TUNABLE METAMATERIAL STRUCTURES FOR CONTROLLING THZ RADIATION

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INTRODUCTION

Bridging radio frequency and optical spectra, THz radiation frequency region is often called THz gap. The term describes the fundamental restrictions which are inherent to the THz spectrum. Natural materials do not have a remarkable electromagnetic response at THz. Magnetic materials tend to have resonances at frequencies below the GHz range, while metals possess resonances at frequencies beyond the mid-infrared. Although there was a remarkable progress during recent decade in the development of efficient THz-wave sources [1], there is still a lack of devices which can manipulate THz radiation such as efficient detectors, phase shifters, filters, modulators, switchers and other basic elements.

Meanwhile the THz frequency range could not be neglected from the field of view of scientists because it is highly attractive from the point of view applications of THz technology in security systems, medical diagnosis, coherent imaging, material analysis, environmental protection, space and earth investigation.

Since natural materials are not capable to effective interacting with THz radiation, artificial structures called metamaterials were introduced for this purpose [2]. Metamaterials are structures with subwavelength dimensions which properties are engineered and defined by the shape and the order of the constitutive particles. That leads to a possibility to design an artificial material with arbitrary parameters not achievable with natural materials (e.g. negative or near zero permittivity or permeability, or refractive index). The limitation for the properties of the metamaterials is basically originated from the technological limitation and also losses in the constitutive particles. Using metamaterials it is possible to form any desired electromagnetic response and manipulate electromagnetic radiation of any frequencies. Examples of metamaterial based structures for controlling THz radiation will be studied in this paper.

THZ PASS-BAND FILTER

THz pass-band filter could be realized as a combination of inductive frequency selective surfaces (FSS) comprising double grid of a two dimensional arrays of slots (wire grid) (Fig 1a). The distance between the adjacent wires *p* is equal to several tenth of micrometers for THz operating frequencies. The bottom layer of the wires is placed on a dielectric low-loss substrate (Fig. 1b). To provide a pass-band filter behavior, the design is completed with additional FSS comprising dielectric dipoles placed on the dielectric low-loss superstrate between two wire arrays. This FSS provides increasing of the slope parameter of the transmittance curve and higher attenuation above the operating frequency leading to a higher selectivity of the filter. To provide 2D isotropy, the dipoles are designed as two orthogonal metallic strips.

The tunability of the filter is provided by changing the permittivity of the dielectric layer between the wire grid arrays. To do that, the space between the top wire grid and superstrate is filled with the nematic liquid crystal (LC). Changing of the permittivity of the LC is provided by applying the biasing voltage to the control electrodes placed on the both sides of the structure (see Fig. 1b). The LC with birefringence of $\Delta n = \varepsilon_1 - \varepsilon_2 = 0.3$ can be used in the filter. The LC permittivity at THz is supposed to be changed from $\varepsilon_1 = 2$ to $\varepsilon_2 = 3$, depending on the voltage applied to the control electrodes.

Simulated transmission characteristic of the filter are shown on Fig. 2. The tuning range about 13% is achieved for the LC birefringence of $\Delta n = 0.3$. The permittivity of the liquid crystal is changed from $\varepsilon_{LC} = 2$ to $\varepsilon_{LC} = 3$. The insertion loss of the filter is 3dB. The selectivity of the filter can be increased by increasing the number of crossed wires forming the FSS.

MIE RESONANCE BASED METAMATERIAL FOR THZ

Another design of the THz filter based onto metamaterial can be realized as a combination of two basic structures: wire medium and dielectric resonator array (Fig 3a). The wire medium behaves as the artificial electric plasma with its plasma frequency shifted to the microwave region (in comparison with optical frequencies for metals) [3]. The dielectric cubes forms the artificial medium with negative effective permeability near the resonance

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frequency of the fundamental Mie resonance mode [4]. 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 are located between the dielectric cubes.

On the top of each dielectric cube the metal strip is placed. The width of the metal strip is *b* = 6 µm, the strip length is *c* = 30 µm. In the middle of the strip the gap of 5 µm length is formed. The gap is used to provide two different states of the strip operating: open and shorted mode. The metal strip disturbs the field distribution inside the dielectric cube under resonance condition. The frequency position of the fundamental Mie resonance (magnetic) strongly depends on the electric length of the metal strip. The tunable component (photosensitive semiconductor) is inserted into the gaps to perform changing the electric length.

The frequency-dependent reflection coefficient S_{21} for this structure is shown in Fig. 3b. The E-field of the plane incident wave is polarized along the wires. On the graph the dashed line corresponds to the open gaps and the solid line 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. These dielectric resonators and metal strips are easily combined with standard CMOS technologies such as photolithography and lift-off process.

MEMS BASED THZ METAMATERIALS

MEMS technology introduces promising concepts of creating tunable devices for THz radiation [5-6]. In this section two versions of tunable metamaterials using piezoelectric cantilevers as controllable elements are considered. Configurations of tunable metamaterials designed as planar metal-dielectric structures of arrays of U-shaped resonators and square metal patches with piezoelectric actuators are proposed.

U-shaped resonator is a half wavelength resonator consisting of three metal strips, forming a letter U (Fig. 4a). The dimensions of the resonator and dielectric permittivity of the substrate are chosen to provide the resonant response in appropriate frequency rage. For THz region the length of the resonator is about 100 µm. For simulation, the width and length of the horizontal and vertical metal strips are taken 40 µm and 120 µm respectively. The thickness and the dielectric permittivity of the substrate is *h* = 40 µm and *ε* = 2.5, correspondingly. The direction of the electric field E and the magnetic field H is shown in Fig. 4a. For the given resonator dimensions, the resonant frequency of the first mode is 0.384 THz. The resonant frequency of the U-shaped resonator can be tuned by embedded controllable cantilevers using piezoelectric materials. Tunable piezoelectric cantilevers are commonly used in microwave frequency range, but can be easily scaled to the THz range using processes of modern microtechnology.

Under the biasing voltage or temperature variation, the cantilever bends at the angle α (Fig. 4b). As a result the electric field is concentrated in the formed gap and a tunable capacitance occurs giving rise to changing the electrical length of the resonator. This in turn results in a shift of the resonant frequency. Control of actuators is provided by metal strips with biasing voltage placed in the middle of each resonator in the array (Fig 4c).

The results of full-wave simulation of metamaterial structure with U-shaped resonators on dielectric substrate are presented in Fig. 5. If the angle α changes from 0° to 15°, the resonant frequency varies from 0.384 to 0.586 THz. Designed metamaterial can be used as a tunable band-stop filter in the THz frequency range. The advantages of this structure are high speed and efficiency of frequency tunability.

The other type of metamaterials is the metal-dielectric-metal (MDM) structure implemented as metallic patches on both sides of a dielectric substrate [7] shown in Fig. 6a. Two metallic patches form the capacitance. The circulated current on patch surfaces produce the magnetic resonance response [7]. The surface current distribution in the unit cell of two coupled metallic patches is shown in Fig. 6b. The resonance frequency of the MDM patch array depends on the value of the capacitance between two coupled patches. If the part of the patch metallization is flexed up, the distance between the patches is changed and the capacitance changes too and provides a shift of the resonant frequency. When the angle between the bended part of the patch metallization and the substrate is increased, the capacitance is decreased and the resonant frequency is blueshifted. Simulation of the transmission coefficient has been done for the MDM patch array with piezoelectric cantilevers (Fig. 6c).

The movability of the cantilever is provided by etching the layer of silicon substrate. The layer of SiO_2 can used as membrane for improvement of the elasticity of the structure. The piezoelectric element produces curvature under applied dc-voltage between the electrodes due to the strength of internal compression. All piezoelectric cantilevers at one side of the substrate are connected together by the biasing bus for the control of its bending angle.

The biasing bus is parallel to the magnetic component of the electromagnetic field for preventing interaction with incident THz radiation. The thickness of metallization is 200 nm. The high impedance silicon with 20 mm thickness and dielectric constant ε_d = 12 with tan(δ) = 0.01 is used as a substrate. The width of the patch is 200 mm, the distance between the patches is 100 mm. The width of the biasing strip is 20 mm. The full-wave simulation results in transmission spectra for different angles of the cantilevers shown in Fig. 7. The amplitude-frequency characteristic of this structure corresponds to low-pass filter response with tunable cutoff frequency. The tunability of the cutoff frequency is 24% for the bending of the movable part of the piezoelectric actuator with respect to the substrate at angle α from 0° to 10°.

The PZT (Pb(Zr,Ti)O_3) or PVDF $(CF_2 - CH_2)_n$ in β-form are proposed to be used as piezoelectric materials in actuators. The crystalline polymer PVDF with a high elastic property can be used for excluding membrane layer from the cantilever structure. The efficiency of the piezoelectric actuators can be increased by using two piezoelectric layers with different signs of the piezoelectric constant. In this case the cantilever bending is provided by both compression and tension. The extent of the actuator bending can be further increased by increasing the length of the movable part, or reducing the thickness of the actuator.

CONCLUSION

A variety of different metamaterial-based structures have been designed and simulated. The structures presented are promising candidates for controlling electromagnetic radiation of THz frequencies. The structures are able to be tuned by means of electrical or optical control. The metamaterial-based THz structures can behave as band-pass, low-pass, band-stop filters, attenuators and switches.

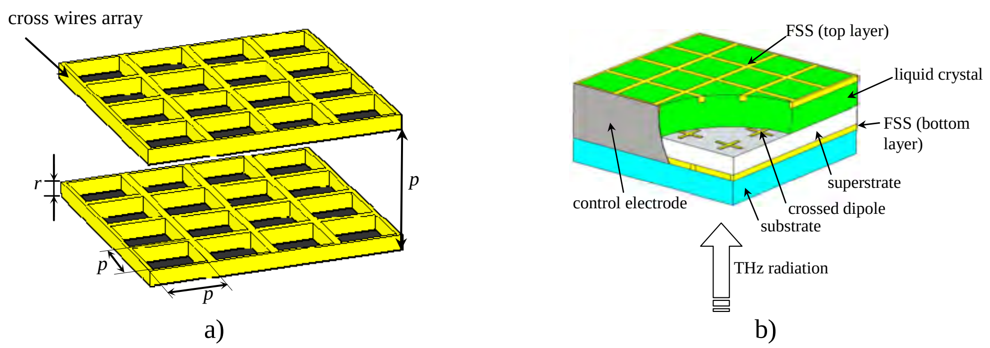


Fig. 1: (a) FSS formed by wire arrays of crossed conducting wires; (b) 3D design of tunable filter.

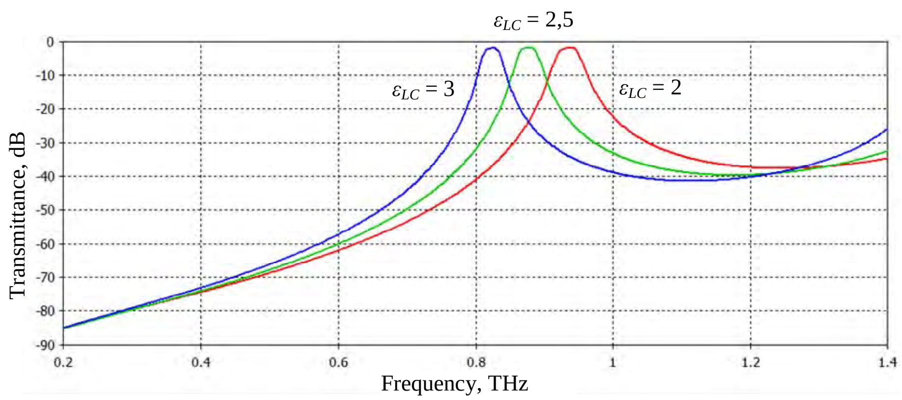


Fig. 2. Simulated transmission coefficient for a filter with different values of the liquid crystal permittivity.

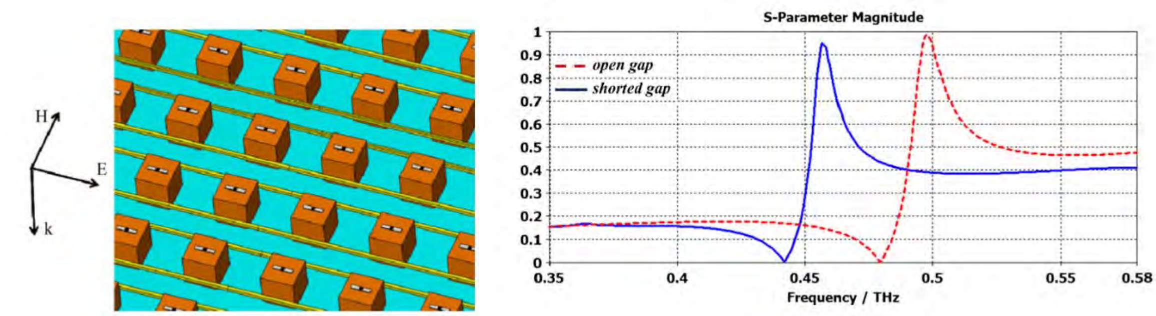
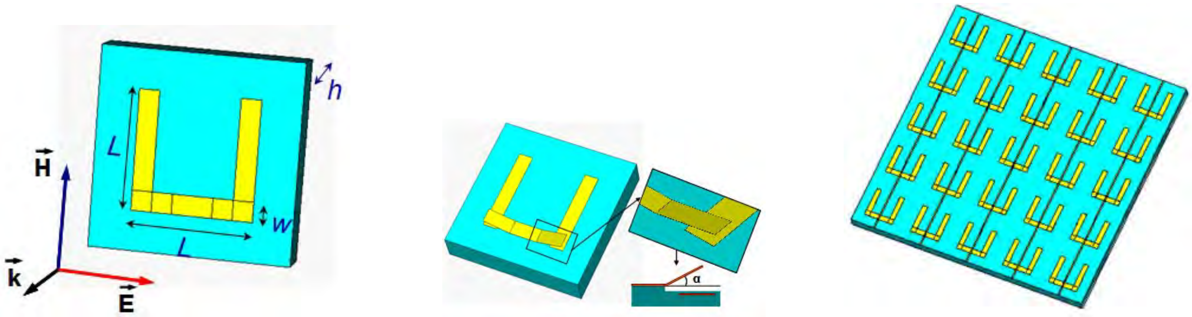


Fig 3. a) Planar dielectric-wire-medium structure with controllable metal strips; b) dependence of the transmission coefficient S_{21} on the gap state in the metal strip.



a) b) c)

Fig. 4. U-shaped resonator (a), with cantilever bending at the angle α (b). Array of the U-shaped resonators (c) with biasing voltage feeding lines.

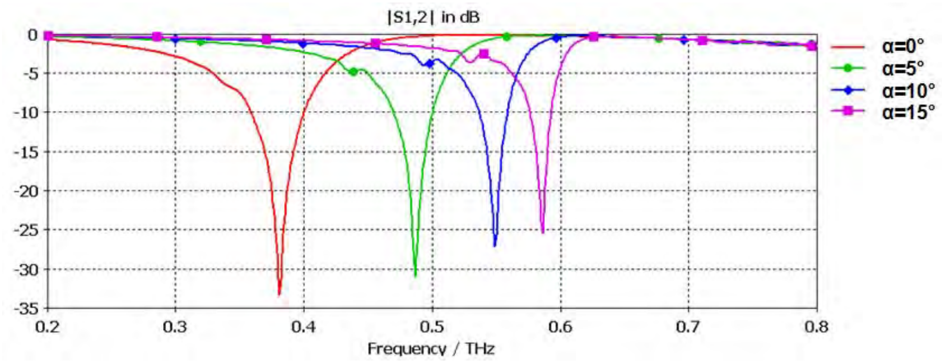
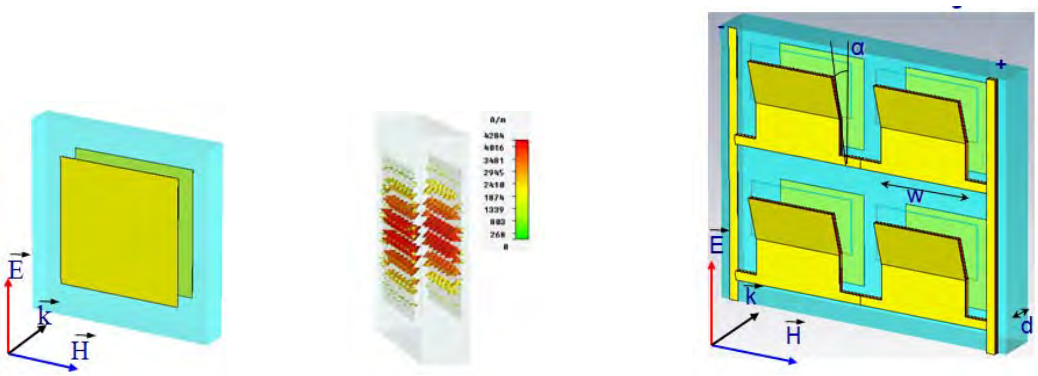


Fig. 5. Frequency dependence of the transmission coefficient of the array at different values of the cantilever bending angle α.



a) b) c)

Fig. 6. MDM structure based on coupled metallic patches: unit cell (a), surface current distribution at the resonant frequency in the unit cell (b), patch array formed by four unit cells with piezoelectric actuator and biasing bus (c).

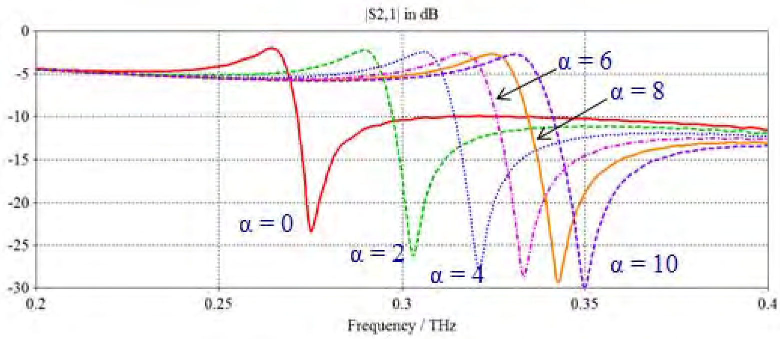


Fig. 7. Transmission coefficients for patch array with different bending angles of the actuator α.

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