Metamaterials for THz and optical applications

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Metamaterials for THz and optical applications

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***Abstract* – Tunable THz metamaterials have been designed and modeled. Three different structures are under investigations: array of U-shaped planar resonators and metal-dielectric-metal patch array with voltage controlled cantilevers and dielectric resonators based structure with disturbed Mie resonance. All structures exhibit efficient control of electromagnetic response.**
An optical superlens based on a coupled pair of 2-D arrays of plasmonic nano-ellipsoids is presented and analyzed. The superlens is capable of restoring sub-wavelength features of an object for s- and p-polarization of light. Simulations revealed sub-wavelength resolution at a distance of nearly 1.4λ_{eff} between the source and the image plane.

I. Introduction

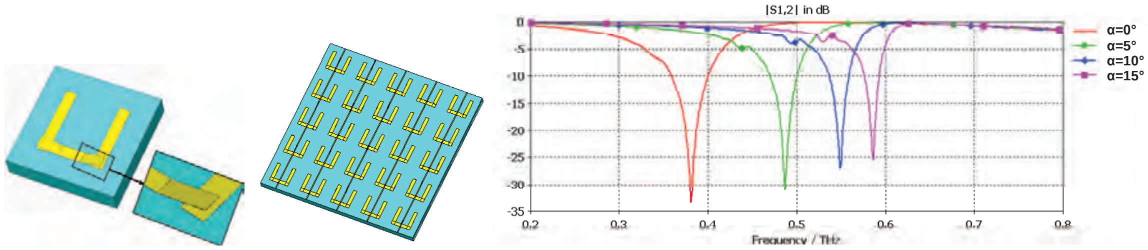
Designing devices and their applications in terahertz frequency range, particularly in medicine and security systems, have been widely investigated. Important is designing THz devices with tunable technical characteristics: operational bandwidth, insertion loss, etc. Three different structures have been suggested and analyzed: i) array of U-shaped resonators exhibiting epsilon-negative behavior near the resonance frequency; ii) the metal-dielectric-metal (MDM) structure implemented as metallic patches on both sides of a dielectric substrate; iii) all-dielectric cubic array in combination with wire medium. All structures are designed for control the THz radiation. Different methods of control are considered including a voltage tunable piezoelectric cantilever [1] and the light control.

The next subject presented in this paper is an optical superlens based on a coupled pair of 2D arrays of plasmonic nano-ellipsoids. An approach based on resonant excitation of surface modes suggested in [2-3] showed that the use of arrays of small resonant particles, such as plasmonic oblate nanoellipsoids, may exhibit flat dispersion curves, so that oscillations with a wide range of wave numbers can be excited by external evanescent fields and thus sub-wavelength imaging and field concentration in the optical region are attained. The anisotropic polarizability of the oblate ellipsoids gives rise to sub-wavelength resolution for both s- and p-polarized sources [3]. A superlens implemented by multi-layer periodic arrays of electrically small silver ellipsoids is considered.

II. Tunable THz metamaterials

Two different designs based on piezoelectric cantilevers are introduced. In the first case we are dealing with U-shaped resonators (Fig. 1a) forming an epsilon-negative medium at the resonance frequency. The structure parameters are chosen to provide a resonant response at the THz region with the length of the resonator of about 200 μm. For a regular array of the U-shaped resonators (Fig. 1b) one can observe the stop-band behavior. The resonant frequency of the structure is controlled by the biasing voltage applied to the cantilevers via strips. Tuning the piezoelectric cantilever is provided by the electrodes movement.

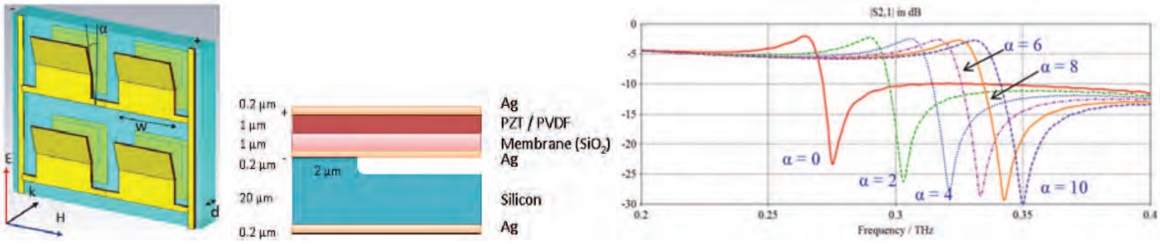
Under the biasing voltage the cantilever bends at the angle α. As a result a tunable capacitance occurs. This in turn results in a shift of the resonant frequency (Fig. 1c). Control of actuators is provided by the biasing voltage applied to metal strips. In line with the results of full-wave simulation the resonant frequency varies from 0.384 to 0.586 THz (40%) for α changing from 0 to 15°.



a) b) c)

Fig. 1. (a) U-shaped resonator with a cantilever, (b) tunable array of U-shaped resonators with a set of metal strips, (c) frequency dependence of the transmission coefficient of the array.

The second design presented is the MDM-structure implemented as metallic patches on both sides of a dielectric plate (Fig. 2a). The circulated current on the patch surfaces produce the magnetic resonance response.

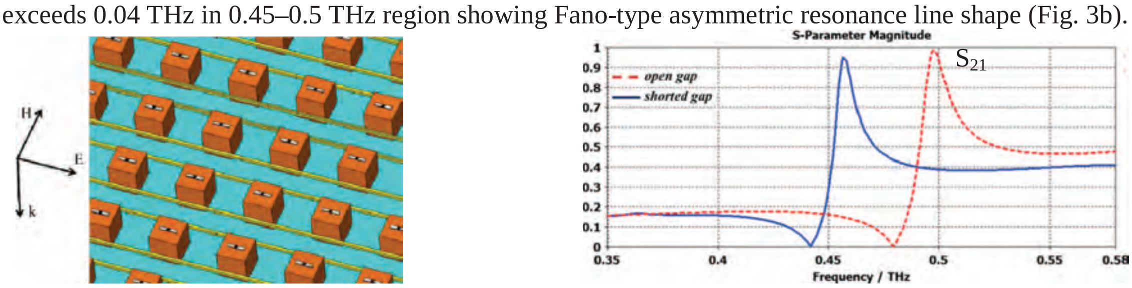


(a) (b) (c)

Fig. 2. (a) Array of MDM-structure (fragment), (b) piezoelectric cantilever, (c) frequency dependence of the transmission coefficient of the array.

If the part of the patch metallization is flexed up, the resonant frequency is shifted. Simulated was the MDM patch array with piezoelectric cantilevers (Fig. 2b) connected with a feed line (Fig. 2a). All the strips are connected together by two feeding busses located at the edges of the substrate. Silver patches are disposed on the surface of silicon substrate (ε_d = 12, tanδ = 0.01) with 20 µm of thickness. Width of the patch is 200 µm, the distance between the patches is 100 µm. Results of electromagnetic simulation (Fig. 2c) reveal the low-pass filter behavior with a tunable cut-off frequency. Tunability of the structure is about 24% (0.275 – 0.35 THz).

The 3D tunable THz structure is based on a set of cubic dielectric resonators in combination with wire medium (Fig. 3a). The structure properties are tuned by change of the resonant frequency of the disturbed Mie-resonance, which is shifted by variable electrical length of the metal strip situated on one face of the cube. The control is provided by a light sensitive gap in the center of the strip. The resonant frequency is shifted by a variation of the conductivity of the material in the gap providing two states: open or shorted gap. The resonance shift exceeds 0.04 THz in 0.45–0.5 THz region showing Fano-type asymmetric resonance line shape (Fig. 3b).

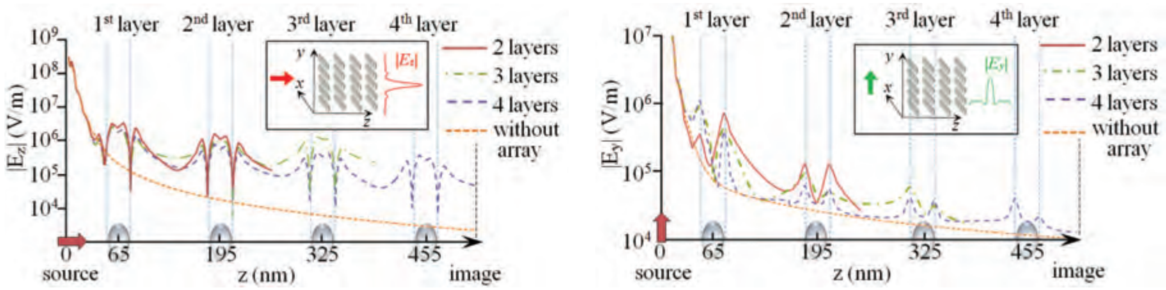


a) b)

Fig. 3. (a) Array of cubic dielectric resonators with a metallic strip on one face; (b) transmission coefficient of the structure. Open gap – red curve; shorted gap –blue line.

III. SUB-WAVELENGTH RESOLUTION AND NEAR-FIELD ENHANCEMENT IN THE OPTICAL RANGE

A metamaterial lens capable of 2-D sub-wavelength focusing at optical frequencies can be realized with a set of coupled 2-D arrays of plasmonic nano-ellipsoids. The host medium is assumed to be poly-methyl methacrylate ($\varepsilon_r = 2.25$). The dimensions of the oblate ellipsoids are $a_x = a_y = 30$ nm and $a_z = 15$ nm, whilst the period of the array is a = 65 nm. In this example, the object (source) plane is at distance $h = a$ from the first array, the distance between arrays is $d = 2a$ and the distance between the last array and the image plane is $h = a$. The electric field distribution is calculated as described in [2-3], for both vertically $\boldsymbol{p} = p_z$ and horizontally $\boldsymbol{p} = p_y$ polarized sources. Commercial software CST Microwave Studio and in-house software have been used in the simulations. The suitable frequency of operation for both polarizations was found numerically by scanning the resolution performance and the maximum field enhancement for a range of frequencies in the vicinity of the resonant frequency of a single ellipsoid. The frequencies found for a 4-layer structure of 23x23 nano-particles were 524THz and 521THz for vertically and horizontally polarized sources respectively. The image of a source was observed at a distance of $1.4\lambda_{eff}$ from the source. The electric field across the array layers at the frequency of operation is depicted in Fig. 4 for vertically and horizontally polarized sources. It can be seen that, in the case of no lens, the incident field decreases as $1/r$ (r is the distance from the dipole) and rapidly becomes very weak. In the presence of the lens, a small incident field is able to excite the resonant mode in the first layer, which in turn produces a strong scattered field in its vicinity. The excited field decays away from the layer, but it is able to strongly excite the subsequent resonant layer and so on. Therefore, the lens allows maintaining the evanescent field across the layers and thus keeps the small spatial wavelengths. This results in sub-wavelength field focalization in the far-field of the source.



a) b)

Fig. 4. Field distribution between the source and the image plane at the frequency of operation providing maximum resolution for vertically a) and horizontally b) polarized sources. The insets show the position of the source and the lens structure as well as the field distribution for both polarizations.

VI. Conclusion

Planar metamaterial structures for THz applications based on U-shaped resonators and MDM resonant patches using voltage control and 3D all dielectric structures of negative index metamaterial using light control can be effectively tuned.

Multi-layer arrays of resonant nano-ellipsoids provide field enhancement and sub-wavelength focusing for vertically and horizontally polarized sources at a distance of $1.4\lambda_{eff}$ from the source.

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