

Surface Metallic Pattern for Enhancement of a THz Field in a Two-Dimensional Electron Plasma

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A metamaterial in the form of a periodic lattice of split-ring resonators on a GaAs/AlGaAs heterostructure was numerically studied at terahertz frequencies. A finite-difference time-domain algorithm was applied to calculate distribution of the electromagnetic field in the layer positioned at 100 nm below the heterostructure surface where a two-dimensional electron gas typically resides in real structures. The results allowed to determine the resonant frequencies of the metamaterial as well as an enhancement factor of the electric field as a function of the period of the metamaterial's lattice.

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1. Introduction

Metamaterials have been objects of broad studies in optics, solid state physics and electronics [1] and reveal a variety of properties which are interesting both from the scientific and applications point of view. In the present paper, we concentrate on a metamaterial whose resonant frequencies fall within the THz range. Such structures form a lattice of so-called split-ring resonators (SRRs) deposited on a dielectric surface. Dimensions of a single resonator are typically of the order of 10 μm which makes a THz metamaterial easy to be fabricated lithographically. From a technical point of view, a SRR is an LC resonant circuit with distributed elements. The capacitive part is formed by slits in the SRR while the metallic body of the resonator serves as an inductance.

There are several aspects which draw our interest towards THz metamaterials. First, a SRR behaves as a resonant cavity for the electromagnetic radiation which opens a possibility to couple its resonances with excitations of other types. For example, such an interaction was observed in Ref. [2] where SRRs were deposited on a GaAs/AlGaAs heterostructure with a high-electron-mobility two-dimensional electron gas (2DEG) and cavity resonances coupled with a cyclotron resonance transition. In that case, the Rabi frequency was comparable to the frequency of the underlying resonances which led to the so-called ultrastrong light-matter coupling, an extremely interesting area of quantum electrodynamics [3].

Second, a resonant character of metamaterials allows to store the energy of an incident electromagnetic wave which leads to strong, resonantly enhanced, electric fields in the slits of the SRR [4]. Then, one can think about observation of nonlinear effects related to such enhanced oscillating electric field and to effects related to the ponderomotive potential.

Third, the metallic structure of a SRR forms a gate electrode which can be used to change the concentration of a 2DEG and thus to allow one to tune the resonant frequency of a metamaterial. This opportunity, together with an additional illumination with a near-band gap light and application of magnetic field, offers a set of control parameters which can be used to make a metamaterial a tunable THz optical element.

Experimental studies of metamaterials based on heterostructures with a 2DEG is our long-term goal. The present work, however, is devoted solely to numerical studies of the interaction of electromagnetic waves with a SRR of a geometry studied in Ref. [2]. The reason of choosing this geometry is that its resonances fall within a sub-THz band which can be investigated using tunable sources accessible at our laboratory. In the present paper, we mainly concentrate on a spatial distribution of the amplitude of the electromagnetic field in the metamaterial as a function separation of neighboring resonators, which was not studied in Ref. [2].

2. Computational method and results

The computational method used was a finite-difference time-domain (FDTD) algorithm [5] implemented in a Meep [6] software package (version 1.1.1 of the package was used). Computations were done in a few steps. First, the structure was “illuminated” with an electromagnetic (EM) pulse, i.e., a propagation of an EM pulse was analyzed. The reason for analyzing a pulse was to decompose it, at subsequent steps of the procedure, to the Fourier components which then would allow to trace propagation of monochromatic waves with given frequency. In the calculations, the pulse width was chosen in such a way that we could analyze a frequency response between 0.1 THz and 5 THz, which roughly corresponds to the frequency range that can be covered by sources available at our laboratory. The incident wave was polarized in the x direction (see Fig. 1) which allowed to effectively induce x -directed currents in the vertical metallic bars forming

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a capacitive part of the SRR. These currents lead to periodic oscillations of charges at the edges of bars and result in a strong field enhancement in the vicinity of the edges. Since we are interested in a response of a two-dimensional electron gas which is buried typically at a depth of about 100 nm below the surface of the heterostructure, we limited our analysis to the plane located at 100 nm below the surface. At this plane, the evolution of EM fields was recorded. In the next step, the same EM pulse “illuminated” a structure without metallization, and the time evolution of EM fields was recorded again. Finally, for each grid point in the x - z plane, the amplitude gain γ was calculated

$$\gamma(E_x) = \frac{|\mathcal{F}(E_x)|}{|\mathcal{F}(\tilde{E}_x)|},$$

where \mathcal{F} denotes a Fourier transform, and E_x and \tilde{E}_x are amplitudes of the electric field with and without the SSR metallization, respectively. We applied a fast Fourier transform algorithm implemented in Octave [7]. In the simulations, we assumed an infinite metamaterial which was achieved by imposing periodic boundary conditions.

Dimensions of the SRR studied can be inferred from Fig. 1 and were $26 \mu\text{m} \times 42 \mu\text{m}$ in the x and z direction, respectively. We analyzed distribution of the electromagnetic field changing the distance d between outer edges of neighboring resonators (the same value of d was assumed for x and z directions). Calculations were repeated for $d = 2, 4, 10,$ and $20 \mu\text{m}$, which corresponds to the lattice period in the x direction $\Lambda = 28, 30, 36,$ and $46 \mu\text{m}$, respectively.

We assumed that the metallization thickness was equal to $2 \mu\text{m}$ and that it was done with a perfect metal (i.e., we assumed no energy dissipation in the metal which forms the SRR).

An example of results of simulations is presented in Fig. 1 which shows a distribution of the amplitude gain of the E_x electric field around one resonator at 0.6 THz in an infinite lattice of SRRs with $d = 10 \mu\text{m}$. One can easily see a highly non-uniform distribution of the electric field whose maximum values are positioned both outside and inside the resonator.

To show a resonant character of the studied structure, we present in Fig. 2 a dependence of the enhancement factor as a function of frequency for a single point which is chosen to be the middle of the left capacitor. There are two bands of resonances, best visible in the inset to Fig. 2: one of them below about 1.0 THz, and the other — at about 5 THz which cannot be precisely described due to a limited range of frequencies which were taken into considerations. The low-frequency band is clearly composed of three different resonances, the strongest of which occurs at 0.6 THz. The resonances are rather broad (a half-width is equal to about 10% of the resonant frequency) and their position on the frequency axis does not depend on the separation between neighboring resonators. However, the enhancement factor is clearly dependent on d and is the highest at $d = 2 \mu\text{m}$. Chang-

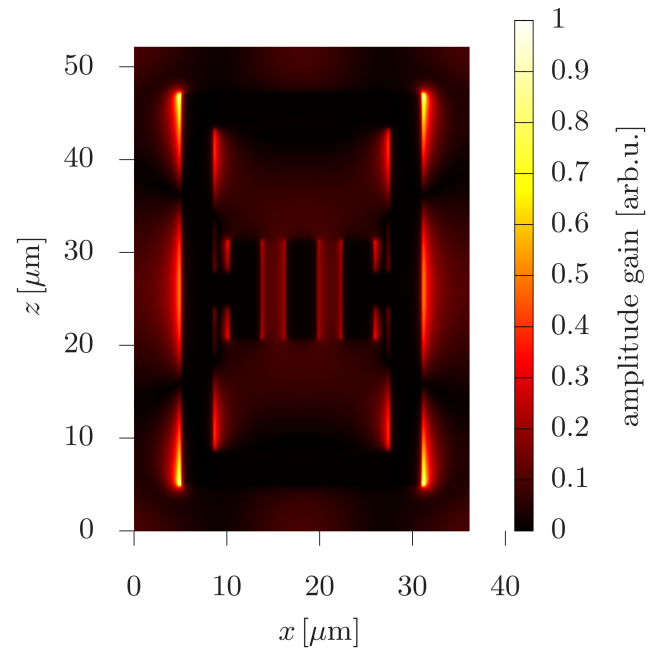


Fig. 1. Distribution of the amplitude of the E_x component of the electric field at the plane positioned 100 nm below the SRR metallization for a horizontal (x) polarization of the incident radiation, the frequency of radiation equal to 0.6 THz and an infinite periodic structure with a distance of $10 \mu\text{m}$ between neighboring SRRs.

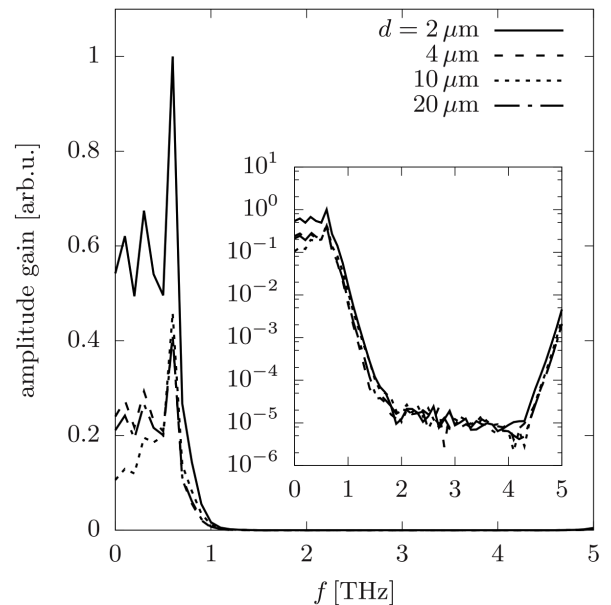


Fig. 2. A frequency dependence of the enhancement factor γ (normalized to the maximum value at 0.6 THz) at the middle of the left capacitor ($x = 15 \mu\text{m}$, $z = 26 \mu\text{m}$ in Fig. 1). The inset shows the same dependence in a logarithmic γ scale.

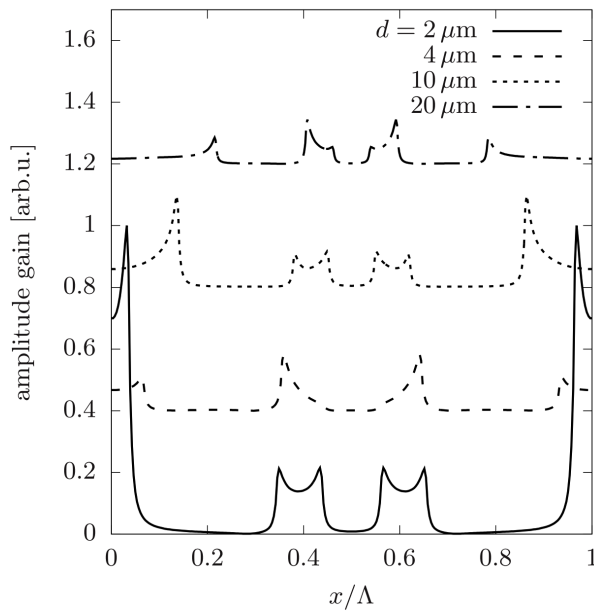


Fig. 3. A cut of the distribution of the amplitude of the E_x component of the electric field along the horizontal symmetry axis of the SRR ($z = 26 \mu\text{m}$ in Fig. 1) for different values of d , indicated in the figure. The curves are vertically shifted for clarity. The coordinate x is normalized to the period of the lattice Λ , and γ is normalized to the maximum value obtained for $d = 2 \mu\text{m}$.

ing the separation between resonators, one can essentially influence the distribution of the electric field in the metamaterial. In Fig. 3 we show how the enhancement factor changes along the horizontal symmetry axis of the SRR at different values of d and at 0.6 THz. The strongest enhancement occurs at the edges of the SRR metallization, which reflects a known phenomenon of appearance of a strong electric field around a sharp charged metallic edge. As one can see, neither the maximum value of the enhancement factor nor its distribution show monotonic changes with increasing d .

3. Conclusions

Numerical studies of a metamaterial in the form of a periodic lattice of split-ring resonators on

a GaAs/AlGaAs heterostructure were carried out as a function of the lattice period and frequency of electromagnetic radiation in the THz band. We show that a distribution of the electric field of the incident radiation at the plane positioned at 100 nm below the sample's surface is strongly dependent on the separation between resonators. This means that for the range of d studied, the resonators interact one with another and make the lattice to behave as one entity. The results give a valuable information for fabrication of structures to be experimentally studied: neighboring resonators should be placed at a distance of single micrometers because this leads to the strongest enhancement of the electric field in the metamaterial.

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References

- [1] W.J. Padilla, D.N. Basov, D.R. Smith, *Mater. Today* **9**, 28 (2006).
- [2] G. Scalari, C. Maissen, D. Turcinková, D. Hagenmüller, S. De Liberato, C. Ciuti, C. Reichl, D. Schuh, W. Wegscheider, M. Beck, J. Faist, *Science* **335**, 1323 (2012).
- [3] Y. Yamamoto, T. Tassone, H. Cao, *Semiconductor Cavity Quantum Electrodynamics*, Springer Tracts in Modern Physics, Vol. 169, Springer-Verlag, Berlin 2000.
- [4] J.H. Seo, T.H. Kim, C. Kang, C.S. Kee, *Curr. Appl. Phys.* **16**, 329 (2016).
- [5] A. Taflov, S.C. Hagness, *Computational Electrodynamics: The Finite-Difference Time-Domain Method*, Artech House, Boston 2005.
- [6] A.F. Oskooi, D. Roundy, M. Ibanescu, P. Bermel, J.D. Joannopoulos, S.G. Johnson, *Comput. Phys. Commun.* **181**, 687 (2010).
- [7] J.W. Eaton, *GNU Octave, a high-level interactive language for numerical computations*.