Bulk Negative Index Metamaterial Operating at THz Frequencies

Oliver Paul[a], Christian Imhof[b], Benjamin Reinhard[a], Remigius Zengerle[b], René Beigang[a]
[a] Department of Physics, [b]Department of Electrical and Computer Engineering,
University of Kaiserslautern, 67663 Kaiserslautern, Germany

***Abstract*—We present a freestanding bulk metamaterial operating in the THz frequency range. The implemented structure consists of pairs of metallic crosses for which the resulting composite medium exhibits a negative index of refraction at about 1 THz.**

I. Introduction

Recent theoretical and experimental results have shown the possibility of creating novel types of microstructured materials that demonstrate the property of negative refraction. These materials are referred to as lefthanded metamaterials. In the GHz range bulk metamaterials can easily be constructed using simple mechanical fabrication methods. Thus, negative refraction effects and applications in this range are widely demonstrated by various groups.

However, in the THz frequency range the wavelength is three orders of magnitude smaller, and so the fabrication of subwavelength elements can only be implemented using lithographic techniques. As a consequence, all metamaterials in the THz range known so far are microstructured surfaces rather than real bulk materials. In order to solve this problem, we have developed a fabrication method for real three dimensional metamaterials with thicknesses up to some millimeters. The described technology allows the inclusion of metallic microstructures in benzocyclobutene (BCB)-based resin using a multilayer lithography process.

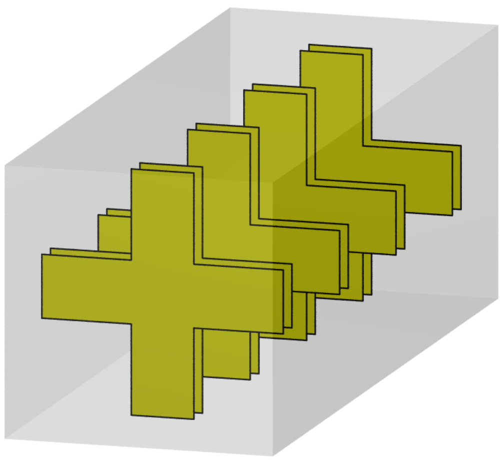

Fig. 1: Four unit cells of the cross pair structure, separation between cross pairs = 52µm, length of a crossbar = 81µm, width of a crossbar = 21µm, cross pair gap = 9.5µm

II. The Cross Pair Structure

The method is demonstrated for a metamaterial consisting of pairs of metallic crosses (Figure 1). The bars of the cross form an array of small electrical dipoles which lead to a negative permittivity. The two opposing bars of the cross pair form an inductance L as well as a capacitance C and hence represent an LC-oscillator which can be driven by a time-varying magnetic field. This leads to a negative permeability. The structure thus satisfies both conditions necessary to reach a negative index and so a lefthanded behavior can be observed for a plane wave impinging perpendicularly to the cross plane [1]. Due to the symmetry of the cross structure, this functionality is independent of the polarization of the wave.

We fabricated films with one and with two layers of cross pairs completely embedded in BCB using a multilayer lithography process with alternating layers of BCB and copper. After processing the films have been removed from the substrate in a solution of KOH. Furthermore, we prepared metamaterials with three and four layers of cross pairs by simply stacking a two-layer film on top of a one- and two-layer film, respectively. Since the coupling between the individual cross pairs can be neglected, the relative alignment of the lifted films is not crucial [2].

III. Results

We have analyzed the transmission properties of the metamaterial using THz time domain spectroscopy as well as supporting numerical simulations which are performed with a commercially available solver for the Maxwell equations [2]. Figure 2 shows the simulated phase for a plane wave at 1.03 THz while propagating through a metamaterial consisting of four layers of cross pairs.

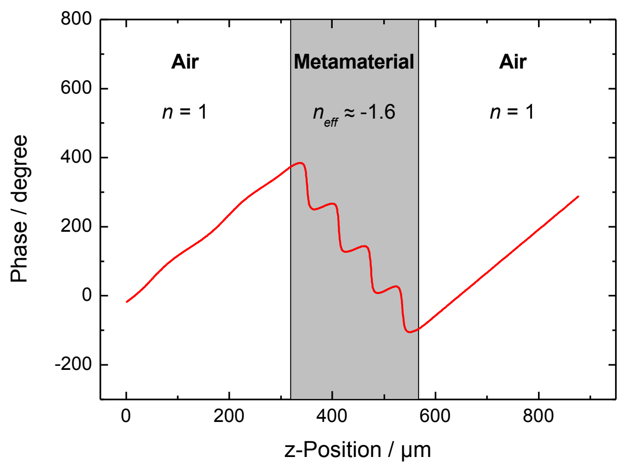

Fig. 2: Phase of the electric field at 1.03 THz

978-1-4244-2120-6/08/$25.00 ©IEEE.

The average slope of the phase changes its sign inside the metamaterial, showing that the phase velocity and thus the refractive index are negative within the observed transmission band. Taking into account the thickness of the slab, the refractive index can be approximated as $n_{eff} = -1.6$.
For a complete quantitative characterization of our metamaterial, we applied a retrieval procedure [3] to calculate the effective index of refraction, wave impedance, permittivity and permeability from the simulated transmission and reflection data. The resulting curve for the refractive index n is plotted in Figure 3 and is compared to the values derived from the phase progression (as shown in Figure 2). The overall agreement between the two methods is excellent and reveals a negative index of refraction between 0.96 and 1.17 THz. Note that for frequencies between 0.74 and 0.96 THZ, the wavelength inside the medium is smaller than the lattice constant of the cross pair structure and the calculated effective parameters are not expected to be reliable.

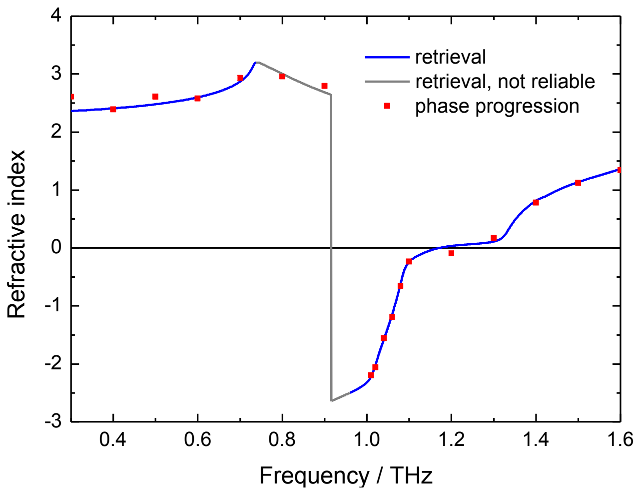

Fig. 3: Effective index of refraction obtained by a retrieval algorithm (blue line) and from the phase progression (red dots)

IV. Conclusion

We demonstrate a lefthanded bulk metamaterial operating in the THz frequency range. The presented structure operates at normal incidence and is independent of the polarization. We have used simple multilayer techniques to embed the functional metallic structures completely in BCB which allows the removal of the silicon substrate after processing. Due to the simple structure design and the polarization independence, the lifted structures can be mechanically stacked on top of another to further increase the thickness and obtain a real bulk metamaterial. The observed transmission spectrum is in good agreement with numerical simulations and evidences a lefthanded transmission band at about 1 THz with a high figure of merit.

References

[1] C. Imhof and R. Zenglerle, “Pairs of metallic crosses as a left-handed metamaterial with improved polarization properties,” in *Optics Express,* vol. 14, 2006, pp. 8257–8262

[2] O. Paul, C. Imhof, B. Reinhard, R. Zengerle, R. Beigang, "Negative index bulk metamaterial at terahertz frequencies" in *Optics Express,* vol. 16, 2008, pp. 6736-6744

[3] X. Chen, T. M. Grzegorczyk, B.-I. Wu, J. Pacheco, Jr., and J. A. Kong, “Robust method to retrieve the constitutive effective parameters of metamaterials,” in *Physical Review E*, vol. 70, 2004, pp. 016608

978-1-4244-2120-6/08/$25.00 ©IEEE.