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Optimization of Nanoantenna-Enhanced Terahertz Emission from Photoconductive Antennas

S I Lepeshov[1], A A Gorodetsky[1,2,3], N A Toropov[1], T A Vartanyan[1], E U Rafailov[3], A E Krasnok[4], and P A Belov[1]
[1] ITMO University, St. Petersburg, Russia
[2] Lancaster University, Lancaster, UK
[3] Aston Institute of Photonic Technologies, Aston University, Birmingham, UK
[4] Department of Electrical and Computer Engineering, The University of Texas at Austin, Austin, USA

Abstract. We present the results of hybrid photoconductive antenna THz emission enhanced by silver nanoantenna arrays. By varying the size of nanoantennas and the distance between them, we obtain the greatest value of optical-to-THz conversion efficiency reached so far. The results of experimental investigations are in a good agreement with numerical simulations. The conversion efficiency reveals over 5-fold improvement at certain frequencies, if compared with similar photoconductive antenna without silver nanoparticles, while previous results for this type of antenna barely exceeded 2-fold conversion efficiency gain.

1. Introduction

The terahertz spectral band of electromagnetic waves has a wide range of perspective applications for spectroscopy [1], biological sensing [2], security imaging [3], detection of dangerous or illicit substances [4,5] and potentially for ultrafast data transmission [6]. However, the widespread use of THz technologies is hampered by the absence of effective THz sources operating at room temperature. The most common source of coherent pulsed terahertz radiation is so-called THz photoconductive antennas (PCAs) [7]. The principles of THz PCAs operation are based on the effect of ultrafast surface photoconductivity of semiconductor substrate under femtosecond laser irradiation. Since such antennas are broadband, they have been applied for spectroscopic investigations of organic molecules [8] and material science [9] as well as wireless THz transmitters and receivers [10]. However, THz PCAs still have low efficiency that prevents data transmission over long distances and do not provide a permissible signal-to-noise ratio. The low efficiency is mainly related to the photocarrier screening effect [11] and the low absorption coefficient of the surface layer of the semiconductor substrate. To overcome these limitations, optical nanoantennas [12] have been proposed to be placed in the gap of THz PCA [13]. Optical nanoantennas are resonant nanostructures capable of transforming incident optical waves in a strong near-field. Nowadays, nanoantennas are used to enhance the absorption coefficient of a semiconductor substrate of PCAs. Nanoantenna-based PCAs have been called hybrid terahertz-optical PCAs (Figure 1). It has been shown that this solution provides high fs-laser pump absorption, shorter photocarrier lifetime and excellent thermal efficiency [13]. Despite the fact that many nanoantenna designs have been studied for enhancement of THz generation from PCA, an optimized geometry has not yet been proposed. Here, the results of optimization of nanoantenna-enhanced THz emission from hybrid PCA are presented. We show that an increase of more than 5-fold in the high-frequency spectral range can be achieved for an optimal design of nanoantenna array.

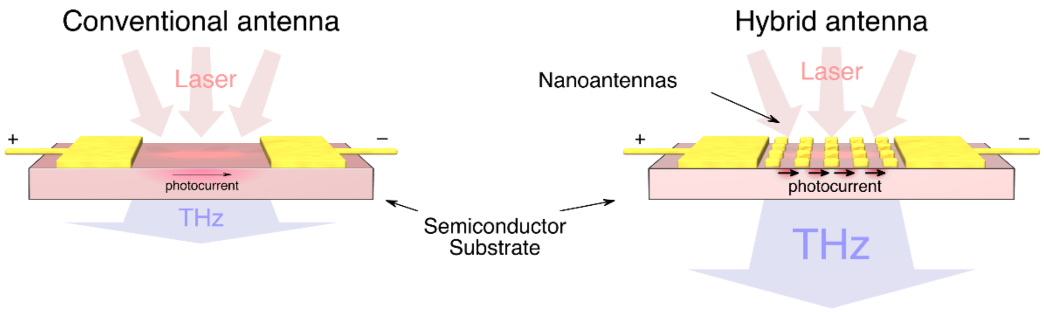

Figure 1. Illustration of the conventional (left) and hybrid (right) photoconductive antenna operation.

2. Numerical optimization of nanoantenna array

First, we carried out numerical calculations of silver (Ag) spheroid nanoantenna array on the high-index Gallium Arsenide (GaAs) semiconductor substrate. It is well known that metallic (particularly Ag) nanoparticles provide localized plasmonic resonances in the optical range [12]. This type of resonances is characterized by a strong localization of the electric field near a metal nanoparticle due to conversion of far-field of the incident wave to near-field of the oscillating electron plasma on the metal surface, which can be considered as an oscillating electric dipole if the size of the nanoparticle is sufficiently small. While nanoparticles are on the surface of the high-index substrate (GaAs), the electric field is mostly concentrated in a thin layer of the substrate surface that increases the absorption of fs-laser radiation near nanoantennas resulting in enhancement of THz emission.

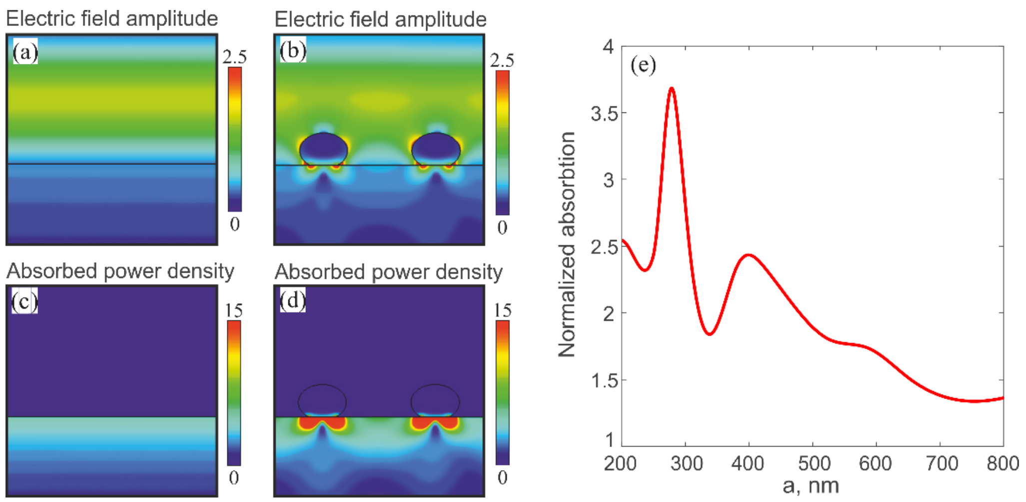

Figure 2. (a) Electric field distributions in the pure GaAs substrate and (b) in the substrate containing Ag nanoantennas at the wavelength of 800 nm. (c,d) The same for absorbed power density. (e) The dependence of the normalized absorbed power on the period of the nanoantenna array *a*.

The results of the numerical calculations of the electric field distribution at the air-GaAs interface with Ag spheroid nanoantenna and without nanoantenna are presented in Figure 2(a,b). For the simulation, we used CST Microwave Studio software package. The structure is excited by the normally incident plane electromagnetic wave at the wavelength of 800 nm. The geometrical parameters of nanoparticle correspond to the most optimal for the excitation of plasmonic resonance in this structure. The large semi-axis of the spheroid is D = 168 nm, the minor semi-axis of the spheroid is d = 106 nm. It can be seen that the magnitude of the electric field under the spheroid (Figure 2(b)) is larger by a factor of 3 than the magnitude of the field at the interface between air and GaAs without nanoparticle (Figure 2(a)). The absorbed power P in a volume V can expressed as

$$P = \frac{1}{2}\int \sigma |\mathbf{E}|^2 \, dV,$$

where $\mathbf{E}$ is a vector of electric intensity in the medium, σ is a medium conductivity. The absorbed power is directly proportional to the value of $|\mathbf{E}|^2$, and thus, the strong localization of the electric field in the semiconductor near nanoparticle causes increase of the absorbed power, which results in photoexcitation of free carriers. Figure 2(c,d) shows a comparison of absorbed power densities in the semiconductor with and without nanoparticles. One has to note that the power absorbed in GaAs with silver nanoantenna is significantly higher than in pure GaAs near the surface.

Then, we have studied the dependence of the absorption of the light in the substrate surface layer on the distance between nanoparticles. For this purpose, we calculated quadratic periodic array of spheroid nanoparticles of the previously obtained optimal size. By varying the period of the array a, different values of the absorbed power density were received and the maximum was found at the period of 270 nm.

3. Results and discussions

To prove our theoretical findings, we performed experimental investigations of hybrid PCA with Ag nanoantennas and compared the obtained results with previous studies [14]. We fabricated the conventional log-periodic PCAs as a basis for next stages. Such antenna construction provides a broad radiation spectrum that allows studying the enhancement in the high-frequency range. The log-periodic antenna electrodes were deposited onto the quantum-dot based InAs:GaAs semiconductor substrate [15,16] by optical lithography. The antennas have a smallest gap of 8 μm, and overall diameter of 1.8 mm. Then, a 20-nm silver film has been arranged onto the substrate surface of one of the fabricated antennas. Upon thermal dewetting process caused by heating, the silver film has been dewetted into a disordered array of spheroid nanoparticles. The size of resulting nanoparticles depends on the thickness of the silver film [17]. The size of the fabricated nanoparticles corresponds to calculated optimal ones and the average distance between nanoparticles is 280 nm.

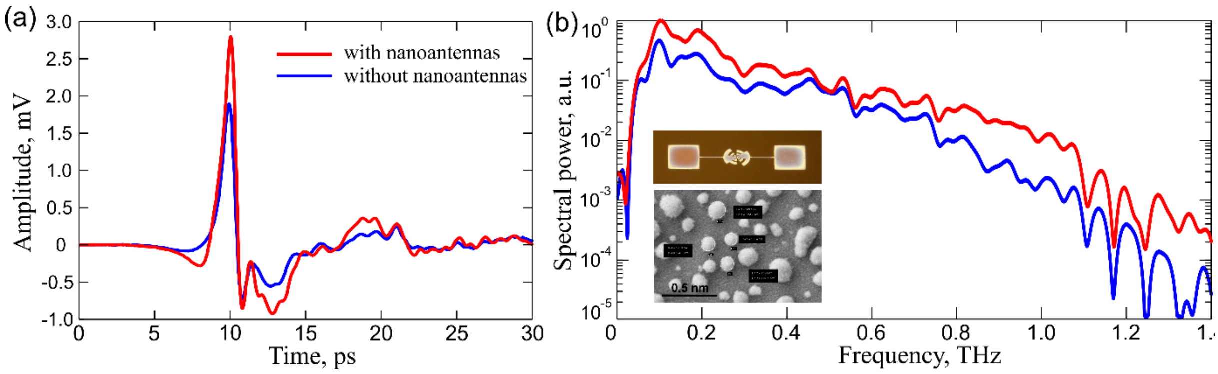

Figure 3. (a) The terahertz signals from the log-periodic photoconductive antenna with silver nanoantennas (red curve) and without nanoantennas (blue curve); (b) the spectra of terahertz signals. Insert: image of log-periodic photoconductive antenna on quantum-dot based InAs:GaAs semiconductor substrate and SEM-image of the silver nanoparticles in the gap of the antenna.

For experimental verification of the proposed hybrid antennas, a standard THz time-domain spectroscopic (TDS) system has been used. THz-TDS is pumped with Sprite-XT (M Squared Ltd.) femtosecond Ti:sapphire laser that delivers pulses of 120 fs duration at 80 MHz repetition rate with central wavelength of 800 nm. As THz detector, LT-GaAs photoconductive antenna made by Teravil Ltd. was used, and the beam was guided between transmitter and detector by two off-axis parabolic mirrors. To estimate the effect of silver nanoantennas, signals from standard and nanoantenna-enhanced transmitters were measured. Figure 3 summarize the obtained experimental results.

Figure 3(a) shows the terahertz signals from the log-periodic photoconductive antenna with silver nanoantennas (red curve) and without nanoantennas (blue curve). Figure 3(b) demonstrates that antenna reveals uneven enhancement across the spectrum, reaching its maximum around 1 THz. Negligible effect from nanoantennas at 0.5 THz can be associated with the change in antenna impedance induced by highly conductive silver in the gap. Thus, our results demonstrate significant amplification of the emitted THz signal spectral power. The results for nanoantennas demonstrate over 5-fold increase in comparison with the case of nanoantenna absent that in 3 times higher than previously reported [14].

4. Conclusion

We have demonstrated, both theoretically and experimentally, an unprecedented enhancement of photoconductive antenna operation by silver plasmonic nanoantennas. The resulting hybrid PCA demonstrates over 5-fold increase in generated THz signal around 1 THz, and over 2-fold increase in overall generated THz power, which perfectly coincides with theoretical estimations. We belive that our results may be useful for many vital applications, including spectroscopy, biological sensing, security imaging, and ultrafast data transmission

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