# Measuring the Spectra of Metamaterials at an Oblique Incidence

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## Introduction

The emergence of electromagnetic metamaterials has given rise to a variety of fascinating applications, including the perfect lens [1] and the optical cloaking device [2]. For a long time the study of the properties of metamaterials was limited to normal incidence only. However, it is extremely important to know the behavior of metamaterials especially in the area of imaging. In this paper, we use COMSOL Multiphysics to model a metamaterial structure at an oblique incidence.

## Use of COMSOL Multiphysics

RF module in COMSOL Multiphysics was used to set up a model for simulating a nano gold strip array illuminated at an oblique incidence. As shown in Figure 1, the structure is made of a very thin metallic array, with 10-nm thickness (*d*). The array is composed of 400-nm wide gold strips separated by narrow strips of silica; the period of the structure is 480 nm (*p*). Floquet periodic boundary conditions are applied to ensure that the electromagnetic wave is mapped from source edge to destination edge with an appropriate phase shift. The complex refractive index of gold was based on the experimental data of Johnson and Christy [3], which was interpolated using our web-based tool [4]. The model was verified using layered planar interface structures and comparing the results with those calculated using a T-matrix approach [5], and they agree with each other very well. The modeling details will be provided later in the paper.

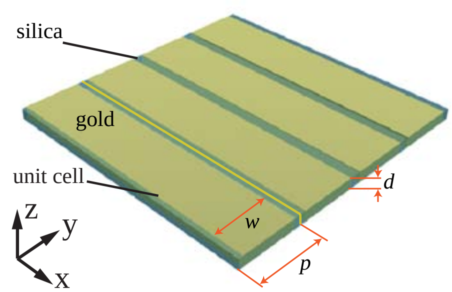


Figure 1. Schematic view of the nano gold strip array layer

## Results and Discussions

A typical field map plot of the nano gold strip array simulation domain is shown in Figure 2. At the left edge, a plane wave with free space wavelength $\lambda$ = 750 nm is generated with an oblique incidence angle $\theta$ = 30°. The wave becomes distorted near the gold strip array and recovers in the far field zone. We may also obtain the wavelength dependent transmittance and reflecttance from the model by doing an appropriate retrieving procedure. In Figure 3 we compare our simulation results with semi-analytical results calculated using 2-dimensional spatial harmonic analysis (SHA) [6]. The difference in the results is almost indiscernible.

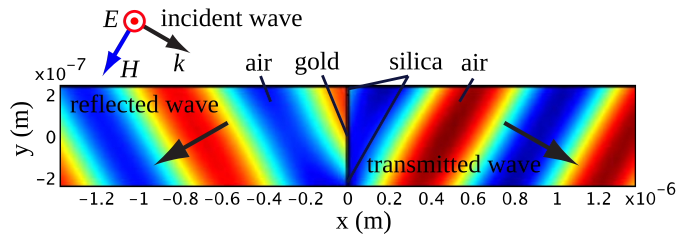


Figure 2. field map for the nano gold strip array model. A planar wave with free space wavelength $\lambda$ = 750 nm is generated at the left edge with an oblique incidence angle $\theta$ = 30°. Colors indicates the magnitude of Electrical field.

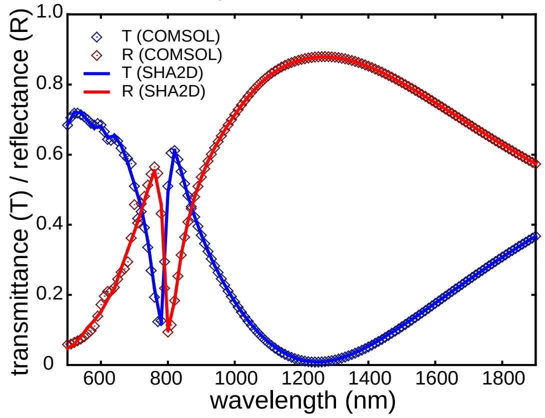


Figure 3. COMSOL-simulated (diamonds) and SHA-calculated (lines) transmittance and reflectance spectra for the nano gold strip array model at oblique incidence angle $\theta$ = 30°

## Conclusion

We set up a model for a nano gold strip array structure at an oblique incidence using COMSOL Multiphysics. The simulated transmittance and reflectance spectra are consistent with those calculated using a semi-analytical meshless SHA method. Additional details on periodic BC and COMSOL-specific modeling of dispersive material properties are discussed.

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