Negative- and Zero-Index Metamaterials at terahertz frequencies

É. Lheurette[1], S. Wang[1], F. Garet[2], J-L. Coutaz[2] and D. Lippens[1]

[1]IEMN, UMR CNRS 8520, Université de Lille 1, BP 60069, 59652, Villeneuve d'Ascq, cedex, France, Tel: + 33 3 10 19 79 03; email: eric.lheurette@iemn.univ-lille1.fr
[2]IMEP-LAHC, UMR CNRS 5130, Université de Savoie, 73376, Le Bourget du Lac, cedex, France, Tel: + 33 4 79 75 86 78; email: Frederic.Garet@univ-savoie.fr

Abstract

In this article, we present the design, fabrication and characterization of double negative metamaterials for the terahertz operating spectrum. Special attention is paid to the near-zero index condition which corresponds to the case of simultaneous infinite phase and non vanishing group velocities. The metamaterial structures are made of metallic films patterned with sub-wavelength elliptical apertures separated by benzocyclobuthene (BCB) layers. The negative index properties have been experimentally demonstrated both indirectly, by means of a retrieval procedure from reflection (R) and transmission (T) characterization of a slab device and directly by angular measurements at the wedged interface of a prism-like structure. Both these experiments were carried out using Time Domain Spectroscopy (TDS).

1. Introduction

For about ten years, the possibility to synthesize an artificial material with lower than unity or even, negative permittivity and permeability has motivated various research fields with key applications such has high resolution focusing [1] or invisibility cloaking [2]. In this context, the case of permittivity and permeability both equal to zero is of great interest because it leads to a zero gap dispersion diagram allowing a infinite phase velocity at a non-zero group velocity. Such a property allows for example the propagation of EM waves through ultra narrow waveguide channels. At microwaves such a condition can be achieved by the so-called complementary transmission line design under balanced condition [3]. In a bulk approach, it has been demonstrated that interconnected metallic resonators with infinite Ω chains are able to fulfil this condition [4]. However this last structure cannot easily be extended up to terahertz frequencies due to the need of a polarized incident wave with the *k*-vector along the planes of metallic particles. Over the past few years, several alternate designs have been proposed allowing artificial magnetism through the contribution of both conductive and displacement currents [5-7]. Among all of these, the fishnet one permitted to target high figure of merit at infrared wavelengths, which paves the way for negative index metamaterial applications in optics. The structures we fabricated here, related to fishnet metamaterials, involve the stack of subwavelength thin film patterned by subwavelength apertures. Firstly, the design and fabrication of these metamaterials is detailed. Secondly, we describe TDS experiments which include R & T characterization, in order to retrieve the complex propagation constant, and angular measurements for a direct assessment of the refraction properties.

2. Design and fabrication of the metamaterials

Finite element simulations have been carried out by means of *HFSS Ansoft* commercial software. The numerical procedure involves three steps. First, the Bloch modes are calculated considering a symmetry boundary conditions applied to a unit cell. Then, R & T calculations are performed on a finite length structure. Finally, radiating patterns are plotted for a prism device including a stair-like output interface. The dimensions of the structure, illustrated in Fig 1, have been determined targeting a ground left-handed passband with a significant transmission level. To this aim, it has been shown that the use of elliptical holes with an aspect ratio of typically 1.8:1 permits one to achieve a quasi-unit left-handed transmission around 0.5 THz due to impedance matching condition with the incident plane

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wave [8]. For this frequency, the periodicity along the propagation direction is about λ/25, where λ is the working wavelength, thus insuring a metamaterial operating condition along this direction.

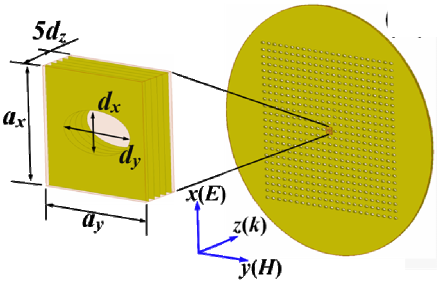

Fig. 1: Sketch ~~view~~ of a 5-layer metamaterial showing the unit cell with $a_x = a_y$.= 340 µm, d_x = 125 µm, d_z = 26 µm, elliptical aspect ratio d_y/d_x = 1.8:1

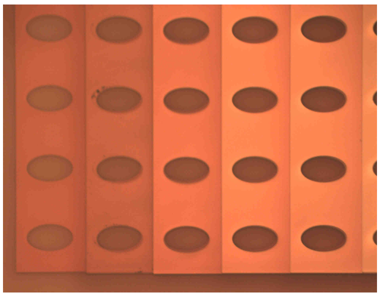

Fig 2: Top view of the prism with a stair-like profile

The deposition sequence involves spin coating, polymerization of BCB under nitrogen atmosphere, and Cr/Au/Cr sputtering with a global metal thickness of 0.4 µm. The elliptical holes arrays are patterned using standard photolithography. The baking sequence of BCB has been optimized in order to limit the stress in BCB layers. Up to 10 BCB layers, which correspond to 10 unit cells along the propagation direction, have thus been deposited. As a final technological step, the GaAs substrate is chemically etched with a $H_2O_2/H_2SO_4/H_2O$ solution in order to define a membrane-like metamaterial. Following this process, two kinds of prototypes have been fabricated. The first one is a slab such as the one illustrated by Fig 1 which permits to assess the dispersion properties from R & T spectra. The second one is a prism including a wedged stair-like output interface for direct characterization of refraction by means of angular measurements.

3. TDS characterization

From R & T spectra we followed a Fresnel relations inversion method in order to retrieve the frequency dependences of complex refractive index n, reduced impedance z, relative permittivity ε and permeability μ [9]. The dispersion of the imaginary part of the wave number K versus frequency is plotted in Fig 3 for different slab thickness. First, we can note that the single layer case does not permit to get a ground left-handed band. This result is obvious since two metallic plates are required to synthesize the negative permeability. Second, as already pointed out by several authors, the dispersion properties strongly depend on the number of unit-cells along the propagation direction. It can be shown that a differential method such as the one described in [10] is able to fit the Bloch modes. This illustrates the strong contribution of the coupling of the incident plane wave with the metamaterial. Finally, this parametric analysis shows a progressive suppression of the band gap when the number of layers is increased up to 5.

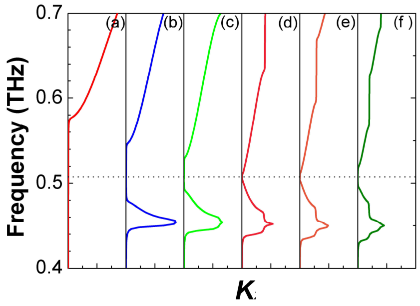

Fig. 3: Dispersion of K for various number of stacked layers : (a) 1, (b) 2, (c) 3, (d) 5, (e) 7 and (f) 10.

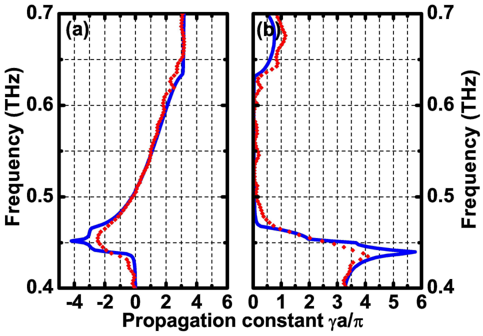

Fig. 4: Dispersion diagram retrieved from R & T spectra: FEM simulation (blue), TDS measurements (red).

This zero-index prototype has been measured using a TDS setup developed at the University of Savoie [11]. This pump-probe method is able to keep the phase information necessary to retrieve the complex n, z, ε and μ parameters. The experimental dispersion diagram follows the predictions, as illustrated by Fig 4, with a zero-gap frequency point corresponding to an equivalence of electric and magnetic plasma frequencies.

For the angle resolved analysis, the transmission measurement setup is completed by a goniometric system which allows the tracking of the transmitted signal versus the angle at the output of the prism-like device (Fig 5). From the curves plotted in Fig.6, a continuous evolution between negative refraction to positive refraction can be evidenced. The limit between these two regimes is indicated by the vertical dotted line which corresponds to the angle of the wedged output plane.

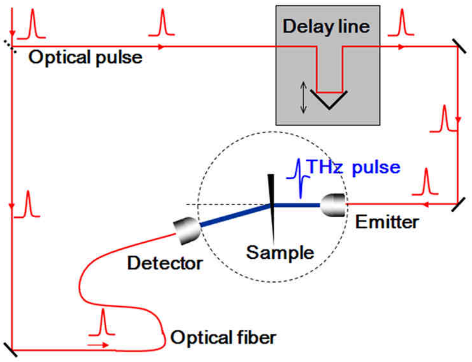

Fig. 5: Schematic view of the TDS goniometric setup

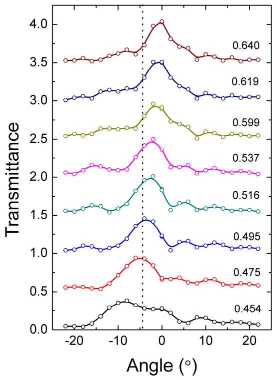

Fig. 6: Transmittance vs angle for various frequencies

6. Conclusion

Double negative metamaterials have been experimentally investigated. Both the R & T and angular measurements show the possibility to work in negative or near-zero index refraction regimes with a high level of transmitted signal. Due to their performance and versatility, these devices are promising for various applicative fields such as environment sensing and electromagnetic wave control.

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