser or white light), a polarizer, an analyzer, two quarter-wave plates and a detector. The two quarter-wave plates are rotated in a ratio of 1:5. The measured light intensity $I(\lambda)$ is derived from a Stokes vector and each Mueller matrices of optical elements which is given by

$$I(\lambda) = \frac{1}{4} I_0(\lambda) [a_0(m_{ij}) + \sum_{n=1}^{12} \{a_n m_{ij}(\lambda) \cos(2n\phi) + b_n m_{ij}(\lambda) \sin(2n\phi)\}] \quad (12)$$

Where ϕ is rotated angle of the polarizer, m_{ij} is a elements of the Mueller matrix of a sample, and a_n and b_n are Fourier series.

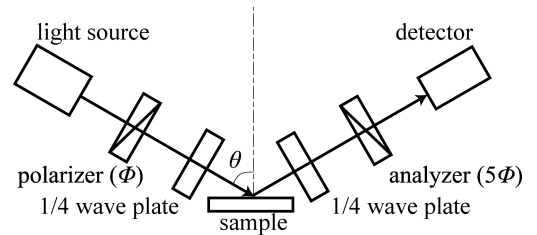


Fig. 2. Optical setup for dual-rotating-retarder Muller matrix polarimeter [5].

In this paper, we applied for a calculation of the Mueller matrix by RCWA. The RCWA is one of rigorous analysis and it is useful for a periodical structure. The RCWA gives electric fields of a reflected light from nanostructure \mathbf{E}_x , \mathbf{E}_y and \mathbf{E}_z . s -electric field \mathbf{E}_s and p -electric field \mathbf{E}_p of the reflected light are given by

$$\mathbf{E}_p = \mathbf{A}(\mathbf{E}_x + \mathbf{E}_z), \quad (13)$$

$$\mathbf{E}_s = \mathbf{A}\mathbf{E}_y, \quad (14)$$

where \mathbf{A} is a rotation matrix as a rotation of angle α . A Jones matrix can be given by

$$\mathbf{T} = \begin{bmatrix} T_1 & T_3 \\ T_4 & T_2 \end{bmatrix} = \begin{bmatrix} \left[\frac{r_{rp} |\exp(i \delta_{rp})|}{r_{ip} |\exp(i \delta_{ip})|} \right]_{E_{is}=0} & \left[\frac{r_{rp} |\exp(i \delta_{rp})|}{r_{is} |\exp(i \delta_{is})|} \right]_{E_{ip}=0} \\ \left[\frac{r_{rs} |\exp(i \delta_{rs})|}{r_{ip} |\exp(i \delta_{ip})|} \right]_{E_{is}=0} & \left[\frac{r_{rs} |\exp(i \delta_{rs})|}{r_{is} |\exp(i \delta_{is})|} \right]_{E_{ip}=0} \end{bmatrix}, \quad (15)$$

where \mathbf{E}_{ip} and \mathbf{E}_{is} are an incident electric fields of s and p directions with phase δ_{ip} and δ_{is} , amplitude r_{ip} and r_{is} , respectively. Then a Mueller matrix of a sample \mathbf{M} is given by

$$\mathbf{M} = \mathbf{A} \langle \mathbf{T} \mathbf{T}^* \rangle \mathbf{A}, \quad (16)$$

where

$$\mathbf{A} = \begin{bmatrix} 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \\ 0 & i & -i & 0 \end{bmatrix}, \quad (17)$$

Equation (16) and (17) gives the Mueller matrix of the sample \mathbf{M} from RCWA,

$$\mathbf{M} = \begin{bmatrix} \frac{1}{2}(E_1 + E_2 + E_3 + E_4) & \frac{1}{2}(E_1 - E_2 - E_3 + E_4) \\ \frac{1}{2}(E_1 - E_2 + E_3 - E_4) & \frac{1}{2}(E_1 + E_2 - E_3 - E_4) \\ F_{14} + F_{32} & F_{14} - F_{32} \\ G_{14} + G_{32} & G_{14} - G_{32} \\ F_{13} + F_{42} & -G_{13} - G_{42} \\ F_{13} - F_{42} & -G_{13} + G_{42} \\ F_{12} + F_{34} & -G_{12} + G_{34} \\ G_{12} + G_{34} & F_{12} - F_{34} \end{bmatrix},$$

where

$$\begin{aligned} E_i &= T_i T_i^* = |T_i|^2, \\ F_{ij} &= -F_{ji} = \text{Re}(T_i T_j^*) = \text{Re}(T_j T_i^*), \\ G_{ij} &= -G_{ji} = \text{Im}(T_i^* T_j) = -\text{Im}(T_j^* T_i), \\ i, j &= 1, 2, 3, 4, \end{aligned} \quad (18)$$

In the following section, we discuss by comparing the Mueller matrix \mathbf{M} from experimental results and it from simulation result. And it's ability for estimation of a surface profile of nanostructure.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

The Mueller matrix of SiO₂ glass plate has been measured for confirmation of a Mueller matrix decomposition. A light source of our system is He-Ne laser and a reflected light is detected by a power meter. And azimuth angles of two wave plates have been calibrated by Goldstein's method [8]. Figure 3 shows a undecomposed Mueller matrix along to changing incident angle θ of the light. For effectiveness our system, a simulation result is also shown in fig. 3. The simulation result is calculated by RCWA. In the simulation, there are nondepolarization because of perfect periodic structure. The measurement and simulation result are in good agreement because of a good flatness of SiO₂ substrate. Especially, in the vicinity of incident angle $\theta = 55$ degrees, the Brewster's angle of the SiO₂ glass plate can be measured by our system. And fig. 4 and 5 are a diattenuation and retardance Mueller matrix decomposed by Chipman's algorithm. In two figures, solid lines are measurement results and dotted lines are simulation results. Experimental results are good agreement with simulation results.

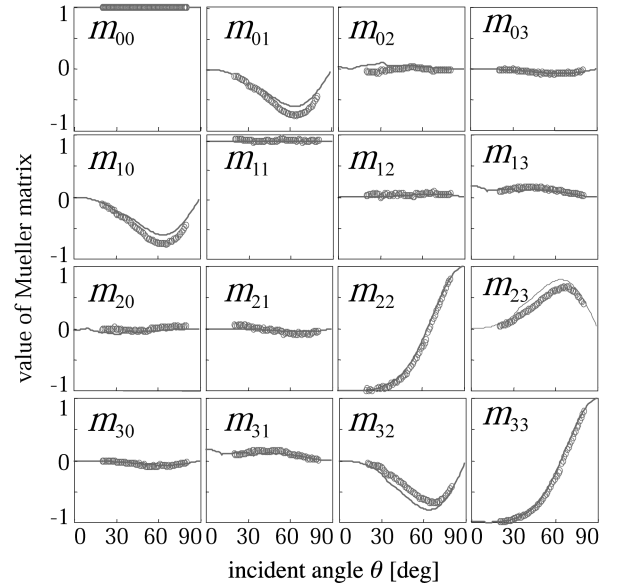


Fig. 3. Mueller matrix of SiO₂ glass plate. Dots are experimental results and solid line is simulation results calculated by RCWA.

355 nm, and a period of 433 nm. Using the obtained profile, a simulation model for RCWA was constructed precisely.

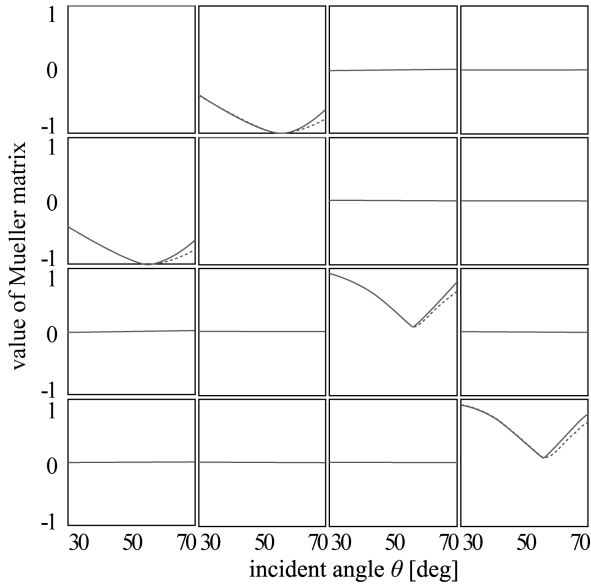


Fig. 4. Diattenuator Mueller matrix of SiO₂ glass plate after decomposition. Solid line is experimental results and dashed line is simulation results.

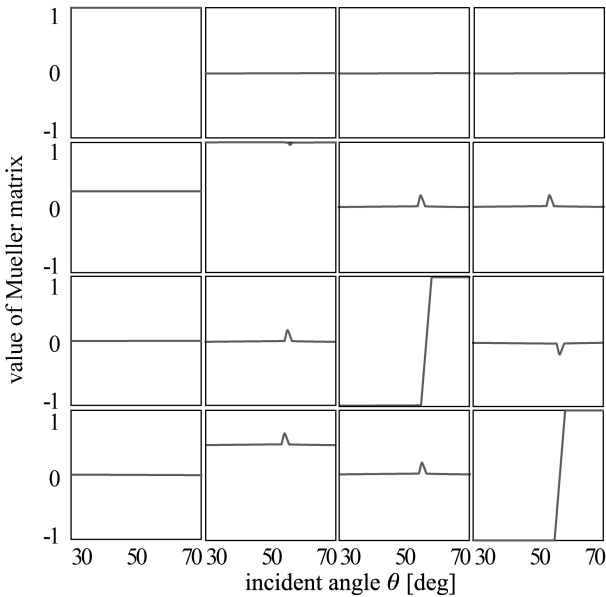


Fig. 5. Retardance Mueller matrix of SiO₂ glass plate after decomposition. Solid line is experimental results and dashed line is simulation results.

Figure 6 and 7 show a part of a surface profile and a typical cross sectional profile of subwavelength structure measured by a critical dimensional atomic force microscope (CD-AFM, Veeco Instruments). The structure was manufactured by nanoimprinting process which mold was made by two-beam interference. A material of the structure is PMMA and it is suitable for anti-reflection of the light of 633 nm. The structure has a width of 200 nm, a height of

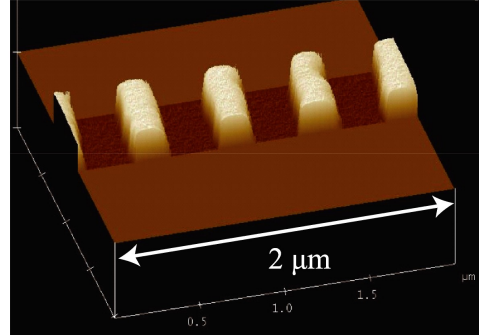


Fig. 6. Part of surface profile of subwavelength structure for anti-refraction obtained by CD-AFM.

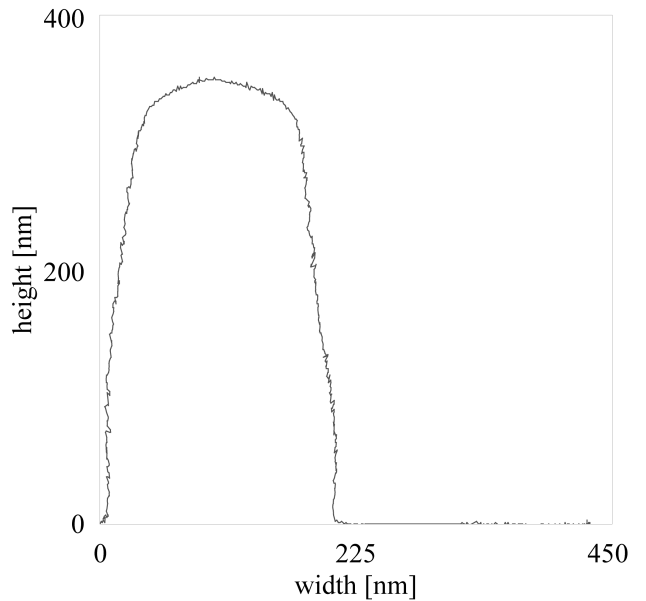


Fig. 7. Cross sectional profile of subwavelength structure for anti-refraction obtained by CD-AFM.

Figure 8 shows an undecomposed Mueller matrix of the subwavelength structure. The experimental results are not agreement with the simulation results, especially, the elements of m_{01} , m_{10} , m_{22} , m_{23} , m_{32} and m_{33} . Because there are some structural fluctuation as shown in fig. 6.

Figure 9 and 10 are a diattenuation and a depolarization of the measured Mueller matrix. In fig.9, both results such as obtained by experimental and simulation is good agreement. However, in fig.10, the experimental results are not agreement with the simulation results. The simulation

results are the unit vector which means there are no depolarization effect because there are no frequently error in the simulation model. In other words, there are frequently errors in the subwavelength structure. The scattered light from the width less than 0.1λ is not affected the polarization state of reflected light. There is a possibility of estimation for the frequently errors of the subwavelength structure less than 0.1λ .

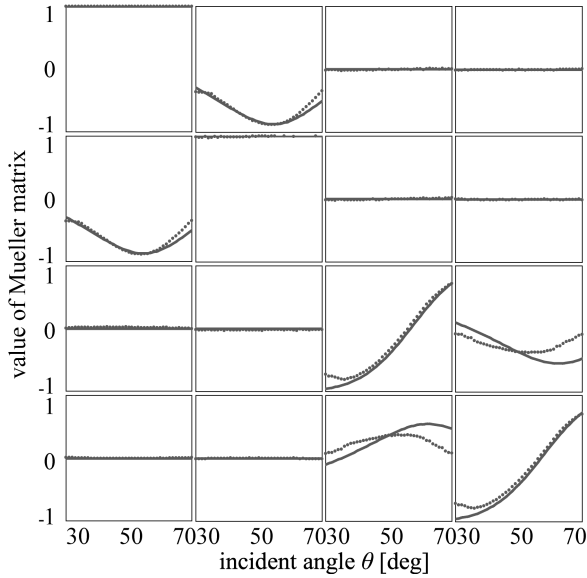


Fig. 8. Mueller matrix of subwavelength structure before decomposition. Dots are experimental results and solid lines are simulation results.

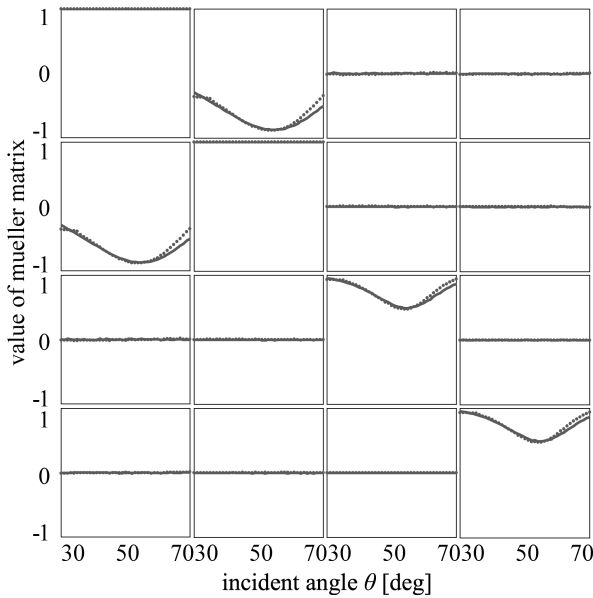


Fig. 9. Diattenuator Mueller matrix of subwavelength structure after decomposition. Dots are experimental results and solid lines are simulation results.

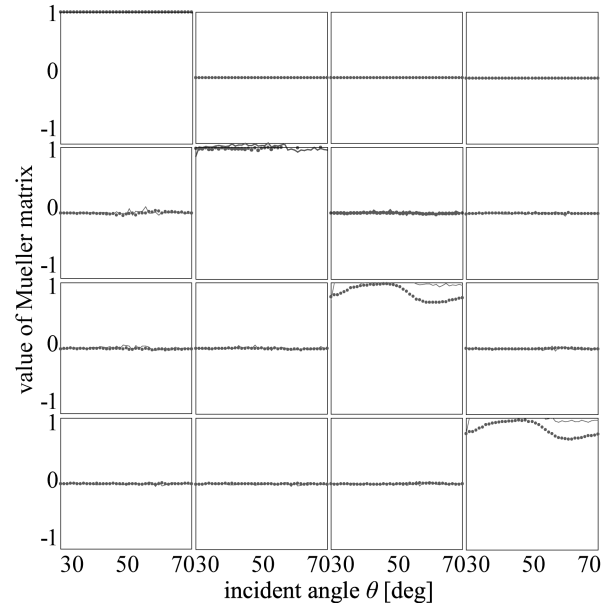


Fig. 10. Depolarization Mueller matrix of subwavelength structure after decomposition. Dots are experimental results and solid lines are simulation results.

4. CONCLUSIONS

The Mueller matrix for the subwavelength structure was measured by double rotating polarimeter and was calculated using RCWA. Comparing the experimental results with the calculated values demonstrated the effectiveness using Mueller matrix to detect the surface of the subwavelength structure. By decomposition of the Mueller matrix, the frequently error of the subwavelength structure has been detected and possibility of an estimation by the depolarization Mueller matrix. In the future, we intend to not only use this technique to measure periodic structures but also to use it to identify defective structures. This will require using an analysis that considers the depolarization due to scattering.

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