

# How to design and characterize metal-dielectric based metamaterials: experimental demonstrations of metamaterial applications at the millimeter-wave regime.

K. B. Alici<sup>1</sup>, and E. Ozbay<sup>1,2</sup>

<sup>1</sup>*Nanotechnology Research Center, Department of Physics, Bilkent University, Bilkent, 06800, Ankara, Turkey*

<sup>2</sup>*Department of Electrics and Electronics Engineering, Bilkent University, Bilkent, 06800, Ankara, Turkey*

**Abstract:** In the present work, after detailed explanation of the metamaterials design methods, we demonstrate two different double negative metamaterial media and their properties in terms of radiation and negative refraction at the millimeter-wave regime.

© 2008 Optical Society of America

**OCIS Codes:** (160.4670) Optical materials; (260.5740) Physical Optics, resonance.

## 1. Introduction

For most solid materials the ions are arranged in a periodic array on the microscopic level [1]. In the presence of an applied electromagnetic field, the materials' response is described by (electric) permittivity ( $\epsilon$ ) and (magnetic) permeability ( $\mu$ ) parameters. By introducing an artificial periodic array wherein repeated elements of the so-called metamaterial (MTM) are arranged, we can obtain a medium with a controllable linear response. The unit cells of metamaterials are commonly composed of metallic structures of several shapes [2-4]. Electrically small nonmagnetic metallic resonators are proposed as constituting elements of a negative permeability medium [2] and metallic wire mesh structures provide a low frequency plasma system with negative permittivity [3]. Applications of double negative (DNG) and single negative (SNG) media involve the electromagnetic phenomena of reflection, absorption, radiation, cloaking, refraction, and subwavelength imaging. A miniaturized rectangular patch antenna with a  $\mu$ -negative medium substrate operating at 250 MHz [5] as well as an electrically small circular patch antenna loaded with a  $\mu$ -negative medium are characterized experimentally and theoretically [6]. A negative permeability medium element loaded monopole antenna was demonstrated experimentally at around 4 GHz in terms of its fundamental limitations [7] and multiple element effects [8]. A negative permittivity shell loaded monopole antenna was developed analytically [9].

## 2. Motivation and Results

Macroscopic Maxwell Equations are applicable for the analyses of electromagnetic materials up to ultraviolet regime, wherein quantum effects come into play and should be taken into account. Theoretical formalism of metamaterials is the same at any frequency domain including the optical regime. However, after the first experimental verification of metamaterial concepts, the studies continued and double negative metamaterials are demonstrated at different regimes of the electromagnetic spectrum. Examples of metamaterials operating at 5 THz [10], 6 THz [11], 100 THz [12], and 370 THz [13] can be found in literature. The significance of these works is not to confirm the same theory. At each band of the electromagnetic spectrum the technological problems and realization of a concept differs. If the cost of an experiment is too high, the verification of the concept would not be possible. 100 GHz is accepted as the starting point of THz regime and for the milli-meter wave applications demonstration of metamaterial concepts is at this band is important. Effective medium

theory characterization of a metamaterial is demonstrated at 100 GHz by Gokkavas et. al. [14]. The fabrication technique in this study was based on optical lithography. The achieved metal thickness was less than the skin depth at this frequency and there are considerable substrate losses. As a result a negative band with -25 dB maximum is obtained. The dynamic range was around 50 dB and thereby the experimental verification of far field radiation characteristics and negative refraction is not possible by the methods of this referenced paper. On the other hand, in this paper, we demonstrate a much more efficient technique for the fabrication of metamaterials at milli-meter wave regime. In addition to the significant reduction of cost , we obtained a rather low loss metamaterial elements with metal thickness much larger than the skin depth. The examples of the metamaterial samples are shown in Fig. 1. We have demonstrated experimentally: effective medium theory characterization, negative refraction, oblique incidence response, enhancement of transmission passing through a subwavelength slit and effects of metamaterial lens on the far field radiation. The key point in the verification of all of these metamaterial applications is utilization of thick metal features on the low loss substrate at this frequency regime.

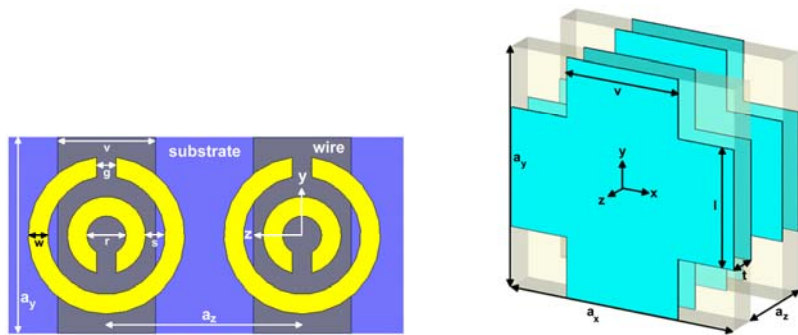


Fig. 1: Schematics of the metamaterials: the srr based composite medium (left), the fishnet structure (right).

### 3. Conclusions

In summary, the characterization of split ring resonator-based metamaterial and fishnet metamaterial operating at 100 GHz was demonstrated in terms of the qualitative effective medium theory and standard retrieval analysis. The structure layers were produced via printed circuit board technology and the transmission response for increasing the number of layers at the propagation direction was analyzed. We observed a stop-band for the SRR-only medium and pass-band for the CMM medium at around 100 GHz. The transmission peak value was  $\sim -2.5$  dB and the metamaterials average loss was  $\sim 2.5$  dB / mm. The experimental results of the SRR-based medium were not very sensitive to the layer disorders or the angle of incidence, and they were in good agreement with the numerical calculations. However, we observed a strong dependence of the transmission response on the angle of incidence for the fishnet metamaterial. Several applications of metamaterials are shown experimentally such as metamaterial lens effect on the far field radiation pattern, negative refraction and enhancement of transmission through subwavelength apertures.

### 4. Acknowledgments

This work is supported by the European Union under the projects EU-METAMORPHOSE, EU-PHOREMOST, EU-PHOME, and EU-ECONAM, and TUBITAK under the Project Numbers 105E066, 105A005, 106E198, and 106A017. One of the authors (E.O.) also acknowledges partial support from the Turkish Academy of Sciences.

### 5. References

- [1] N. W. Ashcroft, N. D. Mermin, "Solid State Physics", (Saunders College, Fort Worth, 1976), pp.66
- [2] J. B. Pendry, A. J. Holden, D. J. Robbins, W. J. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," IEEE Trans.

Microwave Theory Tech. **47**, 2075 (1999).

- [3] J. B. Pendry, A. J. Holden, W. J. Stewart, I. Youngs, "Extremely low frequency plasmons in metallic mesostructures," *Phys. Rev. Lett.* **76**, 4773 (1996).
- [4] R. A. Shelby, D. R. Smith, S. Schultz, "Experimental verification of a negative index of refraction," *Science* **292**, 77 (2001).
- [5] K. Buell, H. Mosallaei, K. Sarabandi, "A substrate for small patch antennas providing tunable miniaturization factors," *IEEE Trans. Microwave Theory Tech.* **54**, 135 (2006).
- [6] A. Alu, F. Bilotti, N. Engheta, L. Vegni, "Subwavelength compact resonant patch antennas loaded with metamaterials," *IEEE Trans. Antennas Propag.* **55**, 13 (2007).
- [7] K. B. Alici, E. Ozbay, "Electrically small split ring resonator antennas," *J. Appl. Phys.* **101**, 083104 (2007).
- [8] K. B. Alici, E. Ozbay, "Radiation properties of a split ring resonator and monopole composite," *Physica Solidi Status B* **244**, 1192 (2007).
- [9] A. Erentok, R. Ziolkowski, "A hybrid optimization method to analyze metamaterial-based electrically small antennas," *IEEE Trans. Antennas Propag.* **55**, 731 (2007).
- [10] B. D. F. Casse, M. O. Moser, J. W. Lee, M. Bahou, S. Inglis, L. K. Jian, "Towards three-dimensional and multilayer rod-split-ring metamaterial structures by means of deep x-ray lithography," *Appl. Phys. Lett.* **90**, 254106 (2007).
- [11] N. Katsarakis, G. Konstantinidis, A. Kostopoulos, R. S. Penciu, T. F. Gundogdu, M. Kafesaki, E. N. Economou, Th. Koschny, C. M. Soukoulis, "Magnetic response of split-ring resonators in the far-infrared frequency regime," *Optics Lett.* **30**, 1348 (2005).
- [12] S. Linden, C. Enkrich, M. Wegener, J. Zhou, Th. Koschny, C. M. Soukoulis, "Magnetic response of metamaterials at 100 Terahertz," *Science* **306**, 1351 (2004).
- [13] C. Enkrich, M. Wegener, S. Linden, S. Burger, L. Zschiedrich, F. Schmidt, J. F. Zhou, Th. Koschny, C. M. Soukoulis, "Magnetic metamaterials at telecommunication and visible frequencies," *Phys. Rev. Lett.* **95**, 203901 (2005).
- [14] M. Gokkavas, K. Guven, I. Bulu, K. Aydin, R. S. Penciu, M. Kafesaki, C. M. Soukoulis, E. Ozbay, "Experimental demonstration of a left-handed metamaterial operating at 100 GHz," *Phys. Rev. B* **73**, 193103 (2006).