Dual-Band Negative-Index Metamaterials in the Near-Infrared Frequency Range

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Introduction

In recent years, the science and engineering communities have witnessed a growing interest in the design and demonstration of negative-index metamaterials (NIMs). Latest developments now include NIMs that operate in the near-infrared (near-IR) [1] and the visible [2] spectrums. To date, all the NIM designs reported in the literature exhibit single-band negative-index behavior. This paper introduces NIM designs in the near-IR range that feature negative index behavior in two distinct bands by extending the two-dimensional single-band NIM design reported in [3]. The transmission and the reflection coefficients corresponding to the scattering problem of a single-layer metamaterial illuminated by a time-harmonic plane wave at normal incidence are obtained by a periodic form of the finite element-boundary integral method [4]. The equivalent material parameters are then recovered by a well-established homogenization method [5].

Two-Dimensional Design

Resonators of different physical dimensions can be incorporated into a unit cell of an infinite array to provide magnetic resonances in two separate bands. Noble metals have dielectric functions with negative real parts and relatively low losses at high frequencies. Hence, thin metal films can provide the negative permittivity needed to produce a negative index of refraction. Fig. 1(a) shows the unit-cell geometry of a two-dimensional dual-band NIM design, which is infinite in the $\pm\hat{y}$ directions. A magnetic resonator comprises two thin silver strips of thickness t separated by an alumina layer of thickness d. Two resonators of different widths w_1 and w_2 are placed in one period, and the space between them is filled with silica. Thin silver films of thickness t_f bind the array of magnetic resonators tightly from both sides. Protective silica layers of thickness t_s are applied on the outside. Finally, the entire metamaterial structure is placed on a thick glass substrate, which is treated as a glass half-space in simulations. Alumina, glass, and silica are treated as homogeneous, isotropic dielectrics with the relative permittivities equal to 2.6244, 2.25, and 2.088, respectively. Published measurement data in the near-IR range for the permittivity function of bulk silver [6] with respect to wavelength were used to represent the silver. The metamaterial is illuminated by a plane wave at normal incidence from the $+\hat{z}$ direction with the electric field polarized in the $+\hat{x}$ direction.

Figs. 1(b)–(d) show three effective parameters for an example metamaterial design

— the index of refraction $n = n' + in''$, the effective permittivity $\epsilon = \epsilon' + i\epsilon''$, and the effective permeability $\mu = \mu' + i\mu''$. The thickness of the silver films is given by $t_f = 20$ nm, which is typically considered to be the minimum thickness for silver to form a continuous layer. Two distinct bands of the negative index of refraction can be observed around $\lambda = 1.46$ μm and $\lambda = 2.44$ μm. The indices of refraction in the two bands with the lowest loss are found from Fig. 1(b) to be $n = -1.97 + i2.70$ at $\lambda = 1.43$ μm and $n = -1.56 + i7.48$ at $\lambda = 2.40$ μm. Fig. 1(c) shows the effective permittivity, which is overall a decreasing function of wavelength mainly due to the bulk property of silver. Although the magnetic resonances provide the less-then-unity or possibly negative permeabilities needed for a negative index of refraction, it is noted that an averaging effect over constituent materials is dominant for the effective permittivity. Large negative permittivities are supplied by the silver films, and hence the thickness t_f has a strong effect on ϵ. The effective permeability μ is shown in Fig. 1(d).

Simulation results show that a smaller value of t_f will improve the loss characteristic dramatically compared to what is demonstrated in Fig. 1(b). However, thinner silver films pose a significant fabrication difficulty because the silver will eventually cease to form a continuous layer. This trade-off between the loss characteristic and the fabrication difficulty may be solved by replacing the silver films by thicker silver strips which are periodic in the $\pm\hat{y}$ directions and infinite in the $\pm\hat{x}$ directions. Numerical results show that the periodic strips with thickness 20 nm, width 80 nm, and period 240 nm can reduce the loss of the metamaterial to the level achievable with continuous silver films of thickness 6 nm.

Three-Dimensional Doubly-Periodic Design

The two-dimensional design can be extended to a three-dimensional design so that the dual-band NIM behavior becomes independent of the polarization of the incident field. Fig. 2 shows a doubly-periodic dual-band NIM design and the equivalent index of refraction n. A pair of square plates separated by a thin alumina layer comprise a magnetic resonator. Arranging magnetic resonators of different dimensions in an alternating fashion within the unit cell of a doubly-periodic array can result in dual-band magnetic resonances. Rather than using continuous silver films, thick silver strips running in the $\pm\hat{x}$ and the $\pm\hat{y}$ directions collectively form a mesh with the grid points located at the centers of the magnetic resonators. The dimensions of the silver mesh are designed such that the negative permittivities from the bulk silver outweigh the positive permittivities from other constituent materials in an averaging manner so that the effective permittivity of the metamaterial becomes negative.

For the design shown in Fig. 2(a), the dimensions of the magnetic resonators in the horizontal plane are equal to 450 nm $\times$ 450 nm and 375 nm $\times$ 375 nm, respectively. Their vertical dimensions are the same as in the two-dimensional design. The cross-sectional dimensions of the silver mesh are given by 150 nm $\times$ 40 nm. Two distinct negative-index bands are observed around $\lambda = 1.78$ μm and $\lambda = 2.23$ μm. The imaginary part of n tends to increase with wavelength for $\lambda > 1.7$ μm, but it is important to observe that the overall level of loss represented by n'' is significantly lower than that of the two-dimensional design that uses continuous silver films shown in Fig. 1(b).

Conclusion

Near-IR metamaterials exhibiting dual-band negative-index behavior have been presented. Magnetic resonances in two bands are obtained by incorporating two resonators of different dimensions into one period of an infinitely periodic design. Negative permittivities are provided by thin silver films via the naturally available negative dielectric function at near-IR wavelengths. The desired bands of the NIM behavior can be designed by proper combinations of the magnetic resonator dimensions and the silver film thicknesses. A two-dimensional example with two negative-index bands in the near-IR spectrum was demonstrated. The two-dimensional design was then extended to a three-dimensional doubly-periodic dual-band metamaterial design. It has been pointed out that the use of silver strips or meshes in place of thin continuous films significantly improves the loss characteristics of the metamaterial.

Acknowledgments

This work was supported in part by the Penn State Materials Research Institute and the Penn State MRSEC under NSF grant DMR 0213623, and also in part by ARO grant W911NF-04-1-0350, NSF-PREM grant DMR-0611430, and by ARO-MURI award 50342-PH-MUR.

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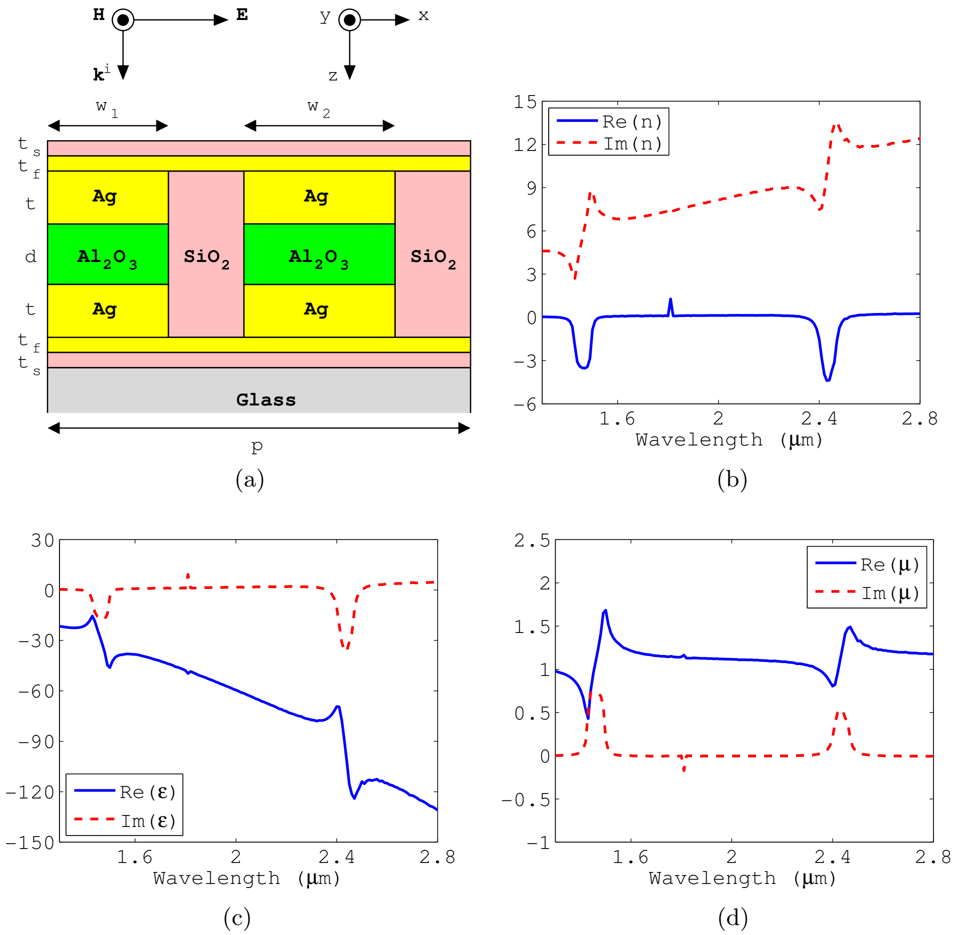

Figure 1: A two-dimensional NIM: (a) The unit cell geometry and the equivalent parameters (b) n, (c) ϵ, and (d) μ for the design with $p = 1200$ nm, $w_1 = 300$ nm, $w_2 = 525$ nm, $t = 30$ nm, $d = 40$ nm, $t_f = 20$ nm, and $t_s = 20$ nm.

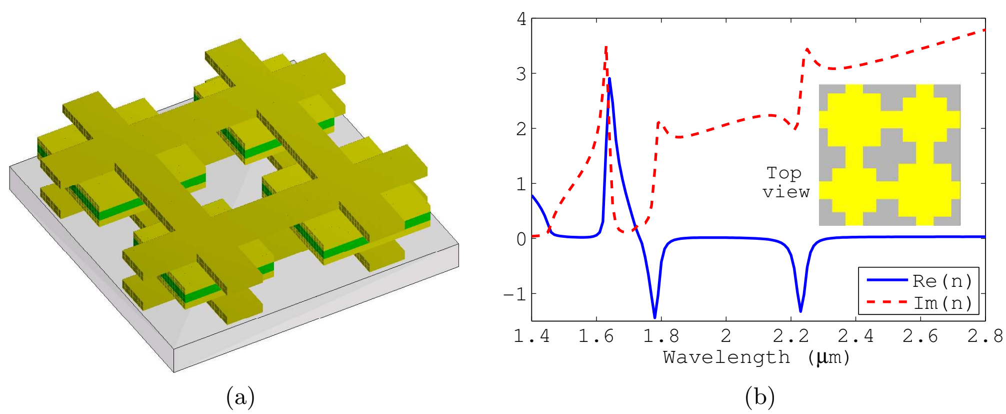

Figure 2: A three-dimensional doubly-periodic NIM: (a) The unit cell geometry and (b) index of refraction n with the top view of the metamaterial shown as an inset.