Effective Parameters of Terahertz Metamaterials Fabricated with Microfluidic-Jet Technique.

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Effective Parameters of Terahertz Metamaterials Fabricated with Microfluidic-Jet Technique

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ABSTRACT

A cost-effective fabrication method to engineer metamaterial structures with micrometer-size features and novel mechanical properties, which are suitable for terahertz applications, is reported herein. The effective metamaterial parameter extraction procedure is employed with the Kramers-Kronig relation to analyze the effective parameters of single- and multilayer metamaterial structures.

INTRODUCTION

As frequencies increase towards the optical range, magnetisation vanishes in all natural materials and the refractive index is always positive. However, novel types of artificial composites called metamaterials were proposed with the striking property of having a negative refractive index [1]. The first physical realization of such a metamaterial was presented ten years ago for microwave frequencies [2]. Since then, researchers have increased the operating frequency of metamaterials to higher values, including the terahertz and even optical frequencies.

A conventional metamaterial design containing split-ring resonators and microstrip wires to achieve the negative refractive index is considered [3]. The novelty of the proposed fabrication procedure is the application of the microfluidic jet technique, which is a cost-effective way to manufacture large areas of metamaterials. This technique allows printing of metallic structures on a large variety of substrates. In particular, by selecting a lightweight or flexible substrate, metamaterials with novel mechanical properties can be manufactured. This can be advantageous, for example in cloaking studies, to cover a cylindrical structure with a metamaterial.

To characterize the fabricated metamaterial structures, the effective metamaterial parameters are retrieved from calculated S parameters. In order to ensure the uniqueness of the effective parameters, the procedure employed here applies the Kramers-Kronig relations to estimate the real part of the refractive index from the extinction coefficient [4].

In practical applications, a metamaterial which is only one unit-cell thick, is not very useful. Therefore we present the calculated effective parameters of single-and multi-layer metamaterials and we comment on the obtained results.

EXPERIMENTAL DETAILS

The microfluidic-jet technique is a cost-effective planar process, which allows mass production of metamaterial structures operating at terahertz frequencies [5]. It is a planar process, yet a three-dimensional metamaterial can be made by stacking several planar metamaterial layers together. In the process presented, liquid polyimide is applied as masking material and placed drop-by-drop on a 25 μm wide copper-clad polyimide substrate to create split-ring resonators and metallic wires. The fabricated metamaterial has a unit-cell size of 180 μm. After the metamaterial patterns are deposited, the sample is annealed at 160°C for 30 minutes. The deposited liquid polymide patterns act as etch-resistant masks when the sample is placed in ferric chloride etchant. Figure 1 presents the geometrical features of the fabricated planar metamaterial sample. In figure 1 (a) and (b), bright field microscope images of the fabricated copper split-ring resonators and copper wires are shown respectively. The insets indicate the geometrical feature sizes in μm. In figure 1 (c) the unit-cell of the fabricated metamaterial is presented.

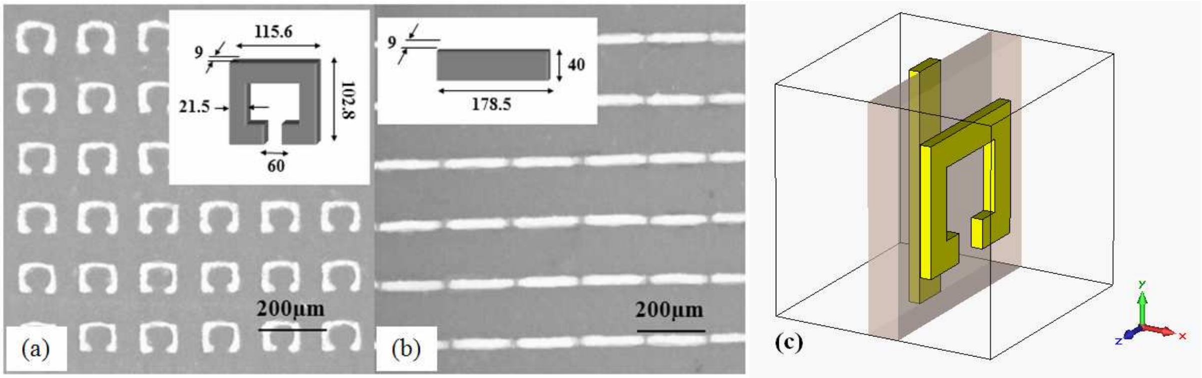
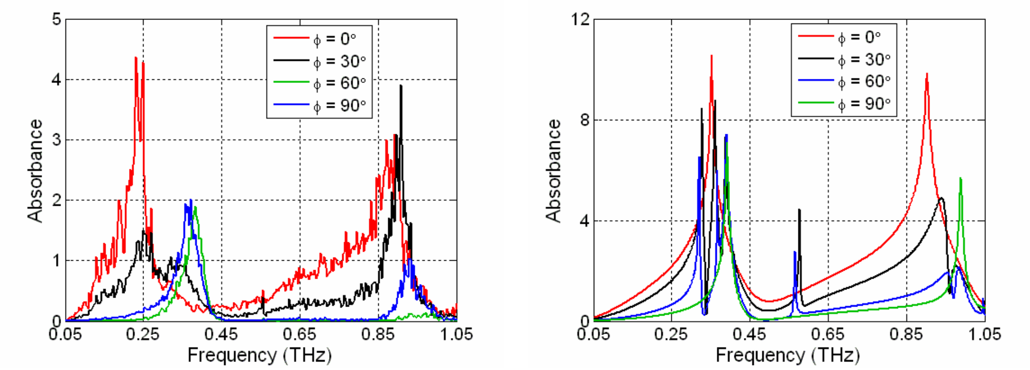


Figure 1. Bright field microscope image of the fabricated metamaterial sample: (a) copper split ring resonators, (b) metallic wires and (c) metamaterial unit-cell.

The fabricated single layer metamaterials are characterized in the frequency range of 0.1 to 1 THz, by measuring the absorbance with time-domain spectroscopy where the spectroscope operates in a transmission mode. The measured and simulated absorbance curves are plotted in figure 2. The simulated electromagnetic field and current density distribution reveal that the first absorbance peek at $\phi = 0^\circ$, corresponds to electric dipole resonance, while at $\phi = 90^\circ$, it is a magnetic resonance that is induced by the electric field in the split-ring resonators [6].



(a) (b)

Figure 2. Measured (a) and calculated (b) absorbance for a singel layer of metamaterial. The plane wave excitation has normal incidence to the surface of the substrate, which means an inclination angle $\theta = 90^\circ$ (according to the coordinate system of figure 1 (c)). The polarization of the electric field is varied with the azimuth angle ϕ. Note that $\phi = 0^\circ$ corresponds to the electric field polarized parallel to the wires.

As the graphs show, the manufactured samples give promisingly sharp absorbance peaks, indicating strong resonances. In order to further characterize the fabricated metamaterials and to be able to distinguish between electric and magnetic resonances, the effective material parameters were retrieved by numerical simulation as described in the next section.

DISCUSSION

The purpose of the effective medium theory is to provide a simplified model of the metamaterial structure by introducing the complex effective electric permittivity and magnetic permeability in such a way, that the far-field electromagnetic behavior of the metamaterial slab is replaced by the electromagnetic response of a homogeneous and isotropic slab. The validity of this simplification must be carefully verified for each particular metamaterial design. The effective medium theory cannot describe the electromagnetic behavior of metamaterials when more than one mode propagates, or when diffraction occurs. There is no obvious guideline on how to decide the validity of the effective medium theory. The usual suggestion is that the effective medium theory can be applied to a system composed of elements which are much smaller in size than the operation wavelengths. However, it is well known that in a dielectric slab, where the magnitude of the refractive index is larger than one, the spatial wavelength is smaller than the free-space wavelength $\lambda_g = \lambda/n$. To decide whether the effective medium theory can be applied or not, the spatial wavelength should be compared to the characteristic dimensions of the metamaterial. However, the effective material parameters of a metamaterial are not known a priori; therefore one cannot judge in advance the validity of the effective medium theory. The electromagnetic behavior of most metamaterial designs is anisotropic, requiring a tensor to properly describe it. Furthermore, a negative refractive index is only possible when the metamaterial is excited by a plane wave with a specific polarization direction and angle of incidence. Even when all elements of the full permeability and permittivity tensor are determined, the model can predict just the far field behavior of the structure. For most metamaterial devices, the coupling effects between the metamaterial and the surrounding structures cannot be neglected. Hence a full-wave simulation must be performed to obtain the correct electromagnetic behavior. In spite of these limitations, the effective medium theory can provide a fast and convenient way to characterize metamaterial structures.

The effective metamaterial parameter retrieval procedure used by the current authors [4] can be summarized as follows. The wave impedance can be uniquely determined by applying the Fresnel-Airy formulas. However, the calculation of the refractive index involves the evaluation of a complex logarithm that is a multi-valued function. The resulting uncertainty is referred to as branching problem, which affects only the real part of the refractive index. To remove this ambiguity, the Kramers-Kronig relation can be applied to estimate the refractive index from the extinction coefficient. The physically realistic exact values of the refractive index are determined by selecting those branches of the logarithmic function which are closest to those predicted by the Kramers-Kronig relation. The algorithm also enforces the continuity of the refractive index versus the frequency.

Consider a metamaterial of infinite extent in the xy plane. The electromagnetic wave is propagated perpendicular to the surface of the metamaterial slab ($\theta = 0^\circ$) and polarized parallel to the metallic wires ($\phi = 90^\circ$). As it will be shown later, a five layers thick metamaterial cannot be represented by effective material parameters above the first resonance peek. Therefore metamaterials with one to five layers of unit-cells in the direction of propagation are considered.

The electromagnetic field analysis and S-parameter calculations were performed with commercial software (CST Microwave Studio). The copper was modeled as a lossy metal with a conductivity of $5.8 \cdot 10^7$ S, and the substrate as a lossy dielectric with electric permittivity 3.5 and tangent delta 0.003 at zero frequency.

The evolution of the absorptance peeks as a function of the number of metamaterial layers is presented in figure 3. The figure focuses on the frequency region, where the first resonance of a single layer of metamaterial occurs. The appearance of more then one absorptance peak, with the addition of metamaterial layers, indicates a transition from single mode to multimode electromagnetic behavior.

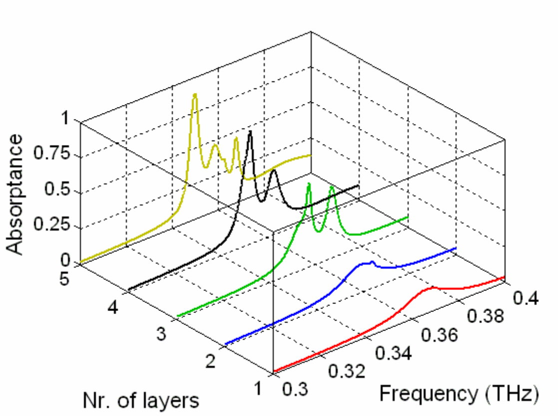


Figure 3. The absorptance of the single and multilayer metamaterials calculated with a full wave electromagnetic solver.

The S-parameters and the extracted effective metamaterial parameters for the single unit-cell thick metamaterial are presented in figure 4. The refractive index follows the branch $m = 0$ all over the investigated frequency region. Note that the change of the gradient in the phase S_{21} occurs at the same frequencies where the refractive index becomes negative. The effective parameters of the metamaterial with a thickness of three unit-cells are presented in figure 5. The figure shows that from 0.427 THz on the refractive index follows the branch $m = 1$ till the end of the investigated frequency region. Figure 6 refers to a metamaterial with a thickness of five unit-cells. Inspecting the continuity of the refractive index, a discontinuity can be observed at 0.3488 THz. The refractive index has a value of 0.2 when approaching the discontinuity point from the left, while it is -0.9 when approaching it from the right. This discontinuity may be interpreted as an upper limit of the effective medium theory [4].

CONCLUSIONS

A metamaterial has been presented for THz frequencies fabricated with the micro-jet technique. The fabricated samples have novel mechanical properties: they are lightweight and flexible. A metamaterial layer with a thickness of one unit-cell is able to produce a 180° phase shift of the magnetic field component as the electromagnetic wave propagates through the metamaterial. This phase shift leads to a negative refractive index in the 0.358 – 0.38 THz frequency region. However, in this frequency interval the near field extends approximately one unit-cell distance around the structure, leading to strong coupling between the unit-cells as the thickness of the metamaterial is increased. By adding unit-cells in the direction of propagation, more than one branch contributes to the physically possible refractive index. As the effective thickness of the metamaterial becomes comparable to the spatial wavelength, the effective medium theory can no longer be applied. The discontinuity of the refractive index indicates that a limit of the effective medium theory has been reached. This is due to the fact that the geometrical feature sizes are of the order of the wavelength in the frequency range of interest. In this context one may regard the fabricated metamaterial as a composite periodic structure rather than an effective material. Future work will involve rolling up the fabricated metamaterials in a cylindrical shape. The characterization and simulation of these structures is currently under investigation.

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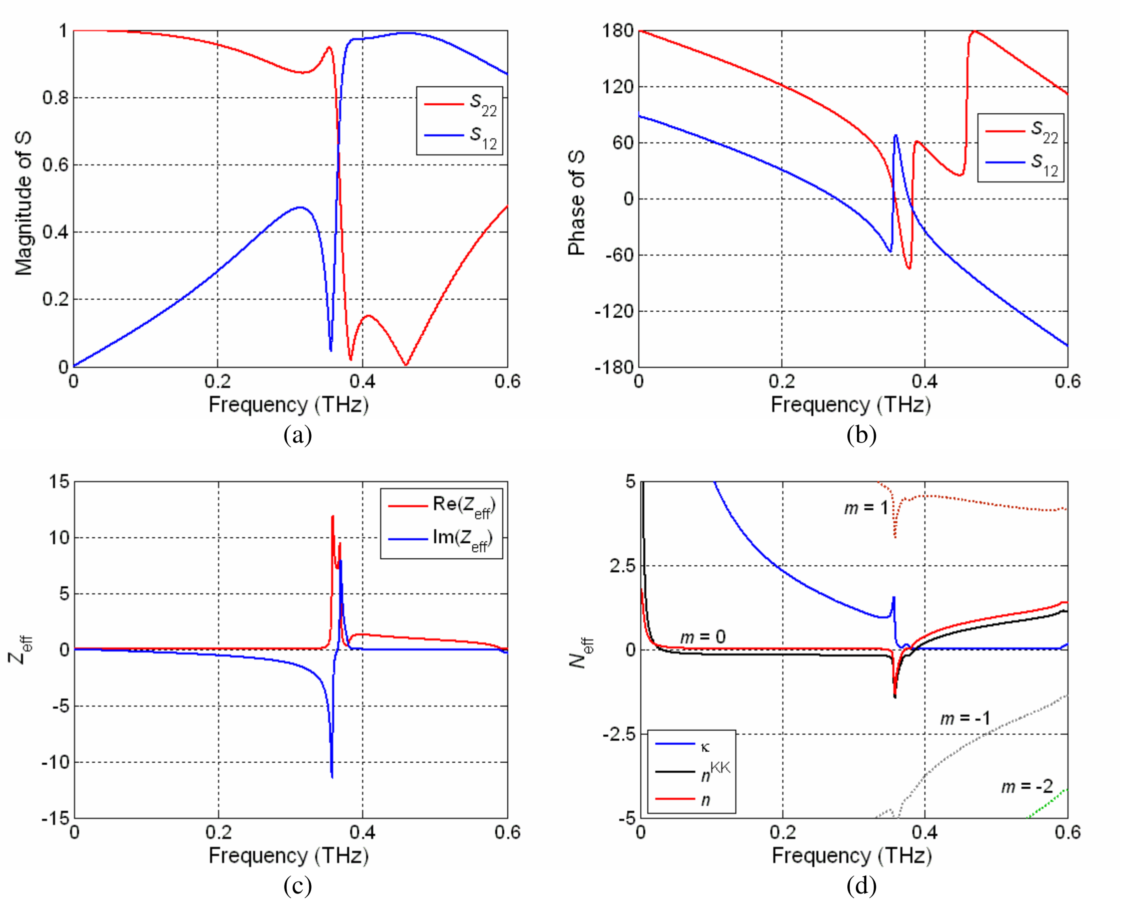
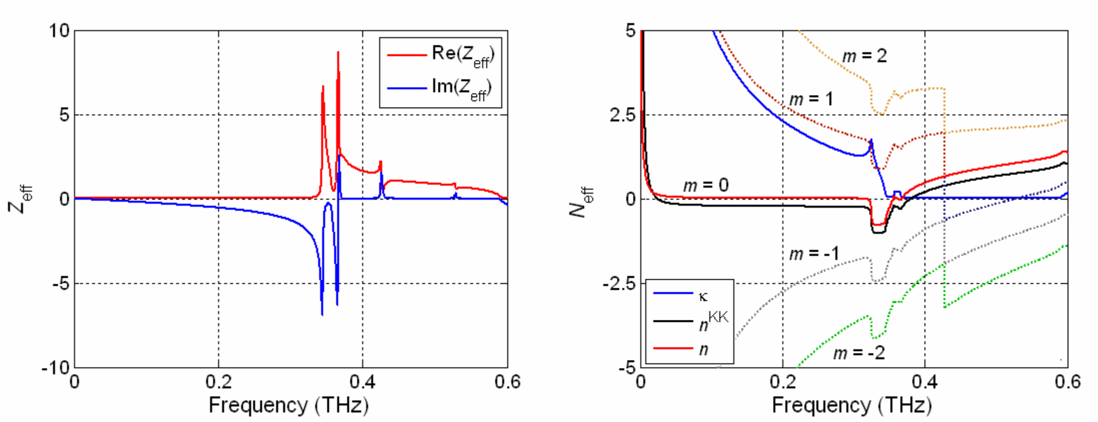


(a) (b)

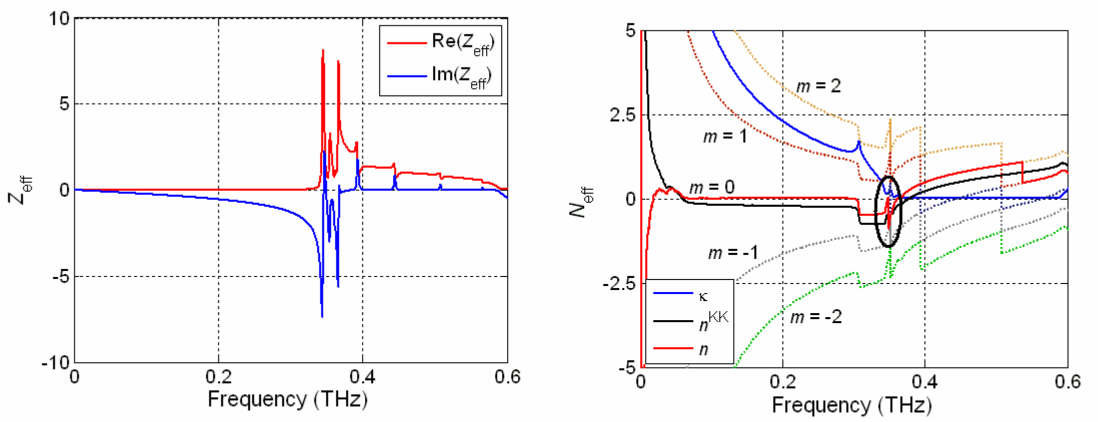
(c) (d)

Figure 4. The S-parameters: (a) magnitude, (b) phase, when the metamaterial slab is only one unit-cell in thickness. The real and imaginary part of the wave impedance is plotted in (c). The real and imaginary part of the refractive index, the Kramers-Kronig approximation and several possible branches are shown in (d).



(a) (b)

Figure 5. The effective metamaterial parameters of the metamaterial slab that is three unit-cells thick.



(a) (b)

Figure 6. The effective metamaterial parameters of the metamaterial slab that is five unit-cells thick.

REFERENCES

1. V. G. Veselago, The electrodynamics of substances with simultaneously negative values of ε and μ, *Sov. Phys. Usp.*, 10, 4, 1967, pp.509–514.
2. D. R. Smith, W.J. Padilla, D.C. Vier, S.C. Nemat-Nasser, S. Schultz, Composite Medium with Simultaneously Negative Permeability and Permittivity, *Phys. Rev. Lett.*, 84, 2000, 4184.
3. R. Marqués, F. Martín, and M. Sorolla, *Metamaterials with NegativeParameters*. John Willey and Sons, 2008.
4. Zs. Szabó, G. Park, R, Hedge, E. Li, A Unique Extraction of Metamaterial Parameters Based on Kramers-Kronig Relationship, accepted for publication in *IEEE Trans. Microwave Theory Tech.*, 2010.
5. N. Engheta, R. W. Ziolkowski, *Metamaterials Physics and Engineering Applications*, John Willey and Sons, 2006.
6. H. Yew-Li, Zs. Szabó, H. C. Lim, J. F. Federici, Er-Ping Li, Terahertz Response of Microfluidic-jetted 3D Flexible Metamaterials, *Applied Optics*, Vol. 49, Issue 8, pp. 1179-1184, 2010.