Dual-Band Planar Electric THz Metamaterial with Resonator Yield Analysis

Thomas H. Hand*+, Yu Yuan*++, Sabarni Palit*, Chris Bingham, Marco Rahm*, David R. Smith,*, Willie J. Padilla**, Nan Jokerst*, and Steven A. Cummer***
**Department of Electrical and Computer Engineering, Duke University, Durham, NC 27708*
***Department of Physics, Boston College, Chestnut Hill, MA 02467*
+thh5@duke.edu, ++yy41@duke.edu

Abstract: THz radiation transmission through a dual-band electric metamaterial is presented, where we analyze manufacturing defects in the metamaterial. Removing different resonator percentages allows us to quantify the effects of manufacturing defects on the material response.

OCIS codes: (040.2235) Far infrared or terahertz; (160.3918) Metamaterials

Metamaterials are artificial electromagnetic structures that have generated a great deal of interest over the past several years. They are realized using subwavelength metallic inclusions engineered to exhibit electric and magnetic responses not readily available in nature. Since the first experimental demonstration of negative refraction using metamaterials [1], significant progress has been made in developing these structures in the microwave regime due to the convenience in fabrication and measurement at these frequencies. Metamaterials responsive to THz radiation require movement towards smaller unit cell sizes. Most natural materials are unresponsive to terahertz radiation, and metamaterials can fill this terahertz "gap," permitting the design of novel devices and components such as antennas, lenses and phase shifters [2-5]. We present measurements of a planar electric dual-band resonant metamaterial in the vicinity of 1-2 THz. Our goal is to quantify the effect that manufacturing defects (e.g. missing or damaged resonators) have on the transmission response through the structure. In practice, there will always be some tolerance and defects on the resonator features composing the metamaterial, and the resonator yield will significantly affect the ultimate cost to manufacture these metamaterials. To address this issue, we randomly removed different percentages of the resonators from the sample and analyzed the performance of the structure.

We designed the dual-band planar electric metamaterial using Ansoft HFSS™ full-wave commercial solver and Ansoft Q3D Extractor™. The substrate used in the simulation was Magnesium Oxide, MgO (chosen for its low losses in the THz frequency range: $\varepsilon_r \sim 10$, $\tan\delta_e \sim 0.03$ at 1 THz), and the split-ring-resonators (SRRs) were made of Titanium-Platinum-Gold layers, with thicknesses 30 nm, 40 nm, and 200 nm, respectively [6]. By designing electrically small ($\sim\lambda_0/10$) SRRs with gaps perpendicular to the electric field component of the incident wave, the electric field couples to the ring and excites resonances at $\omega_{0(1,2)} = (L_{(1,2)}C_{(1,2)})^{-1/2}$, where $L_1 \sim 17.3$ pH, $C_1 \sim 0.9$ pF are the self inductance and capacitance of the large ring, and $L_1 \sim 13.2$ pH, $C_1 \sim 0.9$ pF for the smaller ring. The excited resonant frequencies for the individual SRRs alone are $f_{0,1} = 1.29$ THz and $f_{0,2} = 1.48$ THz. The SRR geometries used to realize these circuit values can be seen in Fig. 1. It is clear that mutual coupling between the SRRs will cause a shift in the resonant frequencies, and this coupling is non-negligible between like SRRs (small-to-small and large-to-large SRRs seen in Fig. 1). Since the SRRs are coplanar, the mutual inductance between like rings will be negative, and as a result we expect the effective resonant frequencies due to this interaction to be shifted higher.

The fabricated dual-band SRRs were patterned with a mirror symmetric arrangement on a MgO wafer (500 µm thick), defined by negative photolithography using AZ5214 photoresist. A metal layer consisting of Titanium (30 nm), Platinum (40 nm), and Gold (200 nm) was deposited using electron beam evaporation, followed by metal lift-off in acetone using an ultrasonic agitator. These fabricated structures can be seen in Fig. 2.When fabricating large arrays of metamaterials, there is a possibility of manufacturing defects since a certain percentage of resonators may not form properly during the development process. A study of manufacturing yield is especially interesting as one moves towards the visible wavelength range, since finer feature sizes are required. It is reasonable to investigate how the resonator defect percentage (what percentage of resonators are missing or damaged) affects the material response. In the fabricated samples, we randomly removed approximately 10 % and 30-40 % of the resonators from the substrate by progressive sonication. The corresponding magnitude response was measured for each case, and Fig. 1 contains the plots for different resonator yield percentages. The measurements were made using a Bruker Vertex 80v FTIR spectrometer, and the light source was a mercury lamp with a 4mm aperture in front of it. We used a Si-Bolometer detector cooled with liquid Helium, with the sample and detector in vacuum. It is clear to see from these measurements that larger defect percentages yield weaker resonant

978-1-55752-859-9/08/$25.00 ©2008 IEEE

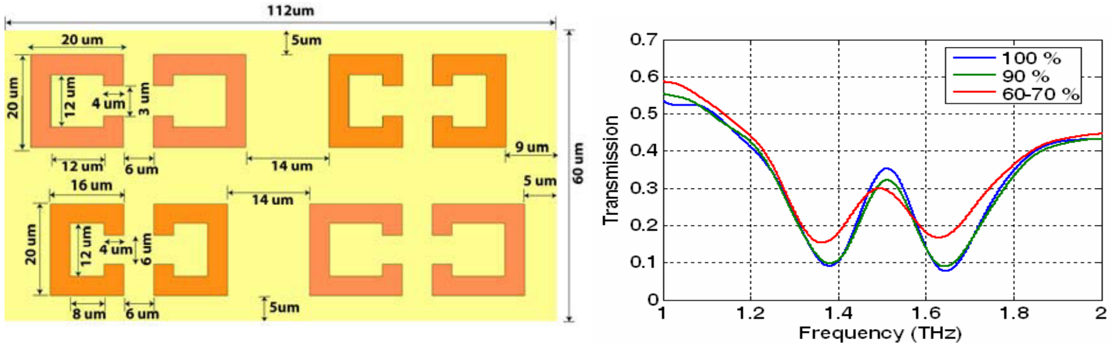

Figure 1: Left: Schematic of unit cell used in the experiment. **Right:** Responses of the samples for various resonator yield percentages.

responses, and this can be attributed to the fact that a more defective medium has a smaller oscillator strength. The quality factor of the individual SRRs and the oscillator strength, which is linked to the spatial concentration of resonators both affect the metamaterial response [7]. The decreased oscillator strength due to larger defects will weaken the magnitude of the transmission minima. From Fig. 1, the bandwidth of the resonances does not change significantly, from sample to sample, implying that the quality factor of the medium is invariant to changes in manufacturing defect percentage. It is also interesting to point out the measurable shift in the resonant frequencies for reducing the manufacturing yield from 100% to approximately 60-70%. This shift is due to the decrease in magnetic coupling between the resonators (due to lower resonator concentration), which reduces the mutual inductance between like particles and increases their effective inductance. This change in coupling is not as pronounced for the sample with a 90% manufacturing yield.

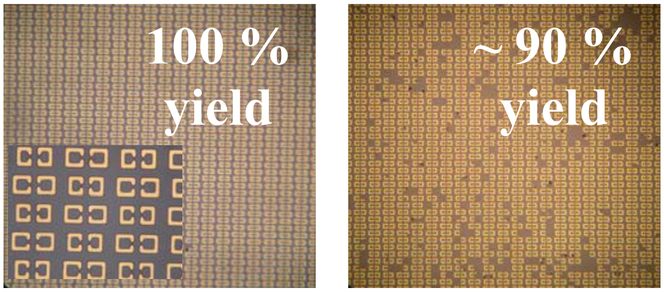

Figure 2. Left: Picture of fabricated planar electric metamaterial with 100% of resonators present. The inset of this picture shows a close-up view of the SRRs. **Right:** metamaterial surface with approximately 90% yield.

In conclusion, a dual resonance electric THz metamaterial was designed, fabricated and experimentally characterized. The metamaterial showed a strong dual band resonant response in the frequency range between 1 and 2 THz. The effect of resonator yield on the transmission response was analyzed, and a weakened transmission response with increased defect percentage was verified. We observed that small (~10%) defects affect the transmission response marginally whereas larger defects (~30-40%) have a non-proportional higher impact on the transmission response of the medium. The detailed understanding of the influence of manufacturing impurities on the performance and functionality of metamaterials is of fundamental importance for the design of such structured materials. These impurity effects will even be enhanced at higher frequencies where smaller structures with wider fabrication tolerances are deployed.

[1] D. R. Smith, Willie J. Padilla, D. C. Vier, S. C. Nemat-Nasser and S. Schultz, *Phys. Rev. Lett.*, **84**, 4184 (2000)
[2] H.T. Chen, W.J. Padilla, J. M. O. Zide, A.C. Gossard, A.J. Taylor, R.D. Averitt, *Nature* **444**, 2006.
[3] W.J. Padilla, A.J. Taylor, C. Highstrete, M. Lee, R.D. Averitt, *Physical Review Letters*, **96** 107401, 2006.
[4] B.D.F. Casse, H.O. Moser, M. Bahou, L.K. Jian, P.D. Gu, *NanoSingapore*, 2006.
[5] C.K. Tiang, J. Cunningham, C. Wood, I.C. Hunter, and A.G. Davies, *Journal of Applied Physics* **100** 066105, 2006.
[6] I. Kawayama, K. Kotani, M. Tonouchi, *Jpn. J. Appl. Phys.* **41**, 2002.
[7] S. A. Cummer, B/-I. Popa, and T. Hand, p. arXiv:physics/0703130, 2007.