Fundamentals for a terahertz-driven electron gun

Simon L. Lange[1*], Filip D. Olsen[1], Krzysztof Iwaszczuk[1] and Peter U. Jepsen[1]
[1]*DTU Fotonik, Technical University of Denmark, Kgs. Lyngby, Denmark*
**slla@fotonik.dtu.dk*

***Abstract*- We present simulations showing how metallic dipole structures can be used as a fundamental platform for electron field emission (EFE) enabled by a strong terahertz (THz) transient. We present space-time mapping of the ultrafast dynamics of EFE with an approximately free-standing dipole versus two dipoles placed with a small gap in between. We conclude that it is possible to make ultra-bright electron bunches shorter than 1 ps and accelerate them to the low keV range over 15 µm using only a single THz transient. Our results are fundamental to understand and build a THz-driven electron gun.**

I. Introduction

In recent years, it has been proven feasible to use short high field electromagnetic, single cycle transients in the THz regime to enable electron field emission (EFE) and subsequent acceleration using 2D metallic structures [1,2]. Such setup is effectively a THz-driven electron gun. It benefits from ultra-high brightness and acceleration gradient in a strong THz nearfield, which means that space charge effects are efficiently limited as the distance from emission point to target can be brought down to a few µm. Moreover, it provides electron bunch durations of just few hundred femtoseconds. These characteristics, in combination with electron energies below 10 keV, pave the road towards femto-chemistry involving free electrons.

It has been already shown that visible and NIR light pulses can induce large EFE from nanotips in the strong field regime [3]. However, such systems suffer from joule heating and the fact that the half-cycle period of the incident light is too short to additionally provide the emitted electrons with significant acceleration. The natural ps-long half-cycle period of THz circumvents this issue.

In this work, we investigate metallic dipole structures for THz-driven EFE using Finite-Element-Time-Domain simulations in CST Particle Studio. We identify fundamental effects related to nearfield enhancement in combination with electron tunneling and we perform space-time mapping of emitted electrons using a Particle-In-Cell solver. Our results show the fundamental mechanisms of importance when designing THz metamaterials with high EFE as well as subsequent control of electron emission during the acceleration in the THz nearfield around the emission point.

II. Results

In Fig. 1(a), the THz-induced EFE process is sketched out using a dipole antenna made of gold.

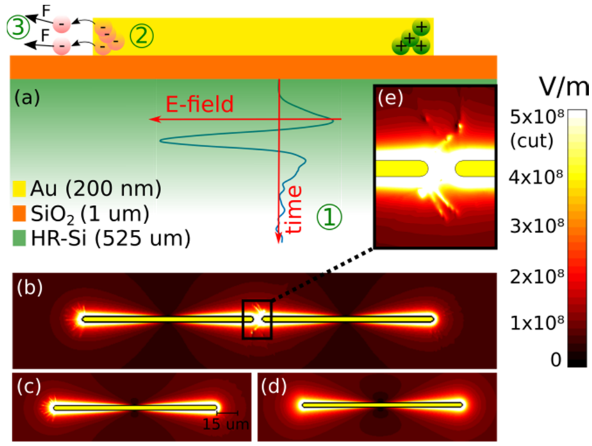

Fig. 1: (a) Principle of THz-induced EFE. 1) A 500 fs long THz transient is incident from the back of a HR-Si/SiO_2 heterosubstrate with an Au dipole on top (dimensions not to scale). 2) THz drives a current in the dipole, and shortly after the incidence of the peak field, the electron volume fraction is enhanced at one tip end, thus creating a strong nearfield. Using an incident peak electric field on the order of 10^7 V/m – which is experimentally obtainable – electrons tunnel out in the nearfield and subsequently 3) gets accelerated due to the relatively long half-cycle period of the THz pulse compared to the tunneling time. **(b)-(d)** Peak field distributions for **b)** two dipole antennas with a 5 µm gap, **c)** a single dipole where the substrate around it has been removed and **d)** a single dipole where the substrate is intact. Colors have been cut at 5×10^8 V/m to better show the absolute field distribution. The inset in **e)** shows how emitted electrons break the symmetry of the otherwise 2-fold symmetric EM problem. This happens due to space charging and the probability-driven secondary electron emission.

The field emission is calculated in CST using a Fowler-Nordheim-type of equation $J = a \cdot E^2 \cdot \exp(-{}^{b}/_{E})$, where *J* is the emission current density and *E* is the electric field. *a*

978-1-5090-5323-0/17/$31.00 ©2017 IEEE

and b are constants for which the system effective work function $\varphi = 0.25eV$, which is obtained from experiments, is used [2].

For simulations, we used the experimentally obtainable peak field strength of 500 kV/cm. Due to the nonlinearity of the EFE and the time dependence of the subsequent electron trajectories calculated using the Lorentz force on each particle, it is not possible to generalize the simulation results to any arbitrary peak field strength. Different field strengths require new simulations.

In Fig. 1(b)-(e), the peak electric field distribution is shown for 3 antenna designs. The EFE contributes to the total field in a non-symmetric way due to charge deposition and accumulation in the substrate, which is shown in Fig. 2(d) as an emerging, negative field offset close to the emission point.

Many of the emitted electrons after initial acceleration hit the substrate or the antenna itself instead of leaving the simulation volume. In Fig. 2(c), electrons are shown to be emitted in 3 bursts (depicted as negative y-values), one of which is the clear main. The subsequent events are shown in Fig. 2(a)+(b), where an antenna with the substrate removed around the antenna allows the main part of the electrons to leave the simulation volume. This can also be seen by comparing the two left most panels in Fig. 2(c). However, as shown in Fig. 2(f), the accumulated emission is higher for an antenna standing on the full substrate than one with the substrate removed, and having a gap between two I-antennas makes for an even 3x higher EFE.

When one investigates the EFE at its highest value, small periodic oscillations appear. These correspond to standing field waves in the transverse direction of the antennas and only become significant close to the peak field. This is shown in Fig. 2(e) for the dipole on a substrate and the 2-dipole system. Whereas the former has the resonance frequency expected from an isolated dipole, the latter has a prolonged period, thus corroborating that there is a coupling between the nearfields from the two closely spaced tips.

Finally, one of the proposed, central merits for the THz-driven electron gun is the combination of high brightness and significant acceleration over a short distance. Fig. 2(a) shows that over the extent of the near field (15 µm from antenna tips), electrons reach energies of a few keV without a significant spread in space while maintaining duration of just few hundred fs.

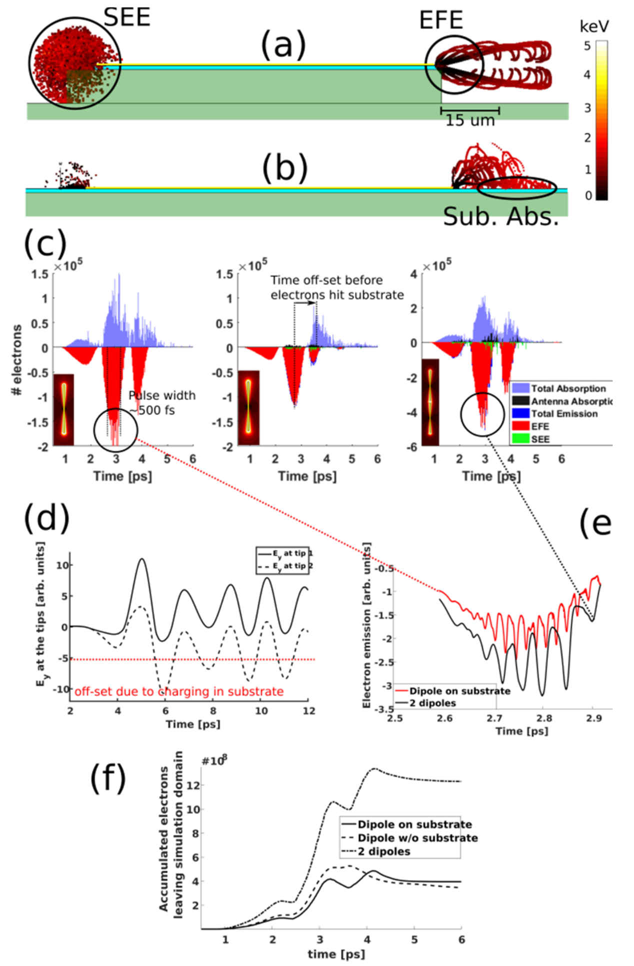

Fig. 2: (a)+(b) Snapshot of space-time mapping of characteristic trajectories for emitted electrons. Secondary emitted electrons (SEE) are emitted in an isotropic cloud, whereas substrate absorption takes place when electrons hit the non-metallic substrate. **(d)** shows that the substrate subsequently charges and gives an offset in the field, but only at one end of the dipole. The panels in **(c)** show the contributions to the total amount of electrons leaving the simulation volume for a dipole on substrate (left), dipole without substrate (middle) and 2 dipoles (right). The small oscillations that are magnified in **(e)** are transverse oscillations arising at high fields. **(f)** shows the accumulated amount of electrons leaving the simulation volume. Due to a much larger field enhancement, the 2 dipole setup dominates. Interestingly, the two other setups yield the same result even though for the dipole without substrate, much less electrons are absorbed. However, the lack of substrate also leads to a lower nearfield and hence lower EFE.

REFERENCES

[1] S. L. Lange, K. Iwaszczuk, M. Hoffmann and P. U. Jepsen, 10.1109/IRMMW-THz.2016.7758702

[2] K. Iwaszczuk, M. Zalkovskij, A. C. Strikwerda and P. U. Jepsen, *Optica*, vol. 2, pp. 116-123, 2015.

[3] G. Herink, D. R. Solli, M. Gulde, Nature, vol. 483, pp. 190-193, 2012