# Generation of Terahertz Radiation by Large-Aperture Photoconductive Antennas

V. N. Truchin, A. V. Andrianov, and N. N. Zinov'ev

***Abstract*—Employing self-consistent analytical approach to the set of non-equilibrium Boltzmann equation and Maxwell equations we have studied the radiation phenomena in non-equilibrium *e-h* plasma excited in the photo-conductive gap of terahertz radiating antenna by an ultra-short laser pulse. The solutions of the radiation problem have established the fundamental role of retardation and non-stationary character of electromagnetic interaction of photo-currents of moving *e-h* plasma in the formation of radiation field. The revealed properties of generated terahertz pulse are crucially depend on the physics of dissipation mechanisms, the ratio of terahertz radiation formation length and sample size, current configurations and relative traveling velocities of *e-h* plasma bunch and terahertz radiation pulse. We have distinguished two major regimes of terahertz emission, single pulse emission and firing twinned pulses at the moments of creation and extinction of moving bunch of *e-h* plasma related to the front and rare boundaries of semiconducting slab respectively.**

***Index Terms*—terahertz, radiation of moving charges, photo-conductive antennas**

## I. INTRODUCTION

RADIATION processes in photo-conductive terahertz (THz) coherent emitters are usually analyzed with the use of several simplified approaches [1]–[9]. The models used in the treatments of experiments on photo-conductive antennas cited above do not take into account the effects of non-equilibrium *e-h* plasma and photo-currents, spatial distribution of EMR generated by photo-currents in the plasma.

In this paper we consider the theory of THz EM pulse generation by a moving bunch of non-equilibrium *e-h* plasma considering self-consistently photo-currents, calculated from the first principles employing non-equilibrium Boltzmann equation, and the generation of external EM field at the non-stationary regimes of *e-h* plasma generation, including the effects of electromagnetic retardation, light-induced transfer effects due to coupling of traveling excitation pulse and generated *e-h* plasma that could develop themselves in markedly different ways at the conditions of $\alpha d < 1$ and $\alpha d > 1$, where $\alpha$ is the absorption coefficient of the pump pulse.

## II. DISCUSSION

We consider a single semiconducting slab of a finite thickness $d$ with *dc*-bias field $\mathbf{E}_0$ applied to the side ohmic contacts.

V. N. Truchin is with Ioffe Physical Technical Institute of Russian Academy of Sciences, 194021 St. Petersburg, Russia

A. V. Andrianov is with Ioffe Physical Technical Institute of Russian Academy of Sciences, 194021 St. Petersburg, Russia

N. N. Zinov'ev is with Ioffe Physical Technical Institute of Russian Academy of Sciences, 194021 St. Petersburg, Russia

N. N. Zinov'ev is also with Department of Physics, Durham University, Durham DH1 3LE, UK

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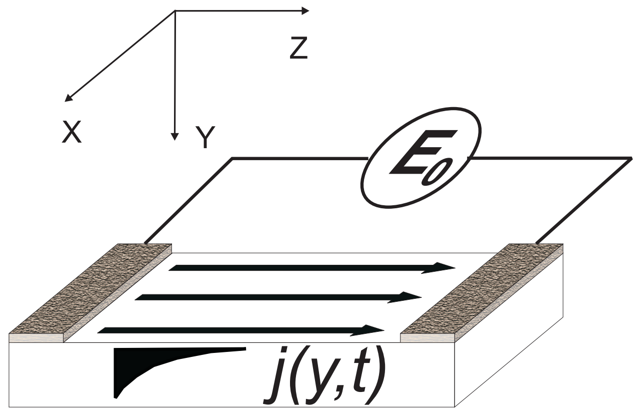


Fig. 1. The sketch of biased semiconductor slab. The black segment shows $y$-distribution of current $j(y,t)$ inside the slab.

Non-equilibrium *e-h* plasma is generated in the slab under the uniform in-plane excitation of the gap between the bias electrodes. Fig.1 shows the side view of semiconducting slab, the coordinate frame, the directions of applied bias electric field and a schematic side section view of the excitation in-depth distribution. Without loss of generality we choose the direction of EMR electric component along *z*-axis and magnetic component along *x*-axis. We also assume that the transient current and electric field induced in *e-h* plasma do not depend on *x*- and *z*-coordinates. It follows from the assumption of the uniform excitation of semiconductor between the bias electrodes. The photo-current density $\mathbf{j}(y,t)$ in non-equilibrium *e-h* plasma created in semiconducting slab biased with an external dc-electric field $\mathbf{E}_0$ is given by

$$\mathbf{j}(y,t) = \frac{\hbar e}{4\pi^3} \int \mathbf{k} \left[ \frac{f_{ae}(\mathbf{k},\mathbf{r},t)}{m_e} - \frac{f_{ah}(\mathbf{k},\mathbf{r},t)}{m_h} \right] \mathrm{d}^3\mathbf{k} \ , \quad (1)$$

where $f_{ae}$ and $f_{ah}$ are the asymmetric terms of the total distribution functions for electrons, $f_e$, and holes, $f_h$, respectively, $\mathbf{k}$ is the electron wave vector, $m_e$ and $m_h$ are the effective masses of free carriers, electrons and holes respectively. The total distribution function for electrons $f(\mathbf{k},\mathbf{r},t)$ is found from the solution of the non-equilibrium Boltzmann equation:

$$\frac{\partial f}{\partial t} + \mathbf{v}(\mathbf{k}) \cdot \nabla_{\mathbf{r}} f + \frac{e\widetilde{\mathbf{E}}}{\hbar} \cdot \nabla_{\mathbf{k}} f = \left( \frac{\partial f}{\partial t} \right)_{\text{col}} \ , \quad (2)$$

where $\widetilde{\mathbf{E}} = \mathbf{E}_0 + \mathbf{E}$ is the total EM field including the bias field, $\mathbf{E}_0$ and the generated EMR field, $\mathbf{E}$. The r.h.s. of (2) represents the collision integral whose expansion finally leads to the integration of (2) and the expression of photo-current

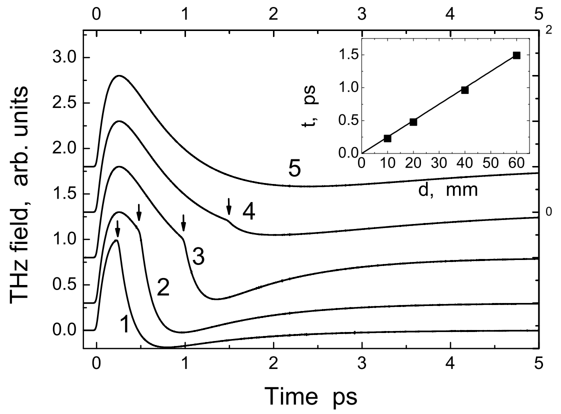


Fig. 2. Calculated waveforms of THz field emitted in backward direction from biased semiconductor slab. The waveforms correspond to different thicknesses shown in the inset. *The inset:* solid squares shows the time positions of the second pulse front edge, solid line - time dependence $t = \frac{d}{\widetilde{v}_g} + \frac{d}{c}$.

of (1) in the form:

$$j_z(\omega, y) = \frac{e^2}{m_e} E_{0z} \frac{G(\omega)}{(\gamma - \imath\omega)(\Gamma + \gamma - \imath\omega)} \exp\left(\imath \frac{\omega}{\widetilde{v}_g} y\right), \quad (3)$$

where $\Gamma^{-1}$ is collision life time, $\gamma^{-1}$ is the life time of non-equilibrium carriers, $G(\omega)$ is the spectrum of excitation pulse, $\frac{1}{\widetilde{v}_g} = \frac{1}{v_{g0}} + \imath\frac{\alpha}{\omega}$ is the complex group velocity. This expression for $j_z(\omega, y)$ has a form of a uniformly traveling with the complex velocity $\widetilde{v}_g$ wave of non-equilibrium *e-h* plasma bunch in *y*-direction, carrying dissipative transverse current in the direction of applied bias, in *z*-direction. The amplitude spectrum of (3) is defined by the spectrum of excitation pulse, $G(\omega)$, and two dissipative factors related to the mean times $\gamma^{-1}$ and $\Gamma^{-1}$. We emphasize the difference in functional dependence of (3) on the resistive current scattering time $\Gamma^{-1}$, life time of carriers $\gamma^{-1}$ and the spatial decay of excitation light beam due to absorption coefficient $\alpha$. Considering the excitation geometry shown in Fig.1, the set of Maxwell equations with the source current (3) is integrated using the boundary conditions requiring the continuity of tangential components of **E** and **H** fields across the sample boundaries.

To develop the full time-of-flight content of THz pulse we choose here the value of $\alpha$ corresponding to the case $\alpha d \lesssim 1$. Fig.2 plots the calculated THz waveform of **E**-field emitted backward into free space from a semiconducting slab of different thicknesses, $\gamma^{-1} = 1 \cdot 10^{-12}$ s, $\Gamma^{-1} = 1.7 \cdot 10^{-13}$ s and $\alpha = 200$ cm$^{-1}$. Fig.2 clearly demonstrates twinned pulse structures of the waveforms. The amplitude and time position of the first pulse remains independent on $d$. This shows that the generation of the first THz pulse occurs at the front surface of semiconducting slab. The front edge of the second pulse, having the sign opposite to the first pulse, shifts linearly with the change of slab's thickness with the amplitude decreasing with thickness. This evidence proves that the second pulse is generated with the delay required for *e-h* plasma to reach the rare boundary and extinct there due to pump pulse exit from the rare surface of semiconducting slab. Fig.2 exhibits convincing demonstration of a close analogy of the generation of twin pulse THz EMR in this case with the phenomena of nonlinear optic waves interactions reported in [10] and elaborated in details in [11].

## III. Conclusion

To summarize, the reported theoretical results unequivocally establish the mechanism of THz emission by moving bunch of non-equilibrium *e-h* plasma carrying transverse current. It predicts new effect of twin THz EM pulse generation in the limit of $\alpha d \lesssim 1$. It has shown that the effect of bias voltage on *e-h* plasma is in induction of transverse current or polarization. The events of creation and extinction of such uniformly moving photo-induced current or polarization source in a dispersive medium with $c \neq \widetilde{v}_g$ cause the radiation of twin THz EM pulses. It convincingly demonstrates a close analogy with the phenomena of nonlinear optic waves interactions [10], [11] forming a part of the large class of radiation phenomena considered within the framework of Tamm problem and caused by the start-stop of uniform motion of a charged or polarized source in a homogeneous medium. If the limiting conditions $\alpha d \gg 1$ are met, then the formation length for THz generation is restricted to the scale of $\pi\alpha^{-1}$ regardless the difference between $v_g$ and $c$ showing similarity of this case to the radiation by a stationary, immobile, source. For both cases the presented theory has revealed the particular roles of the key material parameters: the dissipation times, $\gamma^{-1}$ and $\Gamma^{-1}$, the carrier collision and decay times; the details responsible for formation of spectral content of THz pulse, the role of phase matching and the influence of directional factors and excitation pulse duration on the spectrum of THz pulse.

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