Influence of the incidence radiation polarization on the absorptivity of Electrical Ring Resonator Metasurface in Terahertz frequency range.

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Abstract. The aim of this research is investigation of the incidence radiation polarization influence on electrical ring resonators metasurface absorption in terahertz frequency range. Reflection spectra of 5 metasurface samples in cases of 3 different polarization angles (θ = 0°, θ = 45° and θ = 90°) were experimentally investigated. It was shown that maximal absorption reaches in cases of polarization angles θ=0° and θ=90°.

1. Introduction

Metamaterial devices for terahertz (THz) frequency band have been a subject of close attention for the last decade. A reason behind this interest is a lack of natural materials with strong response to electromagnetic radiation of terahertz frequencies. Particularly there is a need for materials with strong absorption in terahertz frequency range for such applications as terahertz sensing, hyperspectral imaging and screening [1-7] and biomedicine applications [8-11]. The pioneering paper on THz metamaterial absorbers (MA) based on electrical ring resonators (ERR) has been published by Tao [12] (his colleague Landy studied the same structure for far infrared wavelength region [13]). This design can have theoretical absorptivity close to unity (0.99) with full width at half maximum (FWHM) of 4 percent of resonant frequency. The authors verified this design by obtaining experimentally the absorptivity value of 0.7 at 1.4 THz. Such great difference between theoretical and experimental results is explained by variation of material parameters from tabular values and by non-optimized fabrication process. In 2009 Landy [14] proposed another structure, an array of unit cells, which were comprised of two different cross-shaped resonators separated by a dielectric spacer. This MA had experimental absorptivity of 0.75 at 1.15 THz. This structure is polarization-insensitive due to the symmetry of the unit cell. In 2011 Shen et al. [15] and Ma et.al [16] proposed similar MA designs with unit cell comprised of concentric square-ring resonators backed by a layer of metal and spaced by a dielectric layer. This structure acts like a multiband absorber having three absorption peaks equal to the number of square ring resonators. This design is polarization-insensitive and gives absorptivity values of 0.99, 0.96, and 0.98 at 4.02GHz, 6.75GHz and 9.24GHz respectively. Another interesting idea to implement a dual-band absorber was proposed by Wang et al. [17]: the dual-band MA (metasurface-dielectric-metallic ground plane structure) with cut-wire metasurface unit cell. The high-order resonance of the cut-wire was used to obtain the second absorption band of high quality (Q=8.4). The simulation results give the absorptivity of 0.9967 and 0.9973 at 1.42 THz and 2.99 THz with FWHM of 0.2 THz and 0.05 THz respectively.
In this paper, the effects of the incidence radiation polarization on MMA’s absorptivity were described and analyzed.

2. Description of the structure
The proposed structure consists of four layers. Layers functions, materials and thicknesses are presented in table 1.

| Layer | Function                  | Material     | Thickness, μm |
|-------|---------------------------|--------------|---------------|
| 1     | Substrate                 | Silicon      | 300           |
| 2     | Thin film (THz mirror)    | Copper       | 0.5           |
| 3     | Spacer (absorber)         | Polyimide SU-8 | 20            |
| 4     | ERR (resonator)           | Copper       | 0.5           |

The draft of the MA unit cell with double ERR is shown in figure 1. It consists of 2 ERRs connected to each other of one side and could be defined by a set of parameters: \( g \) – an ERR gap; \( w \) – an ERR lines width; \( a, b \) – ERR length and width respectively; \( p \) – a distance between an ERR edge and an unit cell border.

Moreover for description of incidence radiance polarization the parameter \( \theta \) – an angle between short side of unit cell (Y-axis in figure 1) and electric field vector \( \vec{E} \) was added.

3. Fabrication Process
For fabrication of MA, it needs the following metal-semiconductor structure: 5 copper ERR arrays (12x12 mm\(^2\)) with different geometric parameters from table 2 would be marked in silicic 320 mm substrate (because it’s material with the best cost/conductivity ratio), using vacuum evaporation and photolithography process. Photolithography is profitable in case of development of tunable MA: besides high accuracy of fabrication, photolithography allows manufacturing several absorbers on one substrate simultaneously using common emulsive photomask, that increases rate of manufacture and allows cheaply making multitude of experimental samples. At the same time photolithography processes (polyimide laying, exposure, development and etching) occupies plenty of time. For the time
being emulsive photomask and experimental sample of tunable MA were manufactured in “Vavilov State Optical Institute”. Process of MA sample fabrication schematically is sketched in figure 2.

Figure 2. Process of experimental samples manufacturing consists of the following:
- substrate preparing: firstly thin chrome layer (20 nm) and after that copper layer (500 nm) was sputtered on silicon substrate, using ion-vacuum spattering method;
- liquid polyimide solution SU-8 was sputtered using centrifuge;
- photoresist layer was applied by centrifuge and image was formed by photolithography;
- another copper layer was sputtered (0.5 mm) as electronic resonant rings;
- photoresist deleting.

5 MMA samples with different geometric parameters were fabricated for investigation of influence of the incidence radiation polarization on the absorptivity of ERR Metasurface in THz frequency range. Their layer thicknesses are shown in table 1, ERR geometric parameters are presented in table 2.

| MMA sample | a, μm | b, μm | g, μm | p, μm | w, μm |
|------------|-------|-------|-------|-------|-------|
| 1          | 160   | 80    | 15    | 15    | 5     |
| 2          | 176   | 88    | 15    | 15    | 5.5   |
| 3          | 192   | 96    | 15    | 15    | 6     |
| 4          | 208   | 104   | 15    | 15    | 6.5   |
| 5          | 224   | 112   | 15    | 15    | 7     |

4. Experimental setup
In the present work compact TPS (terahertz pulsed spectroscopy) setup was used [18]. The setup operates in reflection mode and allows measuring the THz spectra between 0.25 and 1.75 THz. Figure 3 represents the experimental setup design and illustrates the process of TPS waveform detection. The TPS system makes use of the second harmonic radiation of the Er-doped femtosecond fiber laser with an average power of 200 mW for both THz pulse generation and detection. The central wavelength is 780 nm, and the pulse duration and the pulsed repetition rate are 100 fs and 50 MHz correspondingly. THz-wave generation is produced in a LT-GaAs photoconductive antenna (PCA), and detection of THz pulses is performed in a ZnSe-electro-optical detector. The reflection mode measurements with a beamsplitter and a normal angle of radiation incidence on the sample surface were carried out. Figure 3 shows the details of the experiment. The power reflectivity of the metasurface was determined by the Eq. (1):

$$ R(\nu) = \left| \frac{\tilde{E}_R(\nu)}{\tilde{E}_\nu(\nu)} \right| $$  (1)

where $E_R$ is derived from fourier-domain representation of the reference waveform $E_R = E_\nu(t)$, reflected from the plane gold mirror places behind the rigidly fixed diaphragm, and $E_c$ is derived from
the fourier-domain representation of the sample waveform $E_s(t)$, reflected from the sample of interest placed behind of diaphragm.

**Figure 3.** Design of reflective THz spectrometer.

5. Experimental results
Reflection spectra of 5 fabricated samples (geometric parameters indicated in table 2) were investigated in the frequency range of 0.1-1.6 THz for three polarization angles: $\theta=0^\circ$, $\theta=45^\circ$ and $\theta=90^\circ$. Figure 4 demonstrates spectra of MA samples №1 and №3.

**Figure 4.** The reflection coefficient of the experimental MMA samples №1 and №3 for $\theta = 0^\circ$ (red curve), $\theta = 45^\circ$ (green curve) and $\theta = 90^\circ$ (blue curve).
All structures spectra have 2 resonant peaks: low-frequency for $\theta = 90^\circ$ and high-frequency for $\theta = 0^\circ$, sample №3 spectrum also has absorptivity peak at frequency of 1.4 THz, its appearance could be described by some mistakes during fabrication process. At resonant frequency of $\theta = 0^\circ$ absorptivity of $\theta = 90^\circ$ close to 0 and vice versa. In case of $\theta = 45^\circ$ structure samples spectra have both low- and high-frequency peaks, but its resonant absorptivities are lower than in case of $\theta = 0^\circ$ or $\theta = 90^\circ$. Table 3 presents resonant peak absorptivity for all 5 experimental samples.

**Table 3. ERR geometric parameters.**

| Sample | 1 | 2 | 3 | 4 | 5 |
|--------|---|---|---|---|---|
| Resonant peak frequencies, THz | 0.396 | 1.053 | 0.326 | 0.866 | 0.277 | 0.746 | 0.242 | 0.651 | 0.219 | 0.581 |
| Resonant peak absorption, % | 6.1 | 100 | 4.4 | 99.7 | 4.1 | 83.5 | 9.1 | 89.5 | 7.4 | 85.4 |

### 6. Conclusions

Influence of incidence radiation polarization on MMA’s absorptivity was investigated and following results were received:

- proposed structure is polarized sensitive with maximal peak absorptivity at polarization angles $\theta=0^\circ$ and $\theta=90^\circ$
- frequencies of maximal absorptivity at $\theta=0^\circ$ are frequencies of minimal absorptivity at $\theta=90^\circ$ and vice versa
- polarization angles between $\theta=0^\circ$ and $\theta=90^\circ$ have intermediate value of absorptivity at resonant peaks

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