Appl Phys A (2012) 106:465–470
DOI 10.1007/s00339-011-6716-2

Applied Physics A
Materials Science & Processing

INVITED PAPER

Tunable terahertz metamaterial based on resonant dielectric inclusions with disturbed Mie resonance

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Received: 26 November 2011 / Accepted: 28 November 2011 / Published online: 28 December 2011

Abstract Tunable metamaterial operating in terahertz (THz) frequency range based on dielectric cubic particles with deposited conducting resonant strip was investigated. The frequency of the first magnetic type Mie resonance depends on the electric length of the strip. It can be changed under photoexcitation or applied voltage. This method of control was used for a design of tunable double negative metamaterial based on dielectric resonant inclusions and wire medium.

1 Introduction

Active development of the THz radiation technology was initiated relatively recently. This is mainly due to the fact that natural materials do not provide a pronounced magnetic or electric response in the THz frequency range. The conventional resonant magnetic response occurs in microwave region, while the plasma frequency in metals is observed beyond the mid-infrared range. There is a lack of THz devices, such as sources, modulators, and detectors. The necessity for THz research keeps growing in order not only to overcome these limitations, but also to apply for practical applications such as new spectral imaging and chemical sensing [1]. THz radiation can also be used for nondestructive medical scanning, security screening, quality control, atmospheric investigation, space research, etc. [2]

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Artificially manufactured structures, known as metamaterials, allow obtaining desired electromagnetic properties in any frequency region. Metamaterials operating in THz frequency range have been proposed in [3]. Electromagnetic environment with negative dielectric permittivity, magnetic permeability and refraction index can be created using metamaterial approach. However, manipulation of THz radiation in order to make actively functional devices is a quite challenging task. Controllable devices such as tunable filters, switches (modulators) or phase shifters are required in order to control spectrum, power, and directivity of THz radiation. The problem can be solved by a design of metamaterials with controllable characteristics. In this work, we suggest and analyze tunable metamaterials based on resonant dielectric inclusions. This new design demonstrates properties of a μ-negative metamaterial and a double-negative metamaterial suitable for THz applications.

2 Metamaterial based on dielectric resonators

There is a number of suggestions to create structures with negative values of dielectric permittivity and magnetic permeability. The most popular are structures based on an array of split-ring resonators (SRR), dielectric resonators, and wire medium. As a framework of our design, dielectric resonators have been chosen as constitutive particles of the metamaterial with negative effective parameters due to their advantages. First of all, they are free of conducting losses as compared with SRR structures. Second, dielectric particles allow obtaining both types of resonances: magnetic resonance providing negative magnetic permeability and electric resonance providing negative dielectric permittivity [4–7]. High permittivity dielectric spheres, cubes or rods can be arranged to provide negative effective electromagnetic parameters [8–20]. Generally, these materials are effective for microwave frequencies. Scaling the dimensions and using dielectric materials with a higher dielectric permittivity are required to shift the resonances of these structures to THz region.

A possibility to design μ-negative terahertz metamaterials was experimentally demonstrated in [21] on the polycrystalline TiO_2 cube array on the Al_2O_3 substrate. Only some of described metamaterials operating in THz frequency range are tunable. For example, the structure based on a set of ferroelectric rods [22] uses the dependence of the dielectric permittivity on temperature. Unfortunately, this method of control is rather slow and application of such structures is limited. This is why a novel approach for a design of tunable THz metamaterial based on fundamentally different method of control is proposed.

3 Tunability provided by a metal strip deposited on the dielectric cube face

The dielectric cube, which possesses a conducting resonant strip deposited on one face of the cube, is shown in Fig. 1. Characteristics of the material with cube array are changed by the control of the electrical length of the strip. This dielectric cube made from a dielectric with a high dielectric permittivity has appropriate dimensions providing an excitation of the first Mie resonance in THz frequency range. The incident wave is perpendicular to the front cube face. The direction of the electric component of the EM wave is parallel to the metal strip. For a simulation of the resonant response of the dielectric cube the following dimensions of the structure have been used: the cube edge is $a = 0.22$ mm and the width of the metal strip is $w = 0.04$ mm. The permittivity of the cube dielectric material is $\varepsilon_c = 50$.

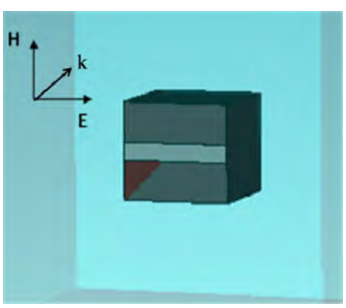


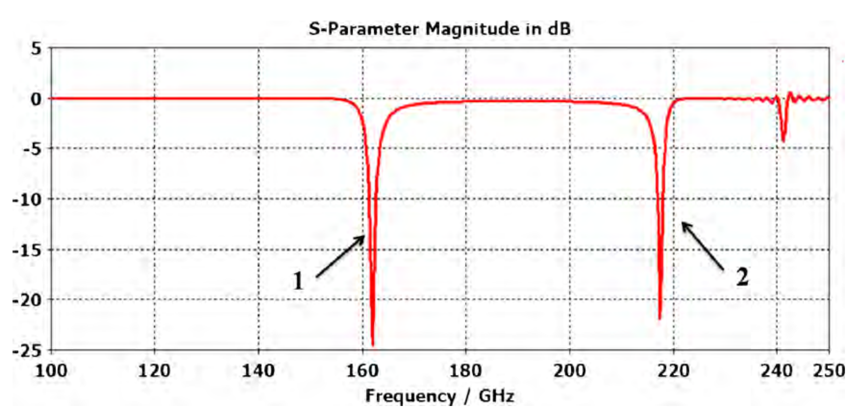
Fig. 1 A single dielectric cube with a metal strip

The transmission coefficient S_{21} for the single dielectric cube without strip is presented in Fig. 2. The low frequency resonance 1 corresponds to the first Mie (magnetic) resonance of the cube. In the narrow frequency range above the resonant frequency the effective magnetic permeability is negative [7–9]. The resonance 2 corresponds to the second Mie (electric) resonance of the cube. Near this region above the resonant frequency the effective dielectric permittivity is negative. The distribution of the magnetic and electric field components corresponding to these Mie resonances are shown in Fig. 3.

The transmission coefficient S_{21} for the dielectric cube with the metal strip is presented in Fig. 4. The frequency of the magnetic resonance is blue-shifted as compared with the previous result in Fig. 2. The frequency of the electric resonance is only slightly influenced by the presence of the metallic strip. A major difference from the cube without the strip is an additional resonance at the frequency $f \cong 125$ GHz. It corresponds to the electric resonance of the metal strip. Effect of shifting the resonances can be explained by the analysis of the distribution of the magnetic and electric field components near the magnetic and electric resonances of the dielectric cube (Fig. 5).

The field disturbance related to the strip influence on the field distribution is evidently strong for the magnetic resonance and exhibits a weak effect on the field distribution in the case of electric resonance. This effect can be used for controlling the resonant frequency of the magnetic resonance. The magnetic resonance strongly depends on the

Fig. 2 The transmission coefficient S_{21} spectrum for the single dielectric cube



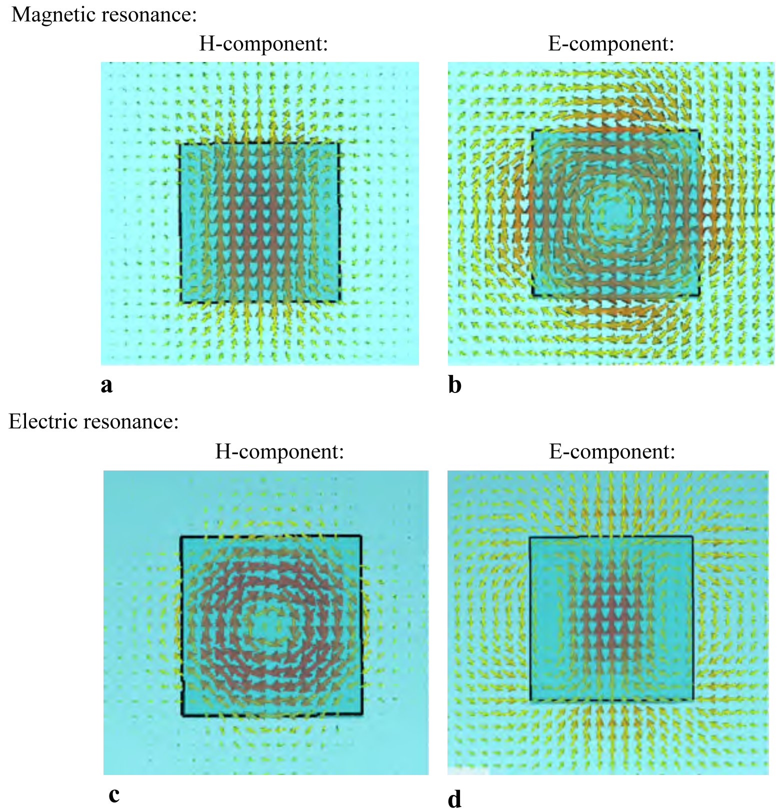


Fig. 3 Distribution of the magnetic (**a**, **c**) and electric (**b**, **d**) field components at the magnetic (**a**, **b**) and electric (**c**, **d**) resonances of the dielectric cube

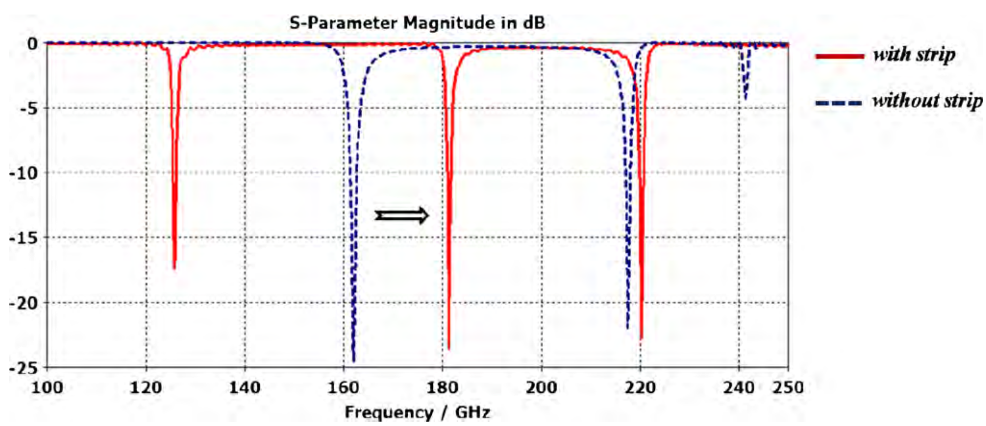


Fig. 4 The transmission coefficient S_{21} spectrum for the single dielectric cube with the metal strip

electric length of the metal strip. The transmission coefficient S_{21} for different values of the electric length of the metal strip *c* is presented in Fig. 6.

The frequency of the strip resonance and the cube magnetic resonance increases with decreasing the length of the strip. In this manner, the electric strip can be used for controlling the resonant frequency of the magnetic resonance of the cube.

The controllable structure is based on using the strip with a gap providing a control of effective electrical length of the strip. The electric length of the strip can be changed by different methods. The first one is creating an active region (purple block) in the gap of the metal strip (gray block) with tunable conductivity (Fig. 7). The maximum of the surface current is observed at the center of the strip. This region can be made of photosensitive semiconductor material. The semiconductor conductivity is changed under optical exposure. Increasing conductivity of the gap is followed by appearance of the short-circuiting bridge in the gap.

The second method is based on a variation of the gap capacitance. In this case, the resonant frequency of the strip can be controlled by applying the voltage to the MEMS structure with a movable cantilever, which is included into the gap. Continuous variation of the resonant frequency can be observed in this case.

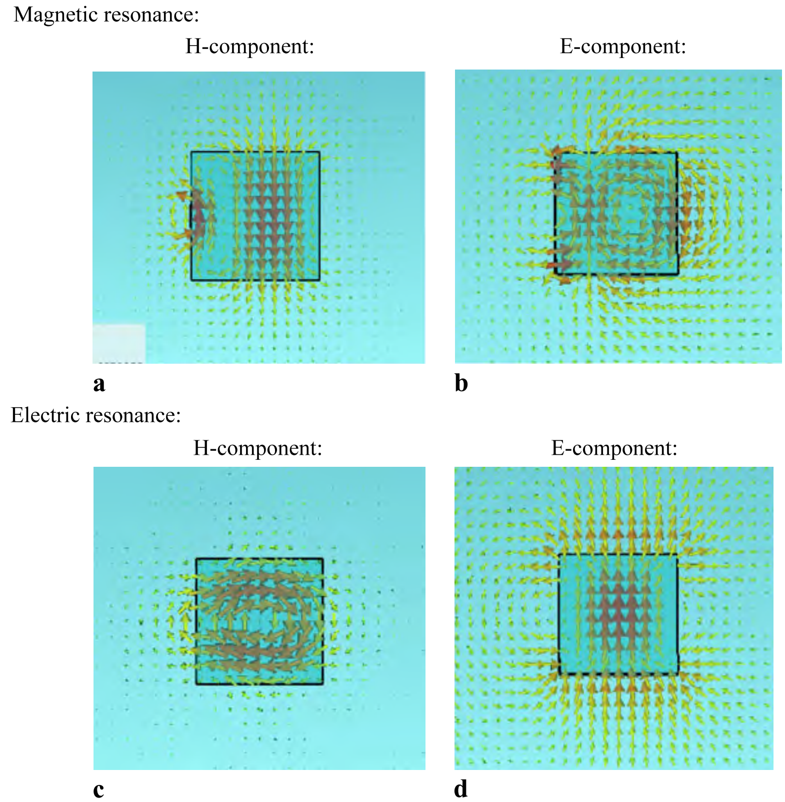


Fig. 5 Distribution of the magnetic (**a**, **c**) and electric (**b**, **d**) field components at the magnetic (**a**, **b**) and electric (**c**, **d**) resonances of the dielectric cube

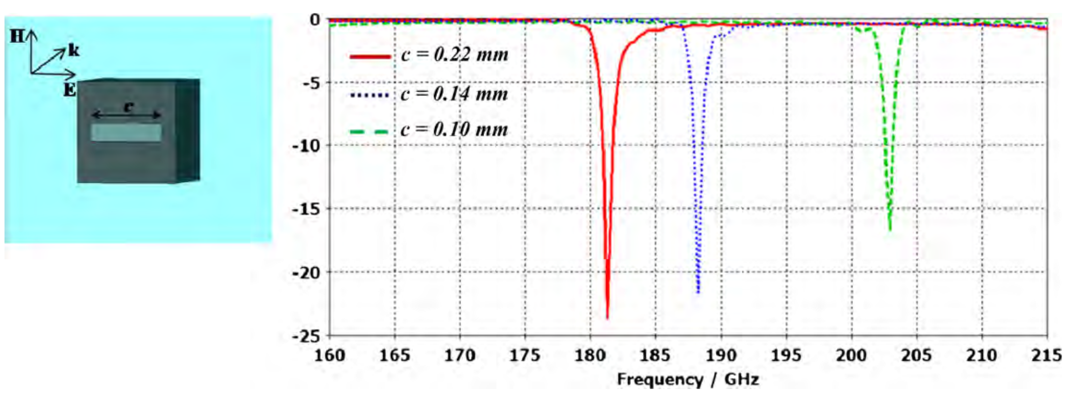


Fig. 6 Influence of the electric length of the metal strip on the transmission coefficient S_{21}

4 DNG tunable THz metamaterial

The double-negative (DNG) metamaterial with negative values of the dielectric permittivity and the magnetic permeability consists of two basic structures: wire medium and dielectric resonator array. Typically the wire medium term is used in meta-structure design for a description of a rectangular lattice of low-loss wire grids placed into the dielectric host (Fig. 8). The wire medium is well studied and is known as the artificial electric plasma with its plasma frequency shifted to the microwave region (in comparison with optical frequencies for metals).

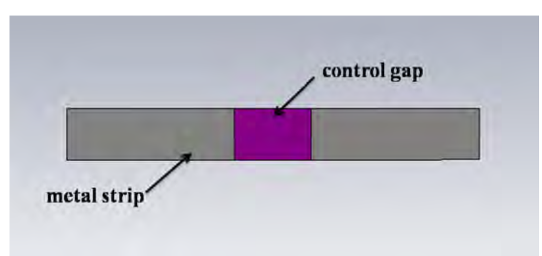


Fig. 7 The metal strip with controllable gap

In a quasi-static approach the plasma frequency of the wire arrays is defined by the following equation [23]:

$$k_p^2 = \frac{2\pi}{p^2} \frac{1}{\ln \frac{p^2}{4r(p-r)}}, \quad (1)$$

where k_p is the wave number, p is the period of the structure (distance between adjacent wires), r is the wire radius. The effective dielectric permittivity of the wire medium is negative below the plasma frequency.

Combining the wire array structure and the dielectric cube array with adjustable period leads to the structure of the tunable DNG metamaterial as shown in Fig. 9. The array of the dielectric cubes (orange) is located on the substrate surface (blue) with the dielectric permittivity $\varepsilon_r \cong 1$. The permittivity of the cube dielectric material is equal to 100. The distance between the cubes p is 120 μm, the cube edge is $a = 50$ μm. Metal wires (yellow) are located between the dielectric cubes. Metal strips (gray) with controllable gaps (black) are located on the cube top faces; the width of the metal strip is $b = 6$ μm, the strip length is $c = 30$ μm, the gap length is $g = 5$ μm. The tunable component (photosensitive semiconductor) is inserted into the gaps (black regions).

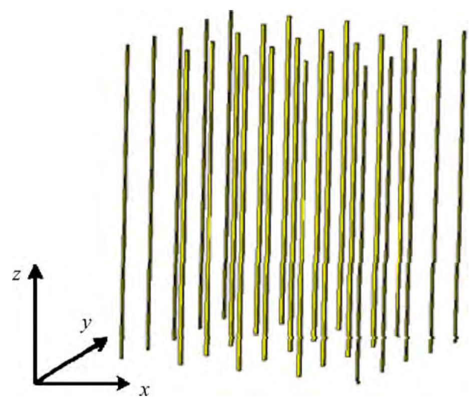


Fig. 8 The one-dimensional wire medium

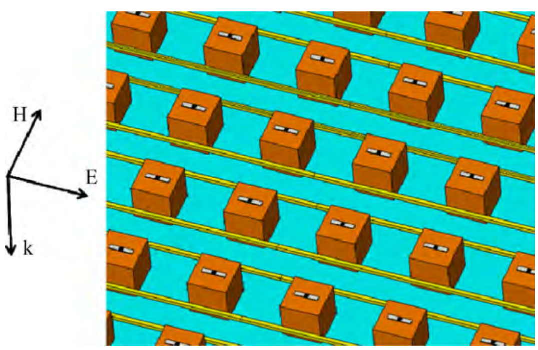
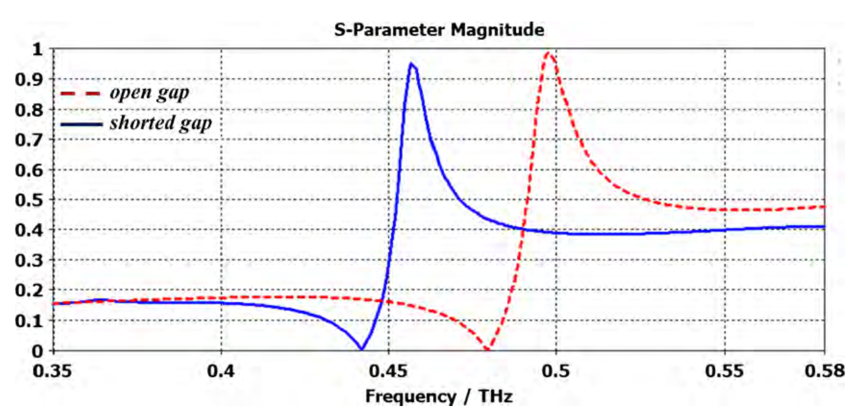


Fig. 9 Planar dielectric-wire-medium structure with controllable metal strips

The frequency-dependent reflection coefficient S_{21} for this structure is shown in Fig. 10. The red curve corresponds to the open gaps; the blue curve corresponds to the shorted gaps. The resonant regions on the plot correspond to the pass bands of the structure with a high transparency of the structure. The resonant frequency is shifted by a variation of the conductivity of the material in the gaps providing two states: open gap and shorted gap. The resonance shift exceeds 0.04 THz in 0.45–0.5 THz region showing Fano-type asymmetric resonance line shape. Off-resonance base line reveals the structure working as a band-pass filter with approximately 0.3 off-on ratio. Since the gap can be controlled by photoexcitation or voltage bias, the modulation speed by estimating response time of the final structure can be as fast as 10 MHz or more.

We further point out that these dielectric resonators and metal strips are easily combined with standard CMOS technologies such as photolithography and lift-off process. Also the control gaps between metal strips can be easily implemented by the same processes. Low-temperature sputtering followed by lift-off may be feasible to fill control gap with photosensitive material or Mott-insulator. As for the electric gap-tuning, it may be impractical to connect every elements and additional metal strips may hinder magnetic resonance with respect to the vertical incidence of light. We are now under investigation to find optimal integration of metal wiring for electric gap-tuning.

Fig. 10 Dependence of the transmission coefficient S_{21} on the gap state in the metal strip



5 Conclusion

A tunable metamaterial based on dielectric cubic resonator with a conducting strip of one face of the cube operating in THz frequency region has been investigated. The original method of tunability based on the field redistribution inside the dielectric resonators is proposed. This effect is obtained due to the disturbance of the first Mie resonance by the conducting strip. The method of control can be provided by the change of dielectric permittivity or conductivity of the gap in the center of the strip. The main advantage of this method is a fast control of the effective electromagnetic parameters of the negative-index metamaterial.

Acknowledgement This work was supported by Samsung Advanced Institute of Technology.

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