All-Dielectric Infrared Metamaterials

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Abstract

We describe the design, fabrication, and characterization of an all-dielectric metamaterial operating in the thermal infrared. The dielectric metamaterials is based on cubic dielectric resonators fabricated from Tellurium and arrayed on a Barium Fluoride substrate. As predicted by analytical and numerical simulation, the metamaterial exhibits a magnetic resonance near 10 μm wavelength, as well as an electric resonance at a slightly shorter wavelength. The retrieved effective parameters indicate a negative permeability (permittivity) in the vicinity of the magnetic (electric) resonance. This work represents a first step toward the development of low loss infrared metamaterials suitable for device applications.

1. Introduction

Metamaterials comprising metallic inclusions such as split ring resonators have been utilized for numerous device demonstrations at microwave frequencies [1–3]. Unfortunately, the increased impact of ohmic losses renders metal-based metamaterials too lossy for devices at optical wavelengths (infrared and shorter). A possible strategy to overcome this fundamental limitation is to replace the metallic inclusions with high permittivity dielectric resonators [4,5], thereby replacing lossy conduction currents with displacement currents. A further advantage of the utilization of dielectric resonators is the isotropic metamaterial response that arises due to the high degree of symmetry exhibited by typical resonator shapes (i.e. spheres and cubes). This paper describes our recent efforts to design, fabricate, and characterize dielectric resonator metamaterials in the thermal infrared (8 – 12 μm) spectral range.

2. Design and Fabrication

Tellurium (TE) was chosen as the resonator material due to its high permittivity and low residual loss in the thermal infrared [6]. In addition, BaF_2 was chosen as the substrate material for its low refractive index and high transmission. The electromagnetic response of an array of Te cubes on BaF_2 was simulated using rigorous coupled wave analysis (RCWA). These simulations revealed that the resonant modes of cubic resonators are qualitatively similar to those of spheres, with the lowest frequency mode corresponding to a magnetic dipole resonance and an electric dipole resonance at a slightly higher frequency. An edge length of 1.7 μm for the Te cube was chosen to center the fundamental magnetic resonance at 10 μm, and the periodicity of the array was chosen to be 3.4 μm

A 1.7 μm Te film was deposited on a BaF_2 optical flat using electron-beam evaporation and the optical properties of the Te film were measured using infrared variable angle spectroscopic ellipsometry (IR-VASE). The films were patterned using electron-beam lithography and etched using a reactive ion etching (RIE) process. Figure 1 shows a scanning electron micrograph of the etched sample. The etching process resulted in excellent uniformity over a 1 cm^2 area, with only a slight over-etching of the pattern. The final resonator element was 1.7 μm tall with a 1.53 x 1.53 μm base and a 10 degree sidewall slope.

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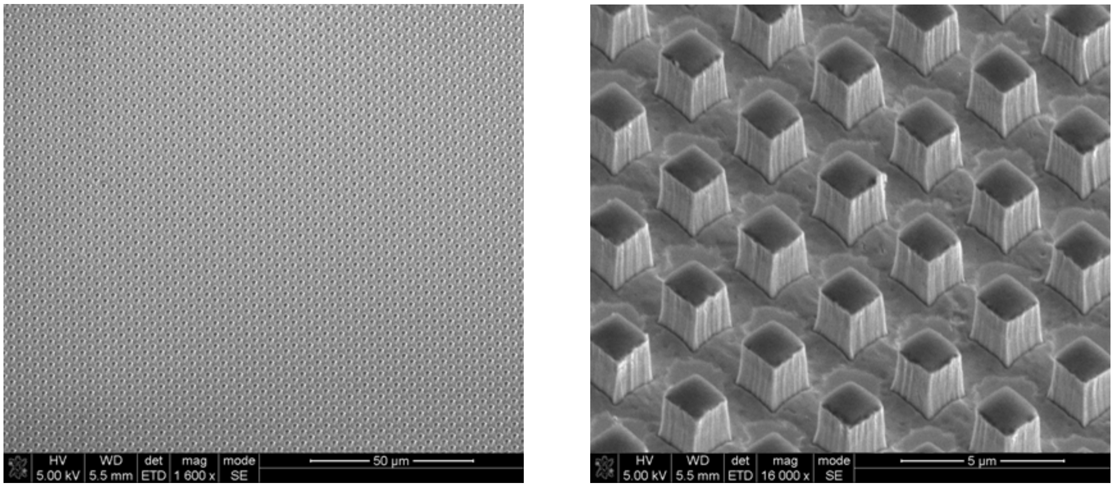

Fig. 1: Scanning electron micrographs of the cubic dielectric resonator metamaterial. (Left)Wide field image showing that excellent uniformity was obtained over large areas. (Right)Close-up showing the features of the cubic resonators.

3. Results

The top panel of Figure 2a shows the measured normal incidence transmission and reflection of the Te metamaterial. The bottom panel of Fig. 2a shows the transmission and reflection obtained using RCWA simulation assuming a cube edge length of 1.45 μm (obtained by averaging the dimensions of the as-fabricated cubes). The measured optical properties of the Te film were used in the simulation. Good agreement is obtained between the measured and simulated spectra, apart from an overall spectral shift. The origin of this shift may be due to the slight slope of the sidewalls of the as-made cubes which was not included in the simulation. The electric field mode patterns obtained from the RCWA simulations at the two reflectivity peaks confirm the magnetic dipole nature of the λ=8.7 μm resonance and the electric dipole nature of the λ=6.8 μm resonance.

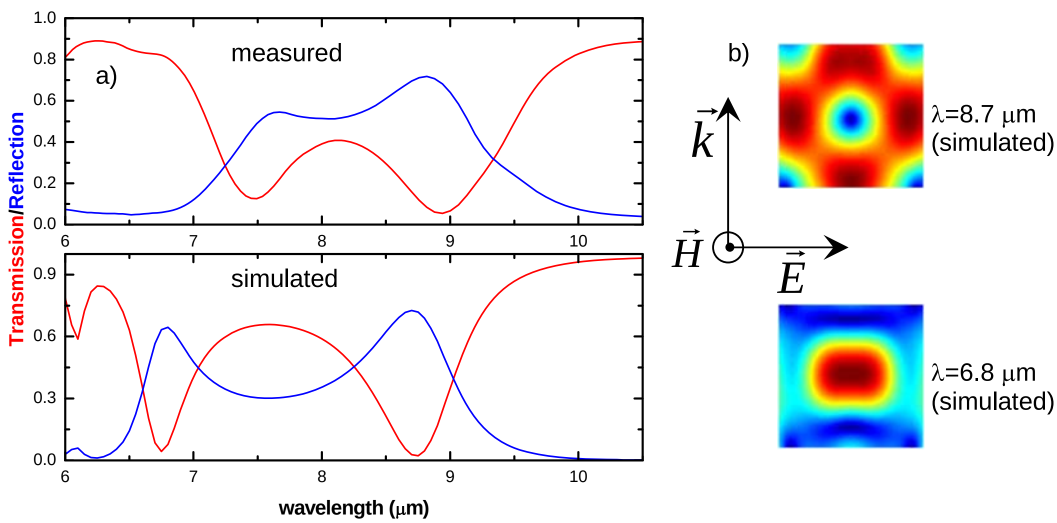

Fig. 2: a)Measured (top panel) and simulated (bottom panel) transmission and reflection of the Te cube based metamaterial. b)Simulated resonant mode electric field profiles for the magnetic and electric dipole resonances.

An estimate of the effective parameters of the cubic dielectric resonator metamaterial may be obtained from the simulated transmission and reflection using a standard parameter retrieval procedure [7]. One must use caution in interpreting the results of this type of retrieval procedure since it is known to produce artifacts in cases such as this where spatial dispersion is significant [8]. This is especially true in the immediate vicinity of the resonances where the large effective refractive index leads to resonant crystal bandgap behavior [8]. Nevertheless, away from the resonances where the effective parameters are not too large the retrieved parameters yield a satisfactory description of the effective medium behavior. The retrieved parameters of the Te based dielectric metamaterial are shown in Figure 3. Resonances in the permeability and permittivity are observed in the vicinity of the reflection peaks at 8.7 μm and 6.8 μm, confirming the assignments of the resonances as magnetic dipole and electric dipole in character. Spectral regions of negative effective parameters are observed on the short wavelength sides of the resonances. The loss tangent of the permeability falls to 0.48 when the real part of permeability is equal to -1. The extinction coefficient of the Te film, as measured by the IR-VASE, is more than two orders of magnitude larger than the literature value for Te [6]. Thus, we anticipate that significantly lower-loss metamaterials will be achievable as the Te loss is minimized.

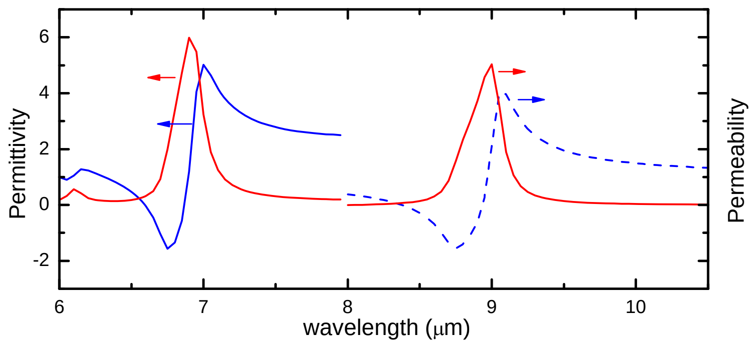

Fig. 3: The effective permeability and permittivity of the Te cubic dielectric resonator metamaterial, retrieved from the simulated transmission and reflection coefficients.

4. Conclusion

We have fabricated an all dielectric metamaterial operating in the thermal infrared. Both magnetic and electric dipole resonances are observed along with regions of negative effective parameters. The overall loss of this sample is dominated by the residual absorption of the Te film utilized which is approximately two orders of magnitude larger than the literature value for Te [6]. We anticipate significant reductions of the metamaterial attenuation losses as the Te film quality improves. If successful, this approach could lead to low-loss metamaterials suitable for applications such as transformation optics devices that require high transparency.

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