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Plasmonic Antireflection Coatings in the Infrared

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Introduction

Antireflective (AR) coatings are used in many optical applications such as flat-panel displays, solar cells, lasers and other optoelectronic devices. Until recently, efforts for realizing low surface reflectivity have been concentrated on thin dielectric films, where the structural profile of the film is used to create a gradual change in the refractive index between the air and substrate. As an alternative to this approach, there has been much interest in pushing frequency-selective-surface (FSS) technology, a technology which is well known in the literature for its filtering characteristics at microwave and millimeter frequencies, to infrared frequencies for filtering applications. With frequency-selective surfaces (examples include periodic conducting elements placed on a dielectric substrate or opening apertures in a conducting sheet), the filtering response is realized due to the photon-plasmon coupling associated with the structured periodic surface rather than through an impedance-matching concept. Thus, following along the path of the microwave community, attention in this work is confined to the transmission response of single-layer FSS screens consisting of arrays of circular apertures and crossed-dipole apertures, in order to ultimately realize an AR surface with a high angular and frequency bandwidth in the mid-infrared frequency range.

Although the theory behind frequency-selective surfaces is relatively mature in the microwave community [1.2], the issue of absorption (ohmic loss) associated with metallic elements has received relatively little attention. While for typical microwave applications the loss associated with the metal is small compared to the dielectric loss, this is not the case in the infrared frequency range. In general, the amount of absorption will be dependent on the operating frequency and also the particular FSS geometry. Thus, for the purposes of further understanding the behavior of FSS surfaces at IR frequencies and ultimately designing efficient AR surfaces that can be practically realized, one aspect of the FSS design process that is examined is the effect of absorption on the spectral response of the structures.

As previously mentioned, there has been considerable effort in demonstrating how the spectral response of an FSS is influenced by the element shape, element size, and periodicity of the array. While the effects of varying these parameters are also considered in this IR work, at these frequencies it important to keep in mind current fabrication technology and the corresponding constraints. To date, Sandia National Laboratories' fabrication capabilities (MESA [3]) allow for minimum feature sizes on the order of a micron and with the preferred choice of plated gold $\left(\rho = 3.1\times10^{-8}\,\Omega/m, \sigma = 3.23\times10^{7}\,S/m\right)$ as the perforated surface, thicknesses of approximately 2 um. Another FSS feature that is of interest here and that will be very closed tied to current fabrication capabilities is a tailoring of the aperture profile through the depth of the perforated metal, as shown in Fig. 1. Although this presents a significant challenge to the fabrication of IR antireflective surfaces, variations in the aperture profile through the metal surface can be used to manipulate the quality factor associated with the aperture and thereby control the FSS bandwidth, as well as stabilize the transmission properties with regard to incident polarization. Measurement and simulated results contrasting the transmission behavior of a circular aperture array with straight hole profiles to the transmission associated with a tapered circular-hole aperture array can be found in [4].

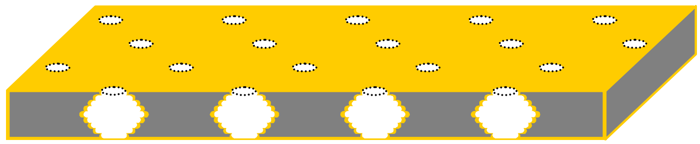

Fig 1. Structured apertures for additional spectral response control.

Design Considerations

The ultimate goal of this work is to produce low-loss, polarization and angle insensitive, and broadband transmittance responses in the 2μm to 5μm range. In this section, we outline some general FSS design rules which are based on physical intuition and that have been validated by numerical calculations.

In order for the overall FSS (the entire collection of unit cells) to be insensitive to the polarization of the incoming plane wave, it is necessary that the unit-cell itself polarization insensitive; i.e. the unit-cell or radiator does not have a preferred direction of excitation. This fact limits the unit-cell geometry to highly symmetrical structures that are preferably as close to isotropic as possible.

To avoid the onset of unwanted higher-order grating lobes at high steering angles, active antenna arrays are often designed conservatively to have a period Λ less than $\lambda_{min}/2$ where λ_{min} is the wavelength corresponding to the highest operational frequency. Conversely, in the receiving mode reciprocity ensures that power received is optimal and is not re-radiated in the grating lobe direction for high angles of incidence. The limitation that the period be less than $\lambda_{min}/2$ for optimal angle reception limits the element size, which has significant consequences on the frequency response of the FSS. Considering a simple dielectric-filled circular aperture with a fundamental cut-off wavelength (TE_{11}) given by $\lambda_c = 2\pi r\sqrt{\varepsilon_r}/1.841$ (r is the radius and ε_r is the relative dielectric permittivity of the aperture), significant attenuation occurs for $\lambda \geq \lambda_c$ and thus the propagation range satisfying both the grating lobe criterion and cut-off wavelength lies within $\lambda_{min} < \lambda_o < \lambda_c$. In order to broaden the bandwidth of propagation through the aperture (given a particular λ_{min}), an increase in λ_c can be realized with an increase in either the radius of the aperture or an increase in ε_r (of the aperture filling). However, since the radius cannot be increased beyond $\lambda_{min}/4$ (since the period should be less than $\lambda_{min}/2$), the hole radius can be maximized to near this limit and further manipulation of the bandwidth can be realized by varying the dielectric constant within the aperture.

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Thus, for angle independence it is desirable to pack as many elements as closely as possible yet still retain the filtering characteristic of the unit-cell. Since decreasing the element size reduces its radiation efficiency, maintaining reasonably high-quality local resonances so as not to lose the filtering response of the FSS is critical.

Preliminary Results

For examining the spectral response of a circular-aperture array, scattering analysis is performed using the Mode Matching-Extended Generalized Scattering Matrix method [4,5](MM-EGSM). Considering a perfect electrically-conducting (PEC) metal sheet with 0.13μm thickness, an aperture periodicity of 1.08μm, an aperture radii of 0.49μm, and a aperture filling of silicon $\left(\varepsilon_r = 11.9\right)$, band-pass transmittance centered at approximately 3.5μm (where a maximum transmittance of ~100%) is realized for both transverse-electric (TE) and transverse magnetic (TM) plane-wave excitations. The incident angles assumed in this analysis are $\theta = 45^\circ$ and $\phi = 90^\circ$. Although additional simulations investigating the behavior of the transmittance response as parameters such as the metal thickness, circular radius, and periodicity are varied, they are not included here in the interest of space.

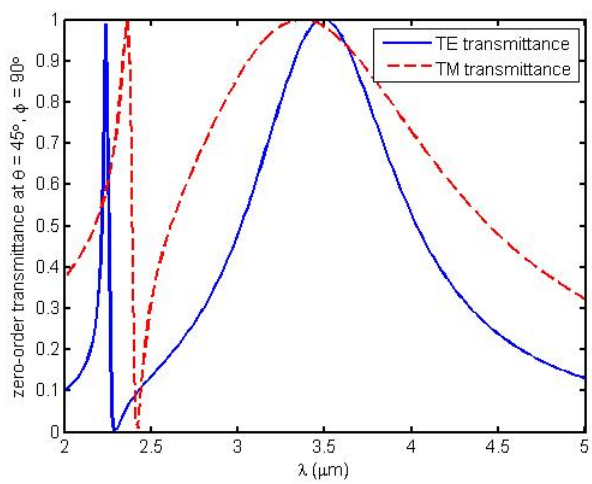
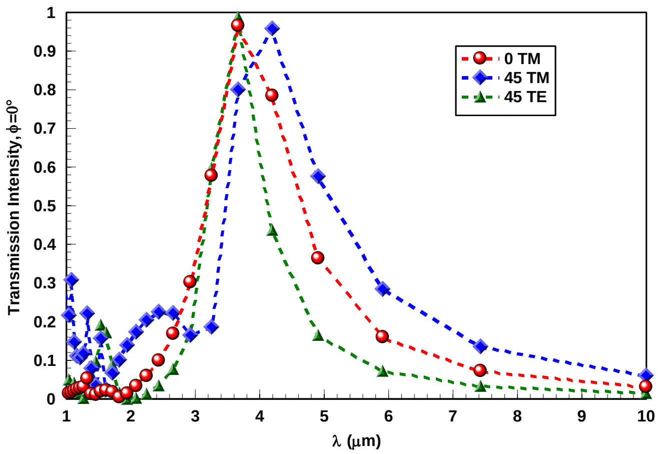
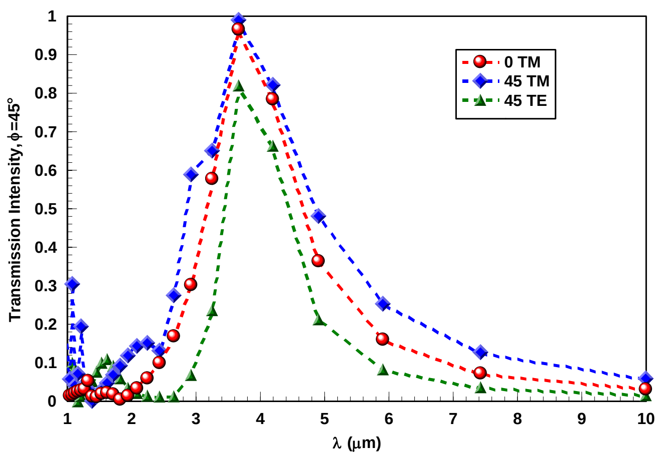


Fig. 2. Simulated TE and TM zero-order plane-wave transmittance at θ = 45° for a thick PEC sheet perforated periodically by a hexagonal array of apertures filled with silicon. The sheet thickness is 0.13μm, the radii of the apertures are 0.49μm, and the array periodicity is 1.08μm.

In order to model crossed-dipole aperture arrays (this structure was chosen over an array of unidirectional dipoles since incidence-angle insensitivity is a design priority), method of moments (MoM) and rigorous coupled-wave analysis (RCWA) Sandia codes were employed. As an initial step, simulations on a PEC perforated by crossed dipoles with arm lengths of 1.75μm, widths of 0.1μm, and a periodicity of Λ=1.85μm are conducted. Fig. 3 shows the FSS performance for a variety of plane-wave excitations along the $\phi = 0, 45^\circ$ planes, predicted by EIGER™ (a MoM code [6]). Clearly, slight shifts in the transmission curves occur but overall similar performance is realized for the excitations considered.



(a).



(b).

Fig. 3. Simulated TE and TM zero-order plane-wave transmittance for a infinitely thin PEC sheet perforated periodically by a square array of crossed-dipole apertures filled with silicon. The dipole arm lengths are 1.75 μm, the dipole arm widths are 0.1μm, and the array periodicity is 1.85 μm. (a). $\phi = 0\,^\circ$ plane (b). $\phi = 45\,^\circ$ plane.

Summary

The preliminary steps in the modeling of a frequency-selective surface with a passband in the mid-infrared frequency have been presented. Further refinement of aperture shapes and profiles within the limitations of fabrication capabilities will lead to a structure that may be fabricated and tested.

References:

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