SAND2010-0874C

Infrared Cubic Dielectric Resonator Metamaterial

J. C. Ginn,[1,*] G. A. Ten Eyck,[1] I. Brener,[1] D. W. Peters,[1] and M. B. Sinclair[1]

[1] Sandia National Laboratories, P.O. Box 1585, MS 1082, Albuquerque, New Mexico 87122
[*]Corresponding author: jcginn@sandia.gov

Abstract: Dielectric resonators are an effective means to realize isotropic, low-loss optical metamaterials. As proof of this concept, a cubic resonator is analytically designed and then tested in the long-wave infrared.

OCIS codes: (160.3918) Metamaterials

1. Introduction

Metamaterials operating in the long-wave infrared (LWIR) have been developed for a wide variety of applications including filters, polarizers, spectral emissivity modifiers, planar surfaces with focusing power, and backward-wave media. The majority of these designs utilize planar metal-dielectric resonators such as split rings, dipoles, and wire meshes. Unfortunately, all of these surfaces suffer from unwanted Ohmic loss [1] and anisotropy. This paper investigates the use of an all-dielectric resonator metamaterial (DRM) surface to help ameliorate some of the limitations of conventional metallic-dielectric metamaterials in the infrared. The advantages of these three-dimensional DRM are that they can be extremely low loss, isotropic, and easily layered as composite thin-films. Initial development of an infrared DRM in the paper follows standard shielded cubic resonator analysis. The article concludes with the fabrication and testing of a practical cubic design with resonances in the LWIR.

2. DRM theory

Much like conventional metallic metamaterials, DRMs achieve effective index properties by functioning as sub-wavelength electric or magnetic resonators. One of the earliest proposed backward-wave DRMs consisted of a periodic arrangement of spherical magneto-dielectric inclusions embedded in a low-index dielectric host medium [2]. Following Lewin's analytical model for embedded spheres [3], the permittivity and permeability of these spheres were chosen to introduce overlapping electric and magnetic resonances in the composite. Wheeler extended this concept by demonstrating in simulation that a magnetic dipole resonance could be realized using spheres with a relative permeability of unity [4], as predicted from the Mie-scattering relations. Subsequently, several groups [5-7] have proposed metamaterial designs based on mediums consisting of a periodic array of two unique spheres (either with different permittivities or different radii). In these designs one sphere is responsible for the electric dipole resonance and the other the magnetic dipole resonance.

Periodically arranged curved surfaces are difficult to fabricate at the size scales necessary for operation in the infrared. Cubic resonators maintain many of the benefits of a spherical resonator including 6-fold symmetry for near-isotropic behavior and a resonant behavior dependent on the dimensions and optical properties of the element. Previous publications have proposed using cubic dielectric resonators for use at rf frequencies [8], but developed the concept assuming isolated resonators. Similarly, rectangular resonators, analogous to having spheres of two radii in one element, have been used to approximate the behavior of a split ring resonator [9].

An analytical solution for the scattering of an array of dielectric cubes does not exist and the Mie scattering algorithm cannot be directly applied. However, the resonant frequencies of the array in air can be estimated using the analytical model of a shielded cube [10]:

$$(fr)_{mnp}^{TE,TM} = \frac{c}{2a\sqrt{\varepsilon_s}}\sqrt{m^2+n^2+p^2} \quad (1)$$

TE: m, n = 0, 1, 2…; p = 1, 2, 3…; m = n ≠ 0
TM: m, n = 1, 2, 3…; p = 0, 1, 2…

where a is the length of the cube, c is the speed of light in a vacuum, and ε_s is the permittivity of the inclusion. Unlike the sphere, the cubic resonator has degenerate TE (electric) and TM (magnetic) modes which precludes the need for variable-size inclusions to achieve backward-wave propagation conditions. The lowest-order resonances of this cavity that can be excited externally are the TM_{111} and TE_{111} modes. While useful for back-of-the-envelope calculations, care must be taken when designing DRMs solely using Eq. 1. Unless a significantly high index material is utilized for the DRM, field leakage out of the cavity will occur. This leakage will result in undesirable coupling between neighboring cubic elements that increases with increasing filling factors. Coupling shifts the cavity resonance frequencies of the DRM and allows for the formation of hybrid modes. In addition, because the TE modes are more sensitive to field leakage and the dielectric host media, the electric resonances will not be perfectly degenerate with the magnetic resonance.

3. Demonstration of a LWIR DRM

To satisfy the classical definition of a metamaterial, the dielectric resonator element must be small relative to the resonance frequency. From Eq. 1, a large index inclusion material is desirable since the index scales with the resonant wavelength. Selection of a high index material also increases the Q of the dielectric resonator by increasing the impedance mismatch between the boundary of the resonator and the host media. Unlike in the rf portion of the spectrum, high index materials with low loss are uncommon in the infrared. Thus, Germanium (Ge) was selected for its reasonably high permittivity ($\varepsilon_r \approx 16+0j$), its lack of phonon resonances in the LWIR, and its familiarity in fabrication processes. From the shielded-resonator equation, a cube with dimensions of 1.75 μm will have a primary resonance that falls around 8.0 μm. A resonator filling factor of 19% was chosen to ensure element separation distances that are compatible with conventional lithography processes and to minimize neighbor cavity coupling. This filling factor yields an element to element spacing of 3.05 μm or 0.38λ at the primary resonance.

Modeling of the 1.75 μm Ge cubes was carried out using the commercially available rigorous coupled wave analysis (RCWA) program, GDCalc. The dispersive optical properties for Ge used in the model were measured using a J. A. Woollam infrared variable angle spectral ellipsometer (IR-VASE) and the cubes were assumed to be suspended in a vacuum. Results are shown in Fig. 1. As expected, the primary resonance of the surface has been shifted to 7.8 μm because of cavity leakage. In addition, an overlapping higher-order resonance can be observed peaking around 6.35 μm. This broad overlap is due to neighbor cavity coupling and the formation of hybrid modes. Most importantly, no loss features can be observed in the spectrum.

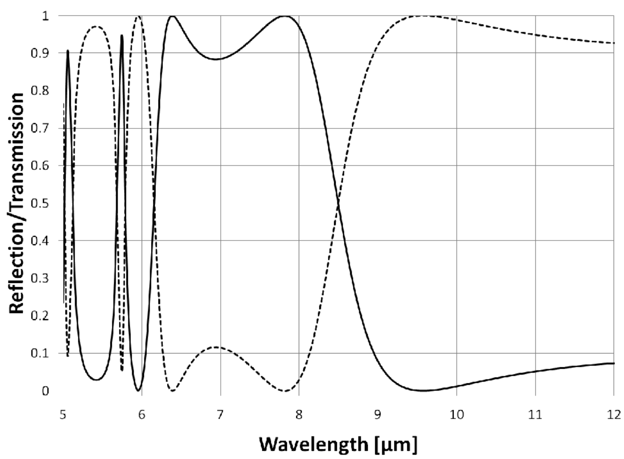

Fig. 1: RCWA results of the spectral transmission (dotted) and reflection (solid) of a periodic array of Ge cubes excited at normal incidence.

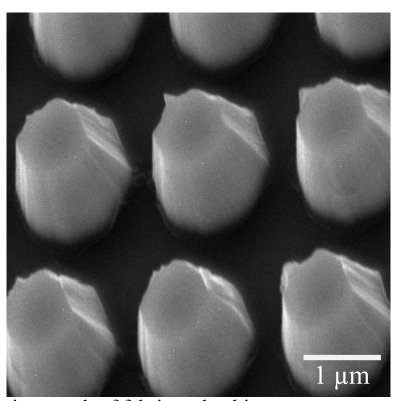

Fig. 2: SEM micrograph of fabricated cubic resonators at a 30 degree tilt.

To further validate the modeled results, a modified version of the Ge DRM surface was fabricated and tested using the IR-VASE system in FTIR mode. Because a support substrate was necessary, the cubes were fabricated on a 1.2 μm thick film of Dow Corporation Benzocyclobutene (BCB) which had been spun-on a 380 μm thick high-resistivity silicon (Si) wafer. The low-index BCB film was required to provide an adequate isolation layer between the high index Ge and Si. Fabrication of the cubes followed a standard contact-lithography process. Development error and residual resist left over from lift-off of the thick 1.7 μm electron beam evaporated Ge film resulted in a trapezoidal distortion of the cubes' geometry, as seen in Fig. 2. Deposition also necessitated a 5nm Ti layer for adhesion which, coupled with the vibrational modes in the BCB film, resulted in the appearance of unwanted thermal loss. Nevertheless, measured results of these cubes demonstrated excellent agreement with modeled (Fig. 3) and the double peak seen in the ideal design is clearly present in the measured data. Below 7 μm, the appearance of appreciable diffraction resulted in deviations between the model and measured data; however, general features are still present. It should also be noted that the dip in transmission around 9.5 μm is due to an absorption in the BCB and not a DRM mode.

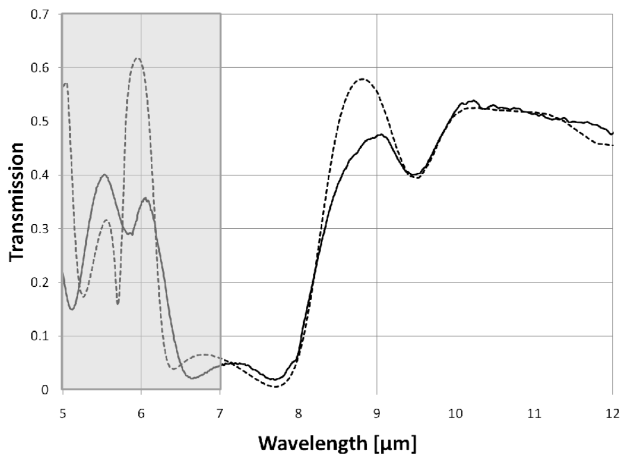

Fig. 3: Modeled (dotted) and measured (solid) transmission for the DRM prototype excited at normal incidence. The grey window represents the spectral region where element diffraction becomes significant. The modeled results are for the 0^{th} order mode of a ideal cube geometry.

4. Summary

A cubic dielectric resonator based metamaterial was designed and experimentally tested in the LWIR showing excellent agreement with simulation and low loss. Dielectric resonators are highly desirable in the optical portion of the spectrum because of their low loss and polarization insensitivity. Future research will be focused on improving lithography and developing higher-index infrared materials.

5. Acknowledgment

This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000

6. References

[1] J. Raynolds, B. Munk, J. Pryor, and R. Marhefka, "Ohmic loss in frequency-selective surfaces," J. Appl. Phys. **93**, 5346 (2003).
[2] C. Holloway, E. Kuester, J. Baker-Jarvis, and P. Kabos, "A Double Negative (DNG) Composite Medium Composed of Magnetodielectric Spherical Particles Embedded in a Matrix," IEEE Trans. Antennas Propag. **51**, 2596-2603 (2003).
[3] L. Lewin, "The electrical constants of a material loaded with spherical particles," Proc. Inst. Elec. Eng. **94**, 65-68 (1947).
[4] M. Wheeler, J. Atichison, and M. Mojahedi, "Three-dimensional array of dielectric spheres with an isotropic negative permeability at infrared frequiencies," Phys. Rev. B **72**, 193103 (2005).
[5] L. Jylhä, I. Kolmakov, S. Maslovski, and S. Tretyakov, "Modeling of isotropic backward-wave materials composed of resonant spheres," J. of Appl. Phys. **99**, 043102, (2006).
[6] I. Vendik, O Vendik, I. Kolmakov, and M. Odit, "Modeling of isotropic double negative media for microwave applications," Opto-Elec. Rev. **14**, 179-186 (2006).
[7] J. Loui, J. Carroll, P. Clem, and M. Sinclair, "Experimental Realization of Low-Loss 3D Isotropic DNG Materials," Metamorphse Conference (2009).
[8] J. Kim and A. Gopinath, "Simulation of a metamaterial containing cubic high dielectric resonators," Phys. Rev. B **76**, 115126 (2007).
[9] B. Popa and S. Cummer, "Compact Dielectric Particles as a Building Block for Low-Loss Magnetic Metamaterials" Pys. Rev. Lett. **100**, 207401 (2008).
[10] C. Balanas, *Advanced Engineering Electromagnetics*, (Wiley, New York, 1989).