Incident Angle Dependence For Dual Band Double Negative Index Material Using Elliptical Nanohole Arrays

T.Cao
Faculty of Electronic information and Electrical Engineering, Dalian University of Technology, China(P.R.C) 116024

M.J. Cryan
Photonics Research Group
Department of Electronic and Electrical Engineering
University of Bristol, Bristol, BS8 1UB, UK

***Abstract*— This paper analyzes the scattering coefficients and displacement current of an elliptical nanohole array (ENA) at different angles of plane-wave incidence to show the ENA is double negative(showing both a negative effective permeability μ_{eff} and a negative effective permittivity ε_{eff}) at multiple wavelengths for *p* polarization over a broad range incident angles.**

Keywords-component; formatting; style; styling; insert (key words)

I. INTRODUCTION

Recently, negative index materials(NIMs) have become an exciting prospect because of their extraordinary optical properties such as negative refraction, near-field focusing and subwavelength imaging[1]. It is well known that Metamaterials (MMs) constitute the most promising variant of a negative refractive index material. As such, research on all-angle negative refraction and imaging of MMs has been paid more and more attention: Liu *et al* theoretically demonstrated that all-angle negative refraction could be achieved by metallic nanowires embedded in a dielectric matrix in the visible region, arising from the hyperbolic constant frequency contour of one unique indefinite metamaterial[2]; Purgos *et al* reported a Metal-Insulator-Metal (MIM) composed of Ag/GaP/Ag coupled plasmonic coaxial waveguides which exhibited a wide angle negative refraction at visible wavelengths characterized by the backward phase propagation [3]; Menzel *et al* reported on the effects of arbitrary incidence angles on the anisotropic "Fishnet" structure consisting of three layers made of Ag/MgF_2/Ag [4], however, they have shown that all retrieved parameters strongly depend on the incident angle and can only be applied to the case of normal incidence. In this work, we numerically study the angular dependence of the Displacement current, J_D in a structure composed of 2D aligned elliptical nanohole arrays (ENAs) in the Au-Al_2O_3-Au material system[5]. According to Faraday's law, the magnetic dipolar mode will be excited at the frequencies in which the formation of enclosed current loops can be observed[6]. Thus using this approach we can predict the effects of the incident angle on the double negative index for the ENA structure

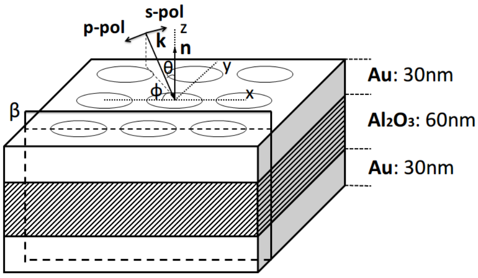


Fig. 1: Schematic of the MIM structure consisting of an Al_2O_3 dielectric layer between two Au films perforated with a square array of elliptical holes suspended in air. The displacement current is shown in the plane β

II. FDTD MODELLING

Figure 1 shows a schematic of the structure which consists of a two-metallic films(30nm thick Au) separated by a dielectric layer (60nm thick Al_2O_3). A two dimensional square lattice ENA(lattice constant: L=687nm, hole diameter: d_1=470nm,d_2=332nm) has been embedded through the entire MIM structure. The unit cell is periodically extended along the x and y directions and the lattice axes coincide with the coordinate axes. The oblique incident angle θ is defined by the angle between wave vector k and the z axis. φ is the angle between the parallel (to the xy plane) component of the wavevector and x axis. The displacement current is shown in the plane β. The layers have a thickness of T_{Au}=30nm and T_{Al2O3}=60nm. A simple Drude model is used for the dielectric constant of the Gold, $\varepsilon(\omega)=1-\frac{\omega_p^2}{[\omega(\omega+i\omega_c)]}$, where $\omega_p=1.37\times10^{16}$ Hz is the plasma frequency and $\omega_c=4.08\times10^{13}$ Hz is the scattering frequency for bulk gold. The refractive index of Al_2O_3 is 1.62. The computational domain (687nmx687nmx1000nm) has perfectly match layer(PML) absorbing boundaries in the z direction and periodic boundaries in the x-y plane. The FDTD mesh size is 10nm which was found to be a good tradeoff between accuracy and simulation run time. A plane wave is incident at variable angle on the structure as described in figure 1. Figure 2 shows the simulated transmission spectrum for the *p* polarized plane wave incident at different off-axis angles θ for a fixed $\varphi=0^0$. It can be seen that the transmittance dip/peak tends to reduce when the angle θ increases. However their locations show no obvious deviation, indicating the negative index can happen at the oblique angle of the incidence.

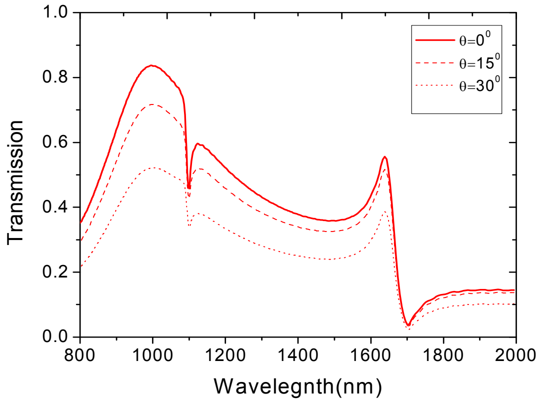


Fig. 2: 3D FDTD simulation of the transmission for the ENA for *p* polarization at different incident angle θ

The longer wavelength resonance at 1680nm is attributed to the L-C circuit resonance, the resonance around 1095nm implies that there is a significant variation in the phase of the light transmitted through the structure because the light going through the different regions interferes destructively. Both of the resonance regions are believed to be connected with the magnetic response. The effective refractive index, effective permeability, μ_{eff} and effective permittivity ε_{eff} for the *p* polarized plane wave at normal incident angle can now be obtained by using the complex coefficients T and R and is shown in figure 3.

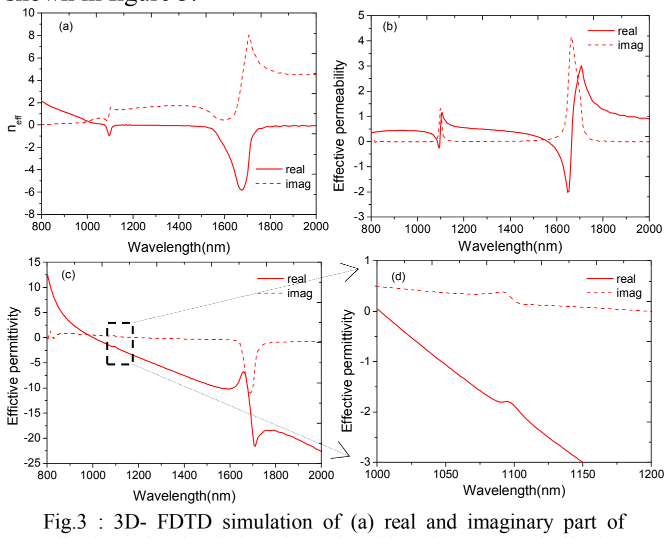
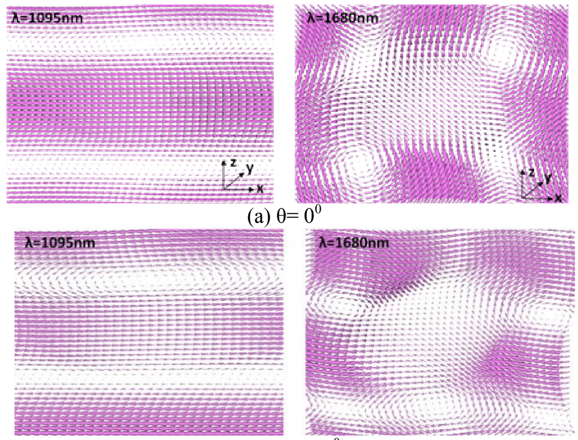


Fig.3 : 3D- FDTD simulation of (a) real and imaginary part of effective refractive index; (b) real and imaginary part of effective permeability μ_{eff} ;(c) real and imaginary part of effective permittivity $\varepsilon_{eff;}$ (d) Zoom in picture of the real and imaginary part of effective permittivity ε_{eff} for the elliptical nanohole array;

In order to validate the existence of the magnetic dipoles, we then simulate the J_D at off-normal incident angle θ. The J_D at different θ is shown in Figure 4 showing the expected magnetic dipole.



(b) θ= 30⁰

Fig.4: The displacement currents inside the ENA for the differently oblique angle of the incidence at λ =1095nm and λ =1680nm respectively:(a) θ=0⁰ ; (b) θ=30⁰

It can be seen that at rather large angles of incidence (30⁰), a loop of the J_D still appears in the structure. This is due to the fact that the orientation of the magnetic dipole is maintained when the incident angle is varied and it can maintain the strength of the magnetic resonance over a wide angle. These results suggest that such a structure can show a negative index over a wide angle of incidence.

III. CONCLUSION

In summary, a broad angle dual band negative index material implemented by an elliptical nanohole array consisting of an Al_2O_3 dielectric layer between two Au films is simulated using the 3D FDTD method. Depending on the polarization of the normally incident light, different spectral behaviour is observed. For *p* polarization, dual band negative index is achieved around 1095nm and 1680nm. We have made a further step in the study of the optical properties of the structure at different incident angle by means of the Displacement current, J_D and transmission spectrum. It can be seen that the formation of closed J_D loops are in a good agreement with the magnetic responses (transmission spectrum) at 1095nm and 1680nm respectively. Such a structure can achieve dual band negative index with broad angle.

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