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# Novel Optimized Hybrid Terahertz Photoconductive Antennas

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# Novel Optimized Hybrid Terahertz Photoconductive Antennas

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**Abstract.** We demonstrate the results of on THz emission from hybrid THz photoconductive antenna loaded with silver nanoantenna. The results of experimental investigations are in a good agreement with numerical simulations presented in our recent work. 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. We propose a cost-effective fabrication procedure to realize such hybrid THz antennas with optimized plasmonic nanostructures via thermal dewetting process, which does not require any post processing and makes the proposed solution very attractive for applications.

## 1. Introduction

Terahertz photoconductive antennas (PCAs) are one of the most promising sources of pulsed THz radiation [1,2]. The principles of THz PCAs operation are based on the effect of ultrafast variations of surface photoconductivity of a semiconductor substrate under fs-laser irradiation: after exciting the gap between the electrodes with a fs-laser, the concentration of charge carriers increases sharply for a short period of time, and THz pulse generation occurs. Since the generated signal is a short single pulse hundreds of fs in duration, its spectrum spreads over several octaves in THz frequency range. The broad bandwidth is ideal for spectroscopic investigations of organic molecules [3], material science [4] as well as wireless THz transmitters and receivers [5]. However, conventional THz PCAs have a rather low conversion efficiency that prevents data transmission over long distances, they do not provide a large signal-to-noise ratio, and require ultrafast laser pump at wavelengths around $\lambda$ = 800 nm, usually provided by expensive and bulky Ti:Sapphire lasers. The low conversion efficiency is mainly related to two predominant factors: the photocarrier screening effect [6], and the low absorption coefficient of the surface layer of the semiconductor substrate. To overcome these limitations, optical nanoantennas have been proposed to be placed in the gap of THz PCA [7,8]. The nanoantenna-based PCAs have been called hybrid terahertz-optical PCAs. It has been shown that this solution provides high fs-laser pump absorption, shorter photocarrier lifetimes and excellent thermal efficiency. Despite the fact that many nanoantenna designs have been studied for enhancement of the THz generation from PCA, an optimized geometry has not yet been proposed.

Here, we present the results of our recent experimental investigations of a log-periodic THz photoconductive antenna coupled to a silver (Ag) nanoantenna array arranged in the gap of a THz antenna [9]. We obtain an enhancement of optical-to-THz conversion efficiency 2-fold larger in comparison with previously reported results [10]. As a byproduct, we propose a cost-effective fabrication procedure allowing to produce such hybrid THz antennas with optimized plasmonic nanostructures via thermal dewetting process.

## 2. Sample fabrication

First, we fabricate the hybrid PCAs with optimized Ag nanoantenna design proposed in Ref. [9]. The PCAs were fabricated on semi-insulating GaAs substrates containing self-assembled InAs quantum-dots (QDs). Such QD based antennas have been recently demonstrated to generate effectively both pulsed and CW THz radiation [11,12]. Since the 800 nm wavelength pump is used, and the carriers are generated in the whole volume of the GaAs matrix, the dots serve only as carrier lifetime shorteners, in a similar way as defects in low temperature grown GaAs [11]. The log-periodic shape of electrodes has been selected for the realization of the THz antenna due to the fact that such design provides a broadband radiative spectrum. The latter circumstance allows studying the THz antenna operation in the wider-frequency range. The log-periodic antenna electrodes have been deposited onto the QD-based substrate by UV optical lithography. The fabricated THz antennas have a smallest gap of 8 μm, and overall diameter of 1.8 mm. Then, a 20-nm silver film has been deposited onto the substrate surface of one of the fabricated antennas. Upon thermal dewetting process caused by heating, the silver film has been transformed into a disordered array of spheroid nanoparticles. The size of the resulting nanoparticles depends on the thickness of the silver film and can further be changed by laser pump [13]. The sizes of the fabricated nanoparticles proximately correspond to calculated optimal ones and the average distance between nanoparticles is 280 nm. The dashed oval in Fig. 1(a) shows the location of the resulting nanoantennas on the radius-center distance map. The SEM pictures of the produced hybrid THz antenna are shown in Fig. 1(a).

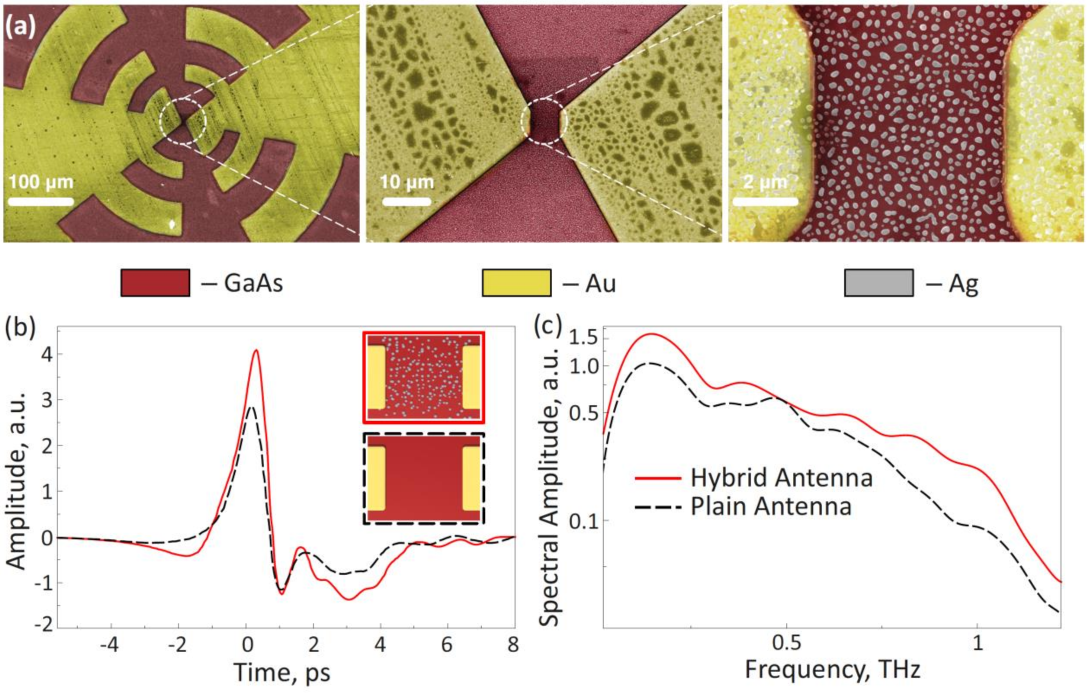


**Figure 1.** (a) The typical SEM images of the fabricated log-periodic THz PCA, its central part and its gap filled with silver nanoantennas. (b) Time domain THz field profiles and (b) their corresponding spectral amplitudes measured for hybrid (red) and plain (black) PCAs.

## 3. Experimental results

Then, we perform experimental investigations of hybrid PCAs with optimized Ag nanoantennas and compare the obtained results with previous studies. For experimental investigation, 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 a THz detector, a LT-GaAs photoconductive antenna made by Teravil Ltd. was used, and the beam was guided between the transmitter and detector by two off-axis parabolic mirrors. To estimate the effect of silver nanoantennas, signals from standard and nanoantenna-enhanced THz antennas were measured for similar pumping and bias conditions. The experimental results are summarized in Fig. 1(b,c).

Fig. 1(b) shows the time domain THz signals generated with the log-periodic PCA with and without Ag spheroidal nanoantennas. The corresponding amplitude spectra, obtained using the Fourier transform, are shown in Fig. 1(c). It can be seen that the antenna demonstrates an uneven enhancement across the spectrum. The enhancement reaches its maximum around 1 THz, and the enhancement value corresponds to the 5-fold theoretically derived value of the power absorption enhancement. Lower effect at other frequencies and negligible enhancement at 0.5 THz can be associated with the change in the THz antenna impedance induced by highly conductive silver in the gap [9]. The results for THz PCAs with nanoantennas demonstrate over 5-fold increase in comparison with the case of nanoantenna absent. This is 3 times higher than the results that have been previously reported [10].

## 4. Conclusion

In conclusion, we have demonstrated an unprecedented enhancement of the photoconductive antenna operation efficiency by optimized spheroidal Ag plasmonic nanoantennas. The resulting hybrid PCA demonstrates over 5-fold increase in the generated THz signal around 1 THz, and over 2-fold increase in overall generated THz power. Moreover, we have proposed the cost-effective fabrication procedure to realize such hybrid THz antennas with optimized plasmonic nanostructures via thermal dewetting process, which does not require any post processing and makes the proposed solution very attractive for applications. We believe that our results may be useful for many relevant applications, requiring compact and effective room-temperature THz sources, including spectroscopy, biological sensing, security imaging, and ultrafast data transmission.

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