The Norton equivalent circuit model of PCA to predict the parasitic effects of the substrate on THz emission saturation

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Abstract— **Photo-conductive antennas (PCAs) are the workhorse of time-domain THz sensing and imaging. In this work, we employ a rigorous Norton equivalent circuit model to identify and estimate the substrate-related parasitic effects, that might limit the THz emission, to better design future PCAs.**

Keywords—Photoconductive antennas, Norton equivalent circuit, GaAs)

I. Introduction

THz spectroscopy and imaging applications [1] are becoming more and more a tangible reality thanks to the emergence and affirmation of pulsed photo-conductive antennas (PCAs) as wide-band THz emitters and receivers (see Fig. 1). The main contribution to the growing maturity of this technology came from the engineering of the photo-conductive materials [2] and the development of theoretical models. The most successful modelling approaches are based on equivalent circuit representations [3][4][5]. In particular, the most accurate model has been reported recently in [4] and well validated experimentally in [5]. This single current generator Norton equivalent circuit is a powerful mean to quantify possible limiting effects in the THz radiation generation, that are caused by specific processes occurring in the photo-conductor. For example, the PCA transmitter circuit proposed in [4] (Fig. 2a) accounts for the voltage drop at the photo-conductive gap, in this case made of low-temperature-grown GaAs (LT-GaAs), during the laser illumination, which explains the observed saturation of the emitted THz power versus the laser power. In this work we employ the same lumped element representation of a PCA transmitter, made of a LT-GaAs layer on semi-insulating GaAs (SI-GaAs) substrate. Our aim is to model the effect of a possible parasitic photo-current in the substrate on the matching of the Norton generator impedance with a given antenna impedance.

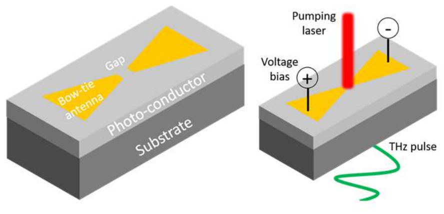

Fig. 1: (a) PCA bow-tie transmitter, (b) PCA transmitter under laser illumination of the photo-conductive gap and voltage bias applied at the antenna contacts.

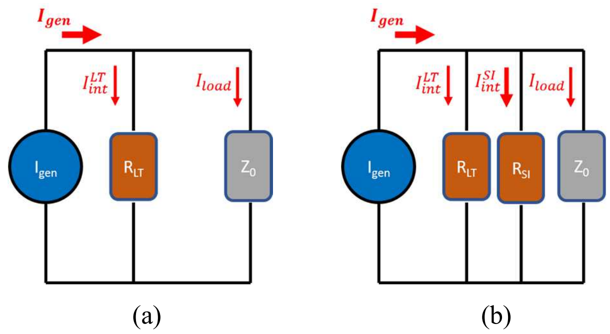

Fig. 2: Norton equivalent circuit of (a) an LT-GaAs PCA transmitter and (b) the same LT-GaAs PCA with the contribution from the SI-GaAs substrate.

II. Norton equivalent circuits and resistance

A. *Only LT-GaAs PCA*

The simplest Norton circuit representation of a LT-GaAs layer on SI-GaAs PCA transmitter is depicted in Fig. 1a. In this case, it is assumed that all (except for the surface reflection losses) the pumping laser light is absorbed within the LT-GaAs and the SI-GaAs has no role (negligible DC dark current). As explained in [4], I_{gen} is the impressed current under the short-circuited gap condition. I_{int}^{LT} is the current flowing in the generator branch. Both currents depend only on the LT-GaAs constitutive relations. In general, the internal generator impedance is a complex, time-varying quantity. However, here we approximated it with a simple real resistance R_{LT}, to better emphasize the impedance matching mechanism. The current associated with the emitted THz radiation is I_{load} and it flows through the antenna impedance Z_0, here also approximated as real and constant (70 Ω for our bow-tie design). According to the approximations made in [6] R_{LT} is given by the following expression:

$$R_{LT} = \frac{2h\nu \cdot W_x^2}{e \cdot \mu_{LT} \cdot \beta_{LT} \cdot P \cdot T} \cdot \frac{\tau_R^{LT} + \tau_S^{LT}}{\tau_R^{LT} - \tau_S^{LT}} \quad (1)$$

Where: hν is the photon energy (1,55 eV for our 800 nm laser), W_x is the size (10 μm) of the square gap uniformly illuminated, e is the electron charge, μ is the DC mobility (210 cm^2/Vs for our LT-GaAs), P is the impinging laser power, T is the laser pulses repetition interval (12,5 ns for our pulsed laser), τ_R and τ_S are respectively the material recombination (300 fs) and Drude scattering time (8 fs). Fig. 3 plots R_{LT} versus the laser power P for β = 0,67 (0,33 losses by surface

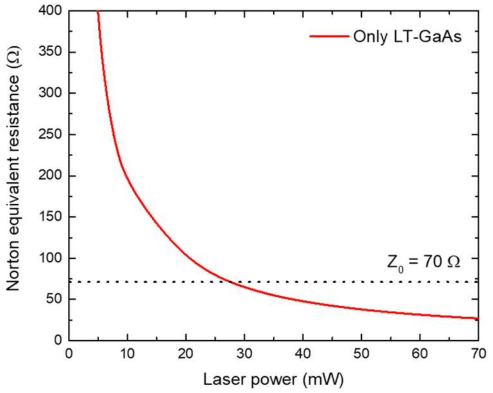

Fig. 3: Norton equivalent resistance R_{LT} vs laser power P, associated to the LT-GaAs photoconductive layer and assuming that all the pumping laser light is absorbed by the layer.

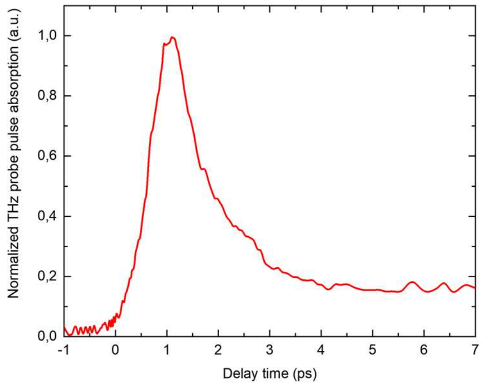

Fig. 4: Normalized transient THz pulse probe absorption. The long recombination time tail is the contribution from the carriers generated deep into the SI-substrate, while the fast decaying peak is related to the LT-GaAs layer.

reflection). In the case of Z_0 = 70 Ω, the antenna impedance matching occurs at P = 27 mW. For higher pumping values, most of the I_{gen} is dissipated as I_{int} and the THz emission saturates.

B. *Contribution from the SI-GaAs substrate*

In this case we consider a 2 μm LT-GaAs layer on a 625 μm SI-GaAs substrate. Since the LT-GaAs absorption coefficient is 1,4 μm^{-1} not all the laser light is absorbed in the LT-GaAs and a small fraction (precisely 0,04) is transmitted to the substrate, generating a parasitic photo-current. This generation of carriers in the substrate is revealed by the transient THz probe absorption curve (Fig. 4), acquired using the set-up and methodology as in [7]. The Norton equivalent circuit is now the one shown in Fig. 2b, with SI-GaAs associated resistance R_{SI} in parallel with R_{LT}. Fig. 5 plots R_{tot} , R_{LT} and R_{SI} versus the laser power. Now for Z_0 = 70 Ω, the matching is shifted to P = 13 mW and the PCA THz emission saturation starts at lower illumination powers.

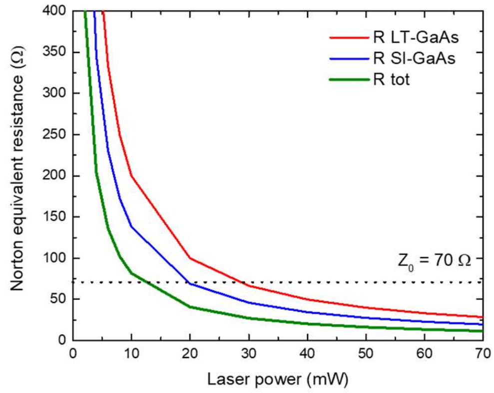

Fig. 5: Total Norton equivalent resistance $R_{tot} = R_{LT} \parallel R_{SI}$ vs impinging laser power, associated to the R_{LT} in parallel with R_{SI}.

III. Conclusions

We have applied the rigorous Norton equivalent circuit [4][5] to a LT-GaAs on SI-GaAs PCA transmitter to analyse the effects of parasitic photo-current in the substrate. We report that already the simplest calculations, based on a Norton equivalent resistance approximation [6] for the two materials, shows that the SI-GaAs photo-current levels down the internal gap total resistance, causing earlier THz emission saturation. A complete time-domain analysis of the circuit in Fig. 2b and a materials characterization will be presented later to seek for the finer details of this substrate effects, especially on the emission spectrum.

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