Characterization of split-ring resonators using spectroscopic ellipsometry

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Abstract

Ellipsometric response of periodically arranged golden split-ring resonators at infrared frequencies is analyzed. Rigorous coupled wave analysis of the structure's optical response revealed excellent agreement with experimental data. The features in the ellipsometric spectra are discussed by analyzing the reflection spectra for p- and s-polarizations. It is shown that ellipsometry can be used to characterize the first few plasmonic modes of split-ring resonators.

1. Introduction

Split-ring resonators are widely used artificial structures for achieving negative effective permeability [1]. One way to determine the resonant frequencies for metallic SRRs is to observe the peaks in the reflection spectra [2]. These resonances can be explained by employing a fully electromagnetic picture [2]. Spectroscopic ellipsometry (SE) measures the ratio between complex reflection coefficients for p- and s-polarized incident waves, r_p and r_s, with the electric field being parallel and perpendicular to the incident plane, respectively. This fact makes ellipsometry a potential candidate for SRR characterization [3].

In this paper we study the infrared (IR) ellipsometric response of the SRRs for two different angles of incidence 40° and 65° with incident plane being parallel to the gap. The measured data were compared to the calculations and a good qualitative agreement was found. The calculated distribution of the perpendicular component of the surface electric field and current density for the resonant frequencies helped examine the nature of the plasmonic modes.

2. Experiment and Simulations

The structure under investigation consists of periodically arranged golden split-ring resonators on Si substrate Fig. 1(a) and 1(b). The period of the unit cell is P = 1000 nm, the lengths of the base l_x and

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side legs l_y are set to be equal $l_x = l_y$ = 780 nm. The size of the gap is d = 250 nm, and the width of the rings is w = 80 nm. The Au layer with thickness t = 54 nm is deposited on the Si substrate with 2 nm thick natural oxide SiO_2 covered by 4 nm thick layer of Ti. The SRRs were fabricated using nano-imprint litography [4].

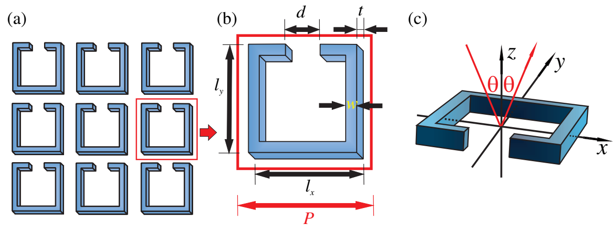

Fig. 1: (a) The part of the periodic structure and (b) unit cell are shown. (c) The incident plane (xz) is parallel to the gap.

The numerical simulations of the reflection coefficients, the electric field distributions and bulk current densities for the structure described above are performed using the commercially available RCWA software RETICOLO-2D [5]. The dielectric function of Si substrate in IR range is assumed to be 11.9, the dielectric function of SiO_2 and Ti are taken from Ref. [6] and the dielectric function of Au was taken from Ref. [7].

Ellipsometric measurements are performed using specially designed microfocus mapping ellipsometer for infrared initiative synchrotron radiation (IRIS) beamline at BESSY II externally attached to FTIR-spectrometer Bruker 66v/S and a photometric MIR lab-ellipsometer. The spectral range for this study is 500-5000 cm^{-1} with resolution of 4 cm^{-1}.

3. Results and Discussion

Standard SE measures two parameters tanΨ = $|r_p|/|r_s|$, the amplitude the ratio, and Δ = $\phi_p - \phi_s$, the phase difference of complex reflection coefficients for p- and s-polarizations. The calculated tanΨ and Δ are shown in Fig. 2(e) and 2(f), respectively and measured tanΨ and Δ are shown in Fig. 2(g) and 2(h), respectively. There is a good qualitative agreement between the corresponding spectra, so it can be assumed that all the other calculated parameters correspond the the real ones. The amplitude and the phase for r_p are shown in Fig. 2(a) and 2(b), respectively and for r_s in Fig. 2(c) and 2(d), respectively.

According to the r_p spectra, there are two well pronounced resonances labeled as ”1” at 800 cm^{-1} and labeled as ”3” at 2220 cm^{-1} (Fig. 2(a) and 2(b)). They are excited by the electric coupling to magnetic resonance (EEMR) [8]. A smaller peak labeled as ”4” (Fig. 2(a)) at 2900 cm^{-1} appears only at oblique incidence due to retardation effects. The snapshots of the electric field distribution and current density at the incident angle 65° for these three resonant frequencies are plotted in Fig. 2 (i-l). According to them, the resonance ”1” at 800 cm^{-1} (Fig. 2(i)) corresponds to the first plasmonic mode, the resonance ”3” at 2200 cm^{-1} (Fig. 2(k)) to the third plasmonic mode and the resonance ”4” at 2900 cm^{-1} (Fig. 2(l)) to the fourth plasmonic mode.

For r_s the electric field is normal to the gap and it induces the resonances labeled as ”2” at 1700 cm^{-1} and labeled as ”4” at 2900 cm^{-1} (Fig. 2(c) and 2(d)) [2]. According to the amplitude nodes in electric field distribution and current density (Fig. 2) these are second (Fig. 2(j)) and forth (Fig. 2(l)) plasmonic modes. At oblique incidence, there is a component of the magnetic field normal to the plane of SRRs which couples with the magnetic dipole of the odd plasmonic modes [9]. This is the reason for the third plasmonic mode ”3” at 2220 cm^{-1} (indicated by arrows in Fig. 2(c) and 2(d)) to appear.

Comparing the peaks in the amplitudes of the r_p and r_s with tanΨ it can be noticed that the peaks in tanΨ in Fig. 2(e) and 2(g) match the peaks in the amplitude of the r_p spectra Fig. 2(a). Also, the resonances

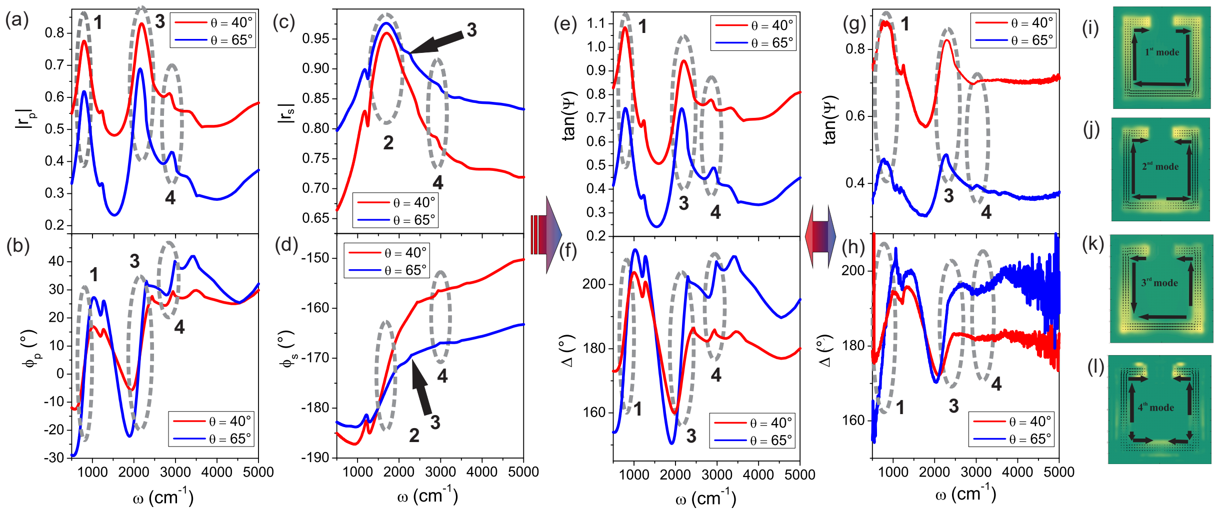

Fig. 2: The incident plane is parallel to the gap. Amplitudes (a), (c) and the phases (b), (d) of the reflection coefficients for p- and s-polarizations, respectively at two different angles of incidence are shown. Calculated (e), (f) and measured (g), (h) ellipsometric spectra are presented. The distribution of the perpendicular component of the surface electric field and current density for (i) first, (j) second, (k) third and (l) forth plasmonic modes.

are seen in ϕ_p and ϕ_s spectra as a steep increase (step), Fig. 2(b) and 2(d). Therefore the steps in ϕ_p correspond to steps in Δ.

In conclusion, it is shown that the first and third SRR plasmonic modes can be clearly identified in the ellipsometric spectra for the incident plane parallel to the gap. The features of the even resonances are not sharp enough to be directly seen in the measured spectra, although they have been clearly identified in calculations. This work was supported by the Serbian Ministry of Scinece under project No. OI171005. We also acknowledge funding by the European Communitys 7th Framework Programme under grant agreement no 228637 NIMNIL (www.nimnil.org).

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