Ultrafast electron field emission from gold resonant antennas studied by two terahertz pulse experiments

Krzysztof Iwaszczuk[1], Maksim Zalkovskij[1], Andrew C. Strikwerda[1] and Peter U. Jepsen[1]
[1]DTU Fotonik, Technical University of Denmark, Ørsteds Plads, Building 345, DK-2800 Kgs. Lyngby, Denmark

***Abstract*— Ultrafast electron field emission from gold resonant antennas induced by strong terahertz (THz) transient is investigated using two THz pulse experiments. It is shown that UV emission from nitrogen plasma generated by liberated electrons is a good indication of the local electric field at the antenna tip. Using this method resonant properties of antennas fabricated on high resistivity silicon are investigated in the strong field regime. Decrease of antenna Q-factor due to ultrafast carrier multiplication in the substrate is observed.**

I. Introduction

It has been recently shown that strong terahertz pulses enhanced in the near field of metal resonant dipole antennas or metal nano-tips can lead to ultrafast electron field emission [1, 2]. Ultraviolet (UV) light emission in the 300 – 400 nm spectral range localized in the volume near the tip of the antenna can be observed if those experiments are perform in air [1]. UV light emission has been attributed to formation of the nitrogen plasma due to impact excitation or ionization of nitrogen molecules by field-emitted electrons with kinetic energies exceeding tens of eV. In this work we use the UV emission as a probe of local electric field at the antenna tips and characterize resonant properties of antennas in the strong field regime.

II. Results

Two strong THz pulses are generated by optical rectification of two NIR pulses in a tilted wavefront configuration in lithium niobate ($LiNbO_3$) crystal [3]. Figure 1 shows the intensity of the UV light measured by the PMT tube with a 10 nm wide 340 nm bandpass filter as the time delay between THz pulses. When two THz transients arrive at the resonant antenna simultaneously, strong and highly nonlinear enhancement of UV emission is clearly visible. As the THz-THz time delay increases, UV emission decreases and oscillates at the resonant frequency. Using nonlinear UV emission intensity scaling dependence, peak THz field at the antenna tip for various THz-THz time delays can be back calculated.

Figure 2 shows amplitude spectrum of THz field at the tip of the antenna for various antenna designs. It is clear that the resonance frequency is shifted to the red with respect to the design frequency (dashed lines). We attribute this frequency shift to THz field induced change of the refractive index of the substrate via ultrafast multiplication of free carriers by impact ionization in silicon [4]. Q factors of various resonant antenna arrays are also calculated and shown on the inset to fig. 2. Measured values are substantially lower than the values obtained from simulation, indicating that nonlinear processes in the substrate can contribute to energy drainage from the system.

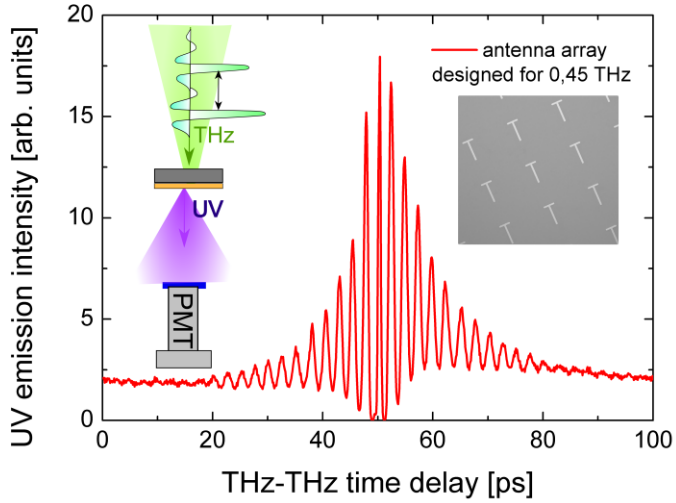

Fig. 1. UV emission intensity as a function of THz-THz time delay in a two THz pulse experiment. Experiment performed for antenna array designed for resonance at 0.45 THz. Inset show SEM image of T-shape antenna array using in experiment.

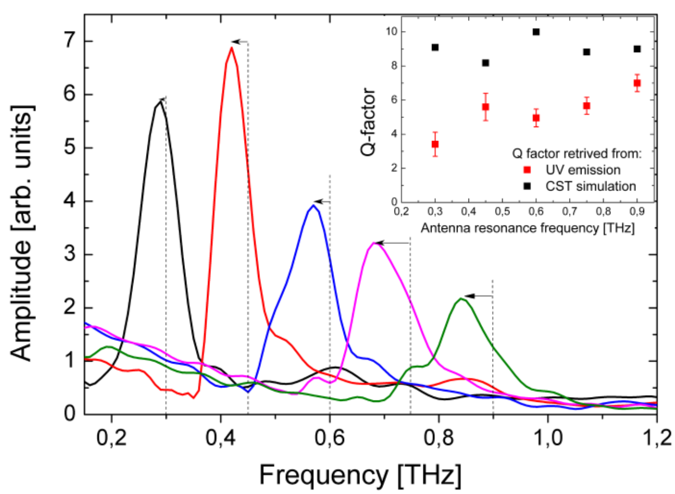

Fig. 2. Amplitude spectrum of THz field at the tip of a T-shape antenna retrieved using UV emission power scaling law. Dashed lines indicate design resonance frequencies and arrows indicate frequency shift attributed to impact ionization in the substrate. Inset: Q factors for various antennas obtained using UV emission profiles and CST numerical simulations.

References

[1]. K. Iwaszczuk, M. Zalkovskij, A. C. Strikwerda, and P. U. Jepsen, "Nitrogen plasma formation through terahertz-induced ultrafast electron field emission," *Optica* 2, 116-123 (2015).

[2]. G. Herink, L. Wimmer and C. Ropers, "Field emission at terahertz frequencies: AC-tunneling and ultrafast carrier dynamics," *New J. Phys.*16, 123005 (2014).

[3]. M. C. Hoffmann and J. A. Fülöp, 'Intense ultrashort terahertz pulses: generation and applications,' Journal of Physics D: Applied Physics 44, 083001 (2011).

[4]. A.T. Tarekegne, K. Iwaszczuk, M. Zalkovskij, A.C. Strikwerda, and P.U. Jepsen "Impact ionization in high resistivity silicon induced by an intense terahertz field enhanced by an antenna array," *New J. Phys.* (accepted, 2015).