Spectroscopic Ellipsometry of the fishnet metamaterial.

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Abstract

Spectroscopic ellipsometry (SE) has great potential for the characterization of optical metamaterials, particularly under oblique incidence. Here we present a method based on Berreman's 4x4 matrix formalism combined with oblique incidence retrieval [1] methods to reproduce the ellipsometric response of a Fishnet metamaterial. The existence of spatial dispersion for different angles of incidence as well as different azimuthal orientation of the design is also discussed.

1. Introduction

Proper utilization of Negative Index Materials (NIMs) requires correct understanding of the response at arbitrary direction of incident fields. Among the different NIM designs fishnet [2] metamaterial is one of the most promising ones to push the functionality of NIMs to the visible region. Normal incidence response of fishnet NIM is well researched while its oblique incidence behaviour still needs more investigation. Spectroscopic Ellipsometry (SE) as a very accurate and well developed method to characterize surfaces and thin films can also be used to study metamaterials. In this technique, the change of the polarization state at reflection or transmission is used for analyzing the optical properties of the thin film. Here we use the technique to analyze the fabricated fishnet structure.

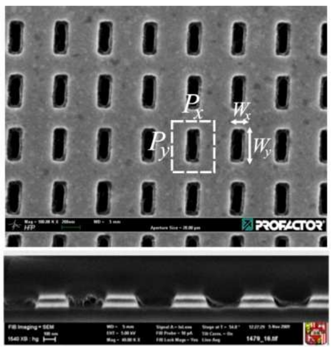

Fig. 1: SEM pictures of the structure from front and side views. Unit cell dimensions are P_x=500nm, P_y=600nm, W_x=135nm, W_y=350nm, layer thicknesses are each 30nm, and sidewall angles, due to the fabrication procedure are ~20°.

2. Spectroscopic Ellipsometry of the fishnet NIM.

SE is a technique to measure the ratios of reflected polarizations rather independent of the intensity. These ratios can be expanded into parallel (p) and perpendicular (s) components of the field to the

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plane of incidence. For the general case of anisotropic structures, there are four possible Fresnel coefficients e.g. R_{pp}, R_{ps}, R_{sp} and R_{ss}, where the first index refers to the emerging polarization and the second index refers to the incident polarization. It is common to use the ellipsometric angles Ψ and Δ to represent the mentioned complex ratios

$$\frac{R_{pp}}{R_{ss}} = \rho = \tan(\Psi)\, e^{i\Delta}$$

We have used Rigorous Coupled Wave Analysis (RCWA) method to simulate the ellipsometric response of the fabricated structure. A very good agreement between measured SE data and RCWA calculations is obtained (Fig. 2).

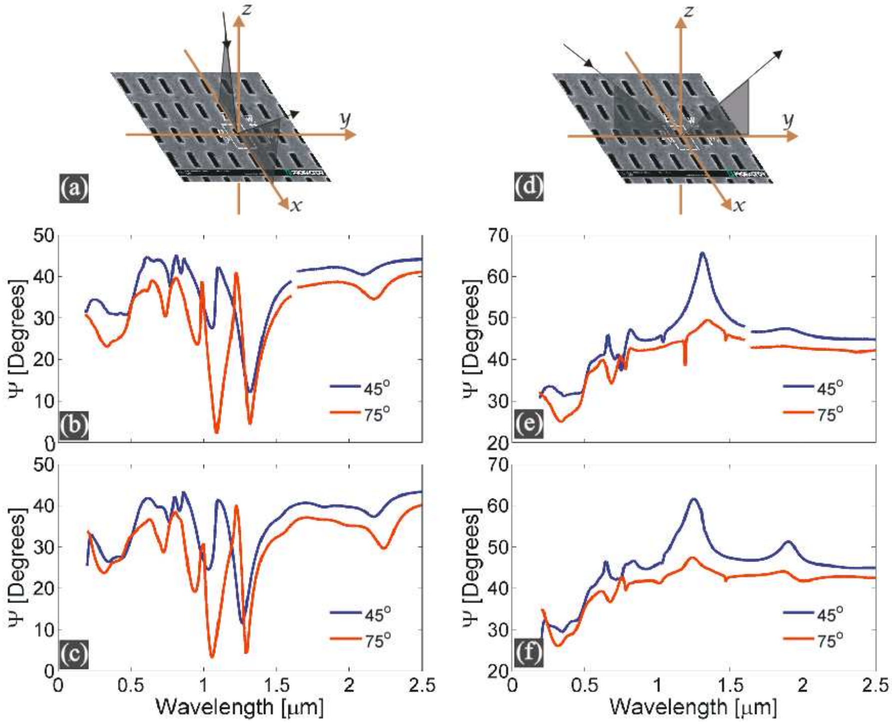

Fig. 2: (a) and (d) Orientation of the sample with respect to the incidence plane. (b) and (e) Measured ellipsometric response of the structure for each orientation, the small gaps at around 1.6 μm are due to use of different ellipsometer devices . The data in (c) and (f) show the simulated ellipsometric response.

3. Berreman's 4x4 matrix formalism

Berreman's 4x4 matrix formalism [3,4] provides the most general description for oblique coherent reflection and transmission from anisotropic homogeneous layers. For a three phase (ambient-film-substrate) model with orthorhombic symmetry, these coefficients can be written in terms of effective material properties where n_a (n_s) represents ambient (substrate) refractive index.

$$R_{pp} = \frac{n_s\cos(\phi_0) - n_a\sqrt{1-\frac{n_a^2\sin^2(\phi_0)}{n_s^2}}}{n_a\sqrt{1-\frac{n_a^2\sin^2(\phi_0)}{n_s^2}} + n_s\cos(\phi_0)} + \frac{2in_a\omega\cos(\phi_0)\left[n_a^2\sin^2(\phi_0)\left(\epsilon_{11}\epsilon_{33}-n_s^4\right)+n_s^2\epsilon_{33}\left(n_s^2\mu_{22}-\epsilon_{11}\right)\right]}{c\epsilon_{33}\left[n_a n_s\sqrt{1-\frac{n_a^2\sin^2(\phi_0)}{n_s^2}}+n_s^2\cos(\phi_0)\right]^2}\delta z + O\left[(\delta z)^2\right]$$

$$R_{ss} = \frac{n_a\cos(\phi_0) - n_s\sqrt{1-\frac{n_a^2\sin^2(\phi_0)}{n_s^2}}}{n_s\sqrt{1-\frac{n_a^2\sin^2(\phi_0)}{n_s^2}} + n_a\cos(\phi_0)} + \frac{2in_a\omega\cos(\phi_0)\left[n_a^2(\mu_{11}\mu_{33}-1)\sin^2(\phi_0)+\mu_{33}\left(\epsilon_{22}-n_s^2\mu_{11}\right)\right]}{c\mu_{33}\left[n_s\sqrt{1-\frac{n_a^2\sin^2(\phi_0)}{n_s^2}}+n_a\cos(\phi_0)\right]^2}\delta z + O\left[(\delta z)^2\right]$$

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By picking a forward calculation route one can reproduce ellipsometric response of the structure by inserting retrieved effective tensor elements of the anisotropic film in the Berreman formalism. This will also give us the freedom to check the behaviour of retrieved data under rotation operations. The retrieval procedure of reference [1] provides in plane elements of the material tensor from reflection and transmission data. Out of plane elements can be calculated from dispersion relations which lead to different values for two different planes of incidence presented in Fig. 1 (a) and (b). Inserting the retrieved values for the configuration of Fig. 2(a) in Berreman formalism generates a surprisingly good fit to the ellipsometric curve of z-x plane (see Fig. 3(a)). Adopting these retrieved values as tensor elements of an anisotropic sample requires the correct behavior of them under rotation. Now, applying a 90° rotation to the established tensor elements shows a discrepancy to the corresponding z-y ellipsometric curve as Fig. 3(b) shows. However replacing the out of plane elements with the second calculated set for the z-y plane of incidence makes a perfect fit again. This shows incorrect behaviour of retrieved tensor elements under a 90° rotation as it is required for anisotropic material tensor. This deviation can be assigned to the theoretically predicted issue of spatial dispersion in fishnet metamaterial. The same issue exists for variable angles of incidence (AOI). One cannot use retrieved data at one AOI to generate the correct ellipsometric response at a different AOI.

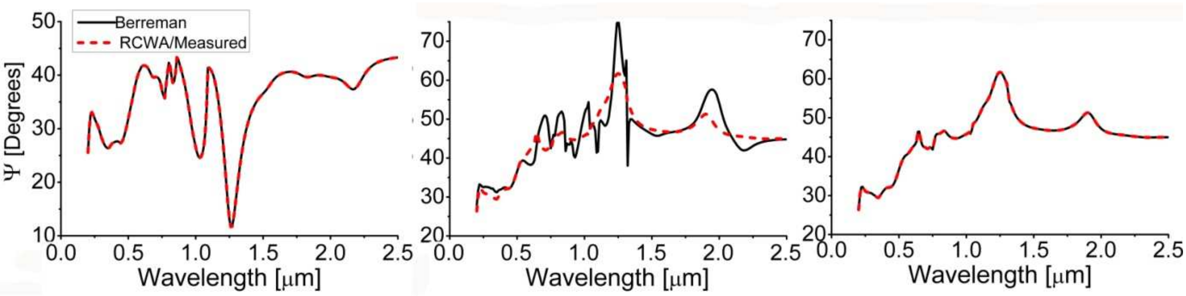

Fig. 3: Solid black lines are Berreman results using the oblique incidence retrieval data from ref. [1] and red dashed lines are expected RCWA/measured curve for each configuration. **(a)** Solid (black) line corresponds to the Berreman calculation using retrieved effective parameters for ***z-x*** plane of incidence (configuration of Fig.1a). **(b)** 90° rotated version of (a). **(c)** 90° rotated version of (a) after replacing out of plane elements with the ones retrieved for ***z-y*** plane of incidence.

5. Conclusion

Spectroscopic ellipsometry as a straight forward technique can provide useful information about resonances of metamaterial structures, although it can not be directly used as an inverse calculation method due to the complexity of fitting tensor components and the missing possibility to vary the angle of incidence due to spatial dispersion. The existence of spatial dispersion for the fishnet structure is shown in this work, for azimuthal rotations as well as different AOIs. With the Berreman formalism one can analytically model the dependence of the transmission and reflection Fresnel coefficients and derive their analytic dependence on the effective permeability and permittivity tensor components. Furthermore, it is shown with analytic formulas, for the fishnet structure in the two geometries mentioned, R_{pp} depends (in any order) only on ε_{11}; ε_{33} and μ_{22}, R_{ss} in any order only on ε_{22}; μ_{11} and μ_{33}.

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