

# Thermally and optically tunable sub-terahertz superconducting fishnet metamaterial



Cumali Sabah<sup>a,b,\*</sup>, Batuhan Mulla<sup>c</sup>, Hakan Altan<sup>d</sup>, Lutfi Ozyuzer<sup>e</sup>

<sup>a</sup> Department of Electrical and Electronics Engineering, Middle East Technical University–Northern Cyprus Campus (METU–NCC), Kalkanli, TRNC/Mersin 10, Guzelyurt 99738, Turkey

<sup>b</sup> Kalkanli Technology Valley, Middle East Technical University–Northern Cyprus Campus (METU–NCC), Kalkanli, TRNC/Mersin 10, Guzelyurt 99738, Turkey

<sup>c</sup> Sustainable Environment and Energy Systems, Middle East Technical University–Northern Cyprus Campus, Kalkanli, TRNC/Mersin 10, Guzelyurt, Turkey

<sup>d</sup> Department of Physics, Middle East Technical University, Cankaya, Ankara 06800, Turkey

<sup>e</sup> Department of Physics, Izmir Institute of Technology, Urla, Izmir 35430, Turkey

## ARTICLE INFO

### Article history:

Received 14 February 2017

Revised 5 September 2017

Accepted 20 October 2017

### Keywords:

Metamaterial

Superconductivity

Terahertz

Thermal tunability

Optical tunability

## ABSTRACT

In this paper, a novel fishnet metamaterial structure is designed and analyzed under different material combinations and under different active controlling techniques. The results indicate that, the proposed fishnet metamaterial has a single resonance with double negativity at 0.39 THz when quartz substrate and aluminum is utilized in the design. Moreover, when the metallic parts are replaced with YBCO, the proposed design also exhibits double negativity with a stronger resonance and can be used as a switch between the double negative and single negative modes if the temperature is altered. In addition to these, when substrate (quartz) is replaced with MgO, the resonance shifts from 0.39 THz to 0.26 THz and shows double negativity. Moreover, switching properties under illumination can also be obtained when the silicon is utilized in the design (MgO-YBCO combination). According to these results, it is found that, in the case that the conductivity of silicon exceeds a certain value, the character of the resonance changes from double negative to the single negative mode.

© 2017 Elsevier B.V. All rights reserved.

## 1. Introduction

Most natural materials do not have a strong response in the low frequency terahertz region where applications in sensing imaging and communication are continuously gaining importance [1–7]. To overcome this limitation, subwavelength, artificially engineered materials, metamaterials, can be utilized in the so called THz gap. Metamaterials can simultaneously exhibit negative permittivity and negative permeability. Simultaneous presence of both the negative permittivity and negative permeability have gained significant attention due to the exotic electromagnetic properties that these materials exhibit [8].

Electromagnetic characteristics of the metamaterials can be tailored by scaling the unit structure of these materials [9]. Therefore, the geometric dimensions can be arranged so that a metamaterial can give a response in the low frequency terahertz region for a desired application. Although the response can change by scaling the geometric dimensions, it is not practical and requires fabrication

of different samples for different applications. However, when the metamaterials are combined with the reconfigurable elements, electromagnetic response can be controlled by just changing the environment instead of changing the dimensions. Hence the active control of the metamaterial can be realized. The reconfigurable elements for active control of the metamaterial can be semiconductors [10], graphene [11], superconductors [12], etc. When an external stimulation is applied to these materials, such as temperature, optical pump, and voltage control, their properties can be altered [1].

In metamaterial structures, generally, conductive elements are made up of metals or semiconductors [13]. With the integration of a photoconductive semiconductor around the metallic structure, active control of the metamaterial is possible. When an external pump beam is applied, changes in the conductivity of the photoconducting semiconductor results in a change in the capacitance of the structure, and therefore a shift in the resonance frequency [14].

In addition to the photoconductive semiconductor materials used in the metamaterial structures, the active controlling can also be done by replacing the metallic parts with superconductors. In most applications of metamaterials, metals are being utilized in the conductive structure. However, the utilization of superconduct-

\* Corresponding author at: Department of Electrical and Electronics Engineering, Middle East Technical University–Northern Cyprus Campus (METU–NCC), Kalkanli, TRNC/Mersin 10, Guzelyurt 99738, Turkey.

E-mail address: [sabah@metu.edu.tr](mailto:sabah@metu.edu.tr) (C. Sabah).

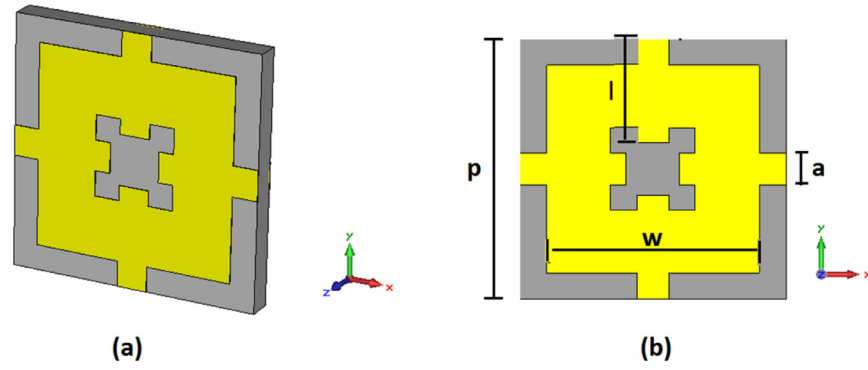


Fig. 1. Geometry of the unit cell of the proposed fishnet metamaterial structure. (a) Perspective view (b) Front view.

tors as the conductive elements is gaining interest [15]. In contrast to metals, the resistance of the superconductors strongly depends on temperature, magnetic field and applied optical fields [16,17]. Moreover, under some appropriate conditions, the ohmic loss of the superconducting material may be reduced to zero [16]. Therefore, by introducing superconductor materials into the metamaterial structures, the direct control of the metamaterial can be possible by changing the temperature which results in a change in the conductivity.

In this paper, a novel fishnet metamaterial design consisting of a dielectric layer sandwiched between the two metallic dielectric layers which provides negative permittivity and negative permeability is introduced and analyzed with numerical simulations. The characterization of the proposed fishnet metamaterial is carried out for different dielectric and metallic layers. In order to turn the designed structure from being a passive metamaterial into an active metamaterial, the metallic layers are replaced with superconductor and/or semiconducting layers. Under this condition, double negativity property of the designed structure is investigated. Moreover, the proposed superconductor based design is also analyzed with respect to its temperature dependence while the semiconductor based layer is analyzed under external illumination.

## 2. Design and simulation

A schematic representation of the proposed fishnet metamaterial with the relevant geometrical dimensional parameters is shown in Fig. 1. The structure is composed of two metallic plates (yellow parts in Fig. 1) and a dielectric substrate sandwiched between the metallic plates. The metallic resonators are composed of the four strips embedded in the square ring as shown in Fig. 1a.

The unit cell periodicity of the proposed fishnet metamaterial structure is given by the parameter “ $x$ ” where the dimensions of the metallic square ring resonators are expressed by the parameter “ $a$ ”. The values associated to the geometric parameters shown in Fig. 1b are  $p = 250 \mu\text{m}$ ,  $w = 200 \mu\text{m}$ ,  $a = 30 \mu\text{m}$ , and  $l = 100 \mu\text{m}$ . The thickness of the metallic parts and the thickness of the dielectric substrate are  $1 \mu\text{m}$  and  $25 \mu\text{m}$ , respectively.

The numerical simulation of the superconducting fishnet metamaterial is performed by a full wave electromagnetic wave simulation based on finite integration technique. The frequency range for the numerical study is chosen to be sub-terahertz. Periodic boundary conditions are employed along the lateral directions while waveguide ports are used for the excitations and detection of the sub-THz wave in the  $z$ -direction.

## 3. Results and discussion

In this paper, numerical simulations for the characterization of the designed structure were performed according to five different

dielectric-metal combinations. For all of the material combinations, the magnitudes of the S-parameters as well as effective permittivity and the permeability of the proposed fishnet metamaterial are analyzed and presented. Initially, aluminum was employed for the metallization, while quartz was used as the dielectric substrate. Then, an active fishnet metamaterial was obtained by replacing the aluminum parts with a high temperature superconductor material, yttrium barium copper oxide (YBCO). As the conductivity of YBCO is strongly dependent on the temperature, the response of the proposed fishnet metamaterial was analyzed under different temperatures. Afterward, quartz is replaced with magnesium oxide (MgO) as dielectric substrate, whose dielectric permittivity is almost stable under low temperatures. Finally, the inner gaps of the metallic parts of the final structure were filled with a semiconductor material, silicon (Si), and studied when an external pump beam is applied to vary its conductivity.

### 3.1. Quartz-aluminum combination

Aluminum with electrical conductivity of  $3.57 \times 10^7 \text{ S/m}$  and quartz with  $\epsilon = 4.45$  and loss tangent of 0.00019 [18] were used as the metallic structure and for the dielectric substrate respectively. The simulation result for S-parameters (for magnitude see Fig. 2a and for phase see Fig. 2b) are shown in Fig. 2. The reflection minima, transmission peak and phase changes occur at around 0.39 THz with a transmission magnitude of 0.71. In order to characterize the resonance, effective parameters (permittivity ( $\epsilon$ ) and permeability ( $\mu$ )) are extracted. The frequency dependent response of the extracted effective parameters is given in Fig. 3 (Fig. 3a being the effective permittivity and Fig. 3b being the effective permeability). The THz response of the structure shows a Drude-like electrical behavior in the permittivity, while it has a Lorentz-like magnetic behavior in the permeability. It means that the dielectric and magnetic constants of the structure under the THz illumination displays dispersive Drude-like and Lorentz-like responses, respectively. For this reason, both the real part of  $\epsilon$  and the real part of  $\mu$  will be negative around the resonant frequency confirming the double negativity for this resonance, as seen from Fig. 3. The magnitude of the  $\epsilon$  and  $\mu$  are  $-0.29$  and  $-0.082$  at around 0.39 THz, in order.

The current distributions on the metallic parts (front and back) at the resonant frequency are shown in Fig. 4. The anti-symmetric response of the surface current distributions (around the upper and lower parts of the structure) corresponds to the magnetic resonance. The displacement current circulates between the plates and closes the current loop. Therefore, a magnetic field is induced as a result of the circulating current. Hence, the induced response (diamagnetism) produces strong resonances which yield as a negative permeability given in Fig. 3. The surface current distributions given

Download English Version:

<https://daneshyari.com/en/article/8164240>

Download Persian Version:

<https://daneshyari.com/article/8164240>

[Daneshyari.com](https://daneshyari.com)