Negative index short-slab pair and continuous wires metamaterials in the far infrared regime

T. F. Gundogdu[1,2*], N. Katsarakis[1,4], M. Kafesaki[1,2], R. S. Penciu[1], G. Konstantinidis[1], A. Kostopoulos[1], E. N. Economou[1,3], and C. M. Soukoulis[1,2,4]

[1]*Institute of Electronic Structure and Laser (IESL), Foundation for Research and Technology-Hellas, P .O. Box 1527, 71110 Heraklion, Crete, Greece*
[2]*Department of Material Science and Technology, University of Crete, 71003, Heraklion, Crete, Greece*
[3] *Ames Laboratory-USDOE, and Department of Physics and Astronomy, Iowa State University, Ames, Iowa, 50011, USA*
[4]*Science Department, Technological Educational Institute of Crete, Greece*
[*]*Corresponding author: tamara@iesl.forth.gr*

Using transmission and reflection measurements under normal incidence in one and three layers of a μm-scale metamaterial consisting of pairs of short-slabs and continuous wires, fabricated by a photolithography procedure, we demonstrate the occurrence of a negative refractive index regime in the far infrared range, ~2.4-3 THz. The negative index behavior in that system at ~2.4-3 THz is further confirmed by associated simulations, which are in qualitative agreement with the experimental results.

OCIS codes: (000.0000) General.

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1. Introduction

Left-handed or negative index metamaterials (LHMs), i.e. artificial materials that exhibit both negative effective electrical permittivity, ε, and magnetic permeability, μ, over a common frequency band [1,2], and therefore negative index of refraction, n, [1] have received recently a lot of attention due to their interesting electromagnetic (EM) properties, which create new perspectives for the manipulation of electromagnetic waves (negative refraction [3-5], evanescent wave amplification, perfect lensing [6] etc). The most typical design of LHMs to date involves split ring resonators (SRRs), i.e. metallic rings with gaps, which provide the negative μ [the SRR behaves as an equivalent inductor-capacitor (LC) circuit, exhibiting a resonant magnetic response, at $\omega_m=1/(LC)^{1/2}$, associated with resonant circular currents in the rings], combined with continuous wires (providing the negative ε) [7-17]. The negative index response in SRRs&wires materials is achieved for applied electric field, $\boldsymbol{E}$, polarized parallel to the continuous wires and magnetic field, $\boldsymbol{H}$, perpendicular to the SRRs plane.

Since the first experimental demonstration of LHMs by Smith, *et al.* [2], there has been a great effort to push upwards the frequency range at which negative μ and/or LH behavior occur, from the GHz range to the infrared and optical regime [18-24]. At such frequencies, however, the losses are considerable and the freedom to manipulate the geometry is quite limited. Moreover, it is rather difficult to measure the transmission and reflection for propagation parallel to the SRRs plane, since it would require a multilayer stack of SRRs, which is difficult to achieve with the current technological capabilities. It is for that reason

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that in most of the THz experiments [18-20], transmission measurements have been performed for propagation normal to the SRRs plane, and the occurrence of resonant magnetic behavior has been concluded indirectly, through the effect of electric excitation of the magnetic resonance (EEMR), i.e. excitation of the resonant circular currents in the SRR by the incident electric field [25, 26]. It has been quite recently that oblique incidence transmission and reflection measurements on a five-layer single-ring SRRs system have directly demonstrated that there is indeed an SRR resonance associated with negative magnetic permeability, μ, at the far infrared regime [24]. (For oblique incidence one can achieve an $\boldsymbol{H}$ component perpendicular to the SRRs plane, $\boldsymbol{H}_{\perp}$. $\boldsymbol{H}_{\perp}$ induces a resonant circular current flow inside the SRRs, which in turn produces, just above the resonance frequency, a large magnetic dipole moment antiparallel to $\boldsymbol{H}_{\perp}$, leading thus to a negative μ.)

To simplify the fabrication and characterization of negative μ and/or LH metamaterials, new improved and simplified designs have been introduced, involving pairs of short-slabs as magnetic resonators. According to theoretical and experimental studies, the parallel short-slab pairs structure could allow replacing the SRR as magnetic resonator [27] but also could possibly give simultaneously negative ε, and negative μ, therefore negative *n* [28,29]. Since the existence of simultaneously negative ε and μ in short-slab pairs structures can occur only under extreme conditions [30], a modification of the structure, consisting of continuous wires in addition to the slab pairs, has been proposed, and the occurrence of negative index, *n*, in the microwave regime has been demonstrated unambiguously, both theoretically and experimentally [30-33]. The short-slab pairs arrangement (with or without continuous wires) has obvious advantages compared to the conventional SRR plus wires design: It is simpler in fabrication and, moreover, LH behavior can be achieved for incidence normal to the short-slab pairs plane, thus enabling the observation of negative index behavior with only a few, if not only one, short-slab pairs layer. The latter feature could facilitate the realization and characterization of high-frequency LH metamaterials.

In this work, we have designed, fabricated, characterized and analyzed a μm-scale structure consisting of short-slab pairs and continuous wires (see Fig. 1) targeting the observation of LH behavior in the far infrared frequency regime. Transmission and reflection measurements of one and three layers of the structure have indicated the occurrence of LH behavior at ~2.4-3 THz. Transmission and reflection simulations, in good agreement with experiments, as well as inversion of those results for the calculation of the effective structure parameters ε and μ, have indeed proven the existence of LH behavior in the far infrared regime for the short-slab pairs and continuous wires design. To our knowledge, similar structures have been tested for LH behavior only in microwaves. Thus it is the first time that LH behavior is demonstrated at infrared in the slab-pairs and wires structure. It should also be noted that three layers of the metamaterial have been fabricated, unlike the usual one layer approach.

2. Experiments and simulations

Our short-slab pairs metamaterial is composed of Ag/Ti slab pairs, that are embedded in a dielectric matrix, while two continuous wires are added on either side of each pair, as shown in Fig. 1, to ascertain a wide negative ε region. For EM waves incident normally to the short-slab pairs structure and the electric field polarized parallel to the continuous wires (see Fig. 1), the short-slab pairs will exhibit a magnetic resonance, providing a negative μ region, and the continuous wires will lead to negative ε, thus providing the possibility to achieve LH behavior. The elements of the pairs are separated by a dielectric spacer of small thickness, t_s. The unit cell (u.c.) of the system is presented in Fig. 1(a) (3D view) and Fig. 1(b) (cross section). The dimensions are α_E = 20μm, α_H = 16μm, α_k= 1.9μm where α are the respective lattice constants in the directions of **E**, **H** and **k** of the normal incident electromagnetic wave. The slab length is l = 16.5μm, its width is w = 8μm, the thickness of the dielectric spacer between the elements of the pairs is t_s= 0.7μm, the continuous wire width is w' = 2μm and finally the continuous wire to short-slab distance (from metal edge to metal edge) is d=1 μm. The metamaterials have been fabricated on silicon wafers in a layer-by-layer method,

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alternating layers of dielectric and silver to get one or three u.c. A spin-on polyimide (DuPont Pyralin SP series PI-2525) with a dielectric constant of 2.5 has been used as matrix material, while silicon has been applied as the high-index dielectric spacer between the pair elements. The layer-to-layer alignment has been done using a Karl Süss MA6 aligner and UV photolithography. The alignment accuracy is of the order of 0.5 μm. After the fabrication, the polyimide-encapsulated metallic structures have been removed from the silicon substrates. The total area of each structure is 25×25 mm^2.

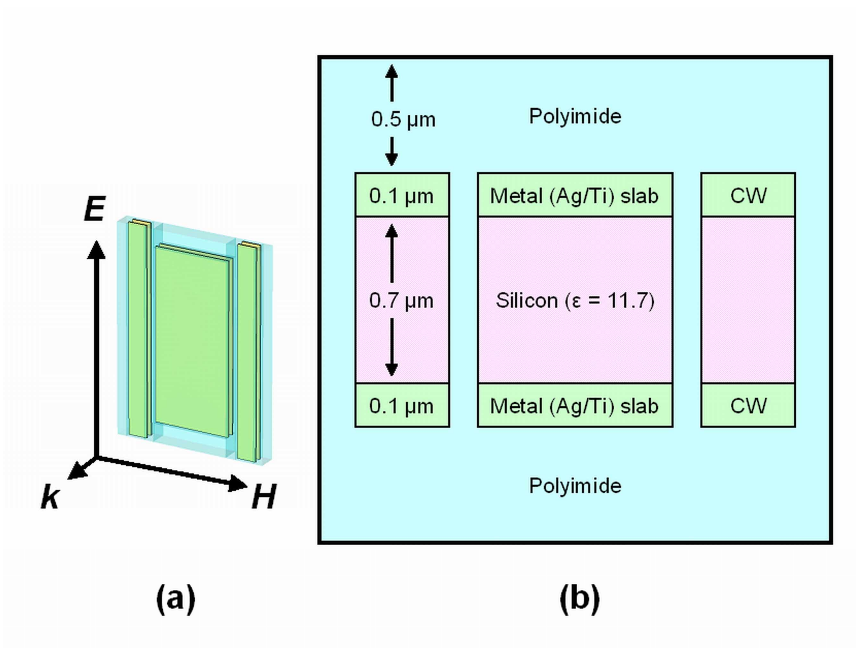

Fig. 1. (a). A single unit cell of the slab-pair metamaterial under study, (b) k-H cross section of the slab-pair metamaterial, passing through the middle of the u.c. along **E** direction (metal thickness 0.1 μm, polyimide 0.5 μm, Silicon 0.7 μm). The figure scaling in the two different dimensions is dissimilar. CW denotes the continuous wires.

The transmission measurements have been taken using a Bruker IFS 66v/S FT-IR spectrometer (with a collimated beam) and a polarizer, at the frequency range of 1.5-10 THz, at normal incidence whereas the reflection measurements were taken at almost normal incidence (77°). The transmission and reflection simulations have been performed using the Finite Integration Technique employed through Microwave Studio commercial software, and considering one and three u.c. along the propagation direction and periodic boundary conditions along the lateral directions. The metal has been treated as a dispersive medium following the Drude dispersion model ($\varepsilon = 1\text{-}\omega_{pm}^2/\,(\omega^2+i\omega\gamma)$, with ω_{pm}=13.66×10^{15} rad/s and γ=2.73×10^{13} s^{-1}). For polyimide and silicon the dielectric constants that have been used are ε_p=2.5 and ε_{Si}=11.9 respectively, while the corresponding loss parameters are tanδ_p=0.03 and tanδ_{Si}=0.04.

In Fig. 2(a) the reflection (*R*) spectrum of a slab-pairs metamaterial consisting of one unit cell (u.c.) along propagation direction is presented, at almost normal incidence (77° angle of incidence), and ***E*** parallel to the continuous wires. Two dips can be clearly observed, a broad one, which is located at ~3.5-5.5 THz, and a narrower one, at ~2.4-3.2 THz. In Fig. 2(b), the transmission (*T*) spectrum of the same slab-pair metamaterial is depicted for normal incidence (***E*** parallel to the continuous wires) (See Fig. 1(a)). At a first glance, one can observe a broad peak centered at ~4.4 THz. It can be noticed though that this broad peak contains a small shoulder, at ~2.9 THz, which is close to the position of the narrow *R*-dip observed in Fig. 2(a).

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This *T*-shoulder and the associated *R*-dip are due to the LH behavior of the system in the frequency region 2.4-3 THz, as it is further confirmed from corresponding numerical study.

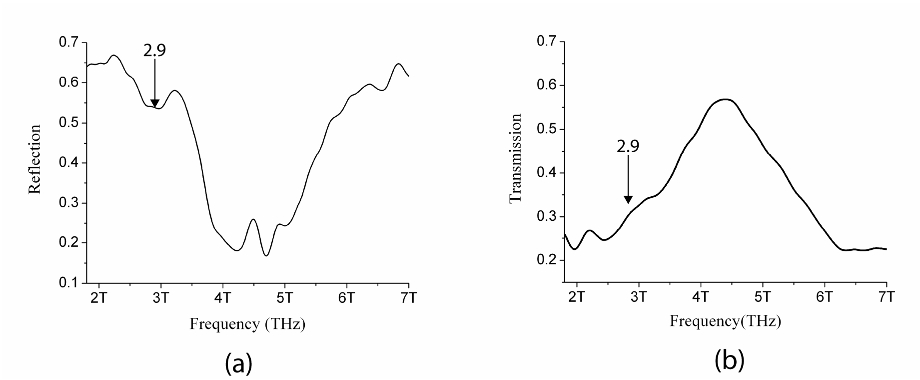

Fig. 2. (a). Measured reflection spectra for our slab-pairs metamaterial, for one u.c, at close to normal incidence (77°) as defined in Fig.1, (b) corresponding measured transmission spectra.

Numerical reflection and transmission results for our system (one u.c. along propagation direction) at normal incidence are shown in Fig. 3. It can be seen that *T* (dashed line) shows a small peak, while *R* (solid line) exhibits a corresponding dip, centered at ~2.7 THz. These spectral features are in very good agreement with the experimental results presented in Fig. 2, thus providing evidence for the occurrence of LH behavior at around ~2.7 THz. To unambiguously confirm that the transmission peak and the reflection dip at around ~2.7 THz, (observed both experimentally and numerically in our structures), are due to negative effective refractive index behavior, we have calculated the effective ε, μ and n versus frequency from the numerical transmission and reflection data, via the standard retrieval procedure [34,35]; the extracted ε, μ and n are shown in Figs. 4(a), 4(b) and 4(c) respectively. The graphs show that the real part of the permittivity is negative up to almost ~4.5 THz, while the real part of the permeability is negative over a narrow frequency band ranging from ~2.6-3 THz. This in turn results in negative n at the frequency region of ~2.6-3 THz as is confirmed in Fig. 4(c). (The slightly broader negative n regime compared to that of negative μ comes from the fact that negative n can also be achieved for a negative ε combined to positive μ but with large Im(μ) values. This negative ε-high Im(μ) regime corresponds to very high losses (see the large Im(n) in Fig. 4(c)) and is not considered here as negative index propagation regime. It is thus clear that all the obtained results, namely measured and calculated *T* and *R*, as well as the effective parameters ε, μ and n, point to the occurrence of a negative refractive index propagation regime at ~2.6-3 THz for our one u.c. short-slab pair/continuous wires metamaterial.

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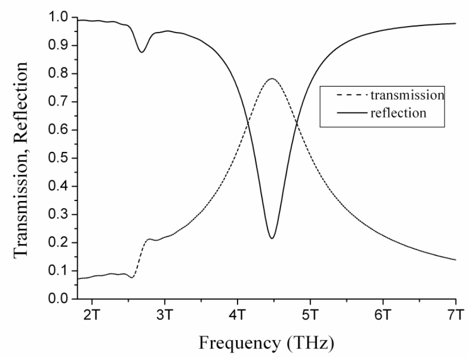

Fig. 3. Calculated transmission (dashed line) and reflection (solid line) vs. frequency for one u.c. of our slab-pair metamaterial.

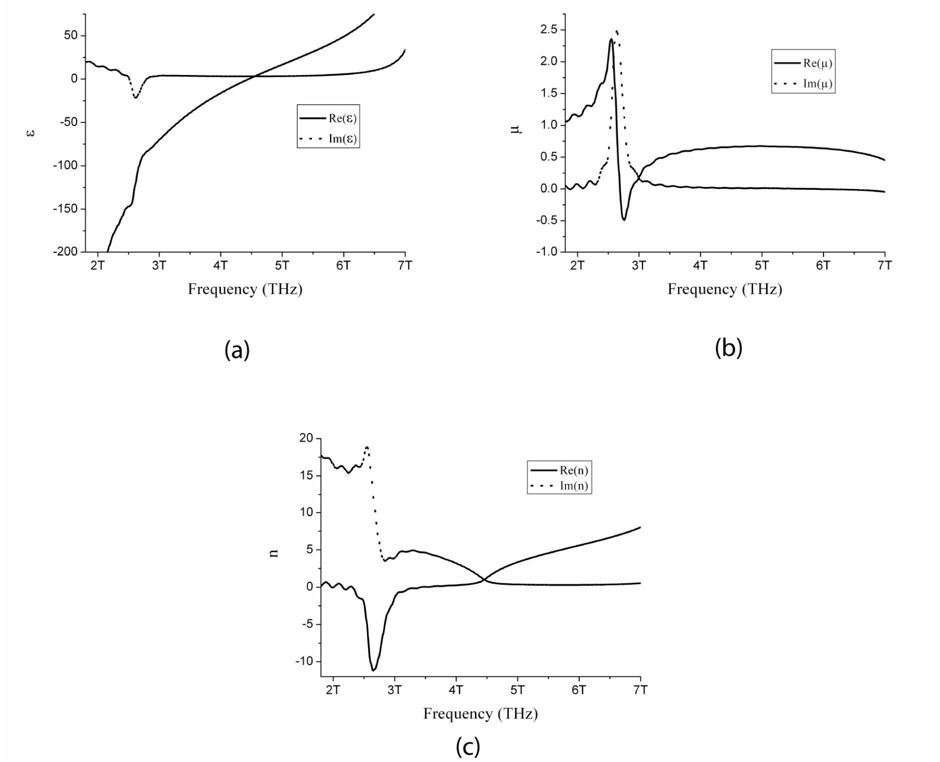

Fig. 4. Real (solid line) and imaginary (dashed line) parts of the effective permittivity [panel (a)], permeability [panel (b)] and refractive index [panel (c)] calculated from the transmission and reflection data shown in Fig. 3.

To add further proof to our arguments and examine further the behavior of our metamaterial, i.e., quality and robustness of LH behavior, we have conducted the same measurements and calculations for three layers of the metamaterial, i.e. three u.c. along propagation direction without any separation between the layers. The corresponding data are presented in Figs. 5-6. In particular, the *T*- and *R*-spectra measured are illustrated in Fig. 5, showing the occurrence of a *T*-peak and a corresponding *R*-dip centered at ~2.3 THz. It is in

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this frequency region that we claim the occurrence of negative n, i.e. left-handed, behavior. (The slight difference between the one u.c. and three u.c. results are possibly due to the non-uniformity in the thickness of the layers of the samples and the interaction between adjacent layers along propagation direction. We suspect that the existence of an electric resonance nearby may play a role given the fact that the relative excitation strengths of the two resonance depend on the incident angle and other aspects of the experiment). The numerical T and R results are presented in Fig. 6. and are in quite good agreement with the experiments. According to the corresponding calculations, the double peak structure that appears between 3.5-5.5 THz can be attributed to Fabry-Perot oscillations.

Finally, we have to note that additional investigating simulations show that by reducing the thickness of the high-index dielectric (silicon) of our structure to 0.25 μm or replacing it with a low-index material (polyimide), the negative index behavior disappears. This is due to the fact that reducing the thickness of the high-index silicon leads to a decrease in the strength of the magnetic permeability, thus negative μ is not achieved; On the other hand, replacing Si with polyimide shifts the magnetic resonance to frequencies higher than the plasma frequency of the system, where the left handed behavior can not be observed.

3. Conclusions

In conclusion, we have fabricated a μm-scale metamaterial composed of slab-pairs and continuous wires, by means of a photolithography technique. Both one and three layers of metamaterial (u.c. along propagation direction) have been fabricated. Transmission and reflection measurements under normal incidence have given indications that our metamaterial shows negative refractive index behavior at 2.6-3 THz. Simulations of both transmission and reflection as well as inversion of the obtained data for calculating the effective parameters ε, μ and n, confirm the existence of a negative refractive index regime at ~2.4-3 THz. The slab-pair and continuous wires design opens new paths for the realization of negative index materials at optical frequencies.

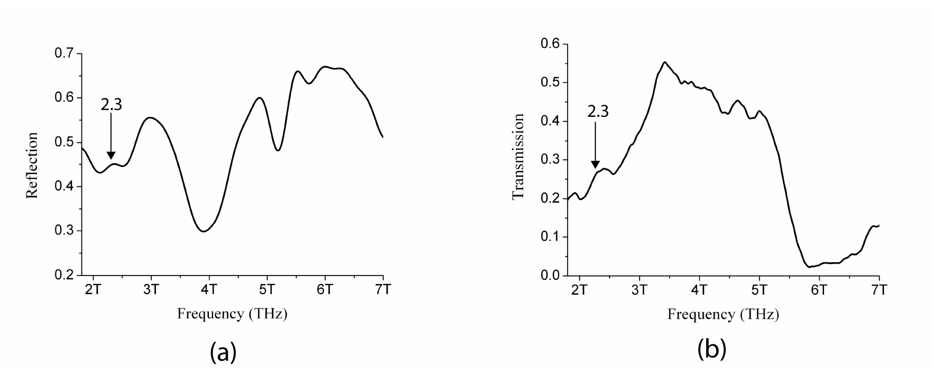

Fig. 5. (a). Measured reflection spectra of three u.c. slab-pairs metamaterial at close to normal incidence (77°), (b) measured transmission spectra for three u.c. of the metamaterial.

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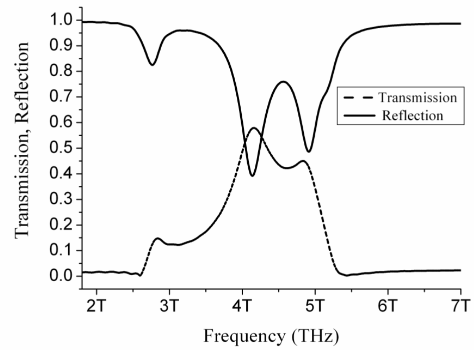

Fig. 6. Calculated transmission (dashed line) and reflection (solid line) vs. frequency for the three u.c. slab-pairs metamaterial.

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