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Modeling the Transmitted Power and Receiver Current of Pulsed Photoconductive Antennas Based on InGaAs:Fe

Martijn D. Huiskes[1], Juan Bueno[1], Alexander Dohms[2], Robert B. Kohlhaas[2], Paolo M. Sberna[1], Nuria Llombart[1], and Andrea Neto[1]
[1]THz Sensing Group, Department of Microelectronics, Delft University of Technology, Delft, The Netherlands
[2]Fraunhofer Institute for Telecommunications, Heinrich Hertz Institute, Einsteinufer 37, 10587 Berlin, Germany

***Abstract*— Transition metal-doped InGaAs material has proven to be extremely efficient when used as photoconductor in photoconductive antennas excited with a 1550 nm wavelength laser. In this contribution, we apply a time-domain modeling procedure to predict the radiated power by InGaAs:Fe strip-line antennas. The simulations are verified with measurements, showing an excellent match between them. Additionally, we model the reconstructed current when such a strip-line antenna is coupled with a receiver through a Quasi-Optical (QO) link.**

I. Introduction

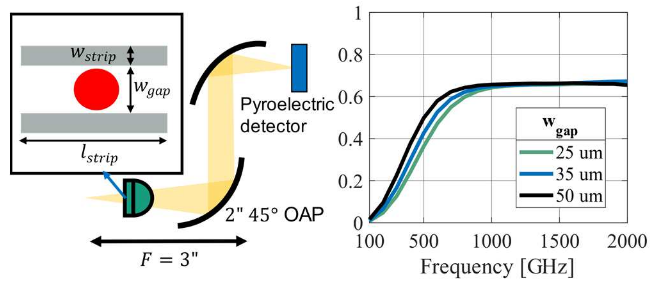
Pulsed photoconductive antennas (PCAs) are widely used for spectroscopy in time-domain spectroscopy (TDS) systems, due to the broad-band nature of the excited photocurrent in materials with a short electron trapping time [1]. Over the past decade, the radiated power by PCAs has increased significantly through advances in photoconductive material engineering, the development of commercial high average power laser sources, and more efficient antenna designs. This increase in THz power opens up possibilities to use PCAs in imaging and sensing applications, where the large bandwidth can be exploited to get both spectral information of the imaged object, as well as a sub-millimeter depth resolution.

Accurate modeling of PCAs is essential to guide the design process, and aid in the system design trade-offs of future sensing systems based on PCAs. The modeling of PCAs in the literature has mainly been done either through full-wave finite-difference time-domain models [2], or through equivalent circuit models [3]. In recent years, a link modeling procedure has been developed that has demonstrated accurate prediction of THz currents within transmitter (Tx) and receiver (Rx) PCA gaps [3]. The procedure employs a time-domain (TD) Norton equivalent circuit for both Tx and Rx PCAs and utilizes a combination of full-wave and physical optics (PO) simulations to assess antenna coupling through a field-matching formalism [3]. This procedure was previously applied to and experimentally verified with antennas based on LT-GaAs material excited with a 780 nm optical source.

In this contribution, we model several fiber-coupled InGaAs:Fe-based PCAs excited by a 1550 nm source, that were designed, fabricated and characterized in reference [4]. More specifically, we model the radiated power by lens-coupled strip-line antennas, and the received TD current when such a strip-line antenna is coupled to a Rx bow-tie antenna through a QO channel.

II. Modeling of the transmitted THz power

In [4], power measurements as a function of the applied optical power are reported for three different lens-coupled strip-line antennas, each with a different gap width $w_{gap} = 25/35/50$ µm. As shown in Fig. 1(a), the radiated THz power

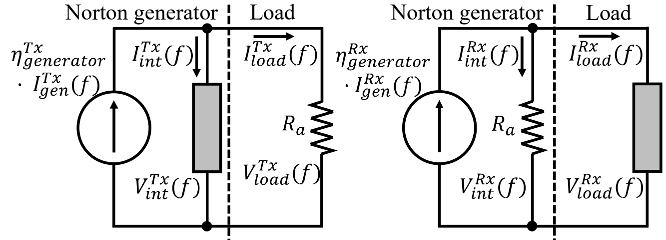


(a) **(b)**

Fig. 1. (a) Schematic overview of the power-measurement setup used in [4], (b) radiation efficiency $\eta_{rad}^{tot}(f)$ of the setup.

is guided to a pyroelectric power detector [5] using two 2” off-axis parabolas (OAP) with a 3” focal length. One has to consider in the modelling that not all the power radiated by the strip-line antennas will reach the detector. We first consider the efficiencies of the antenna itself. The strip-line antenna radiates part of its power into the air medium below the lens, which does not arrive at the pyroelectric detector. Additionally, the power that is reflected inside the silicon lens is assumed to be lost, as the reflections come out of the lens inefficiently, resulting in a large part of this contribution not arriving at the detector. Lastly, part of the radiated power is lost through spill-over on the OAPs. These contributions are quantified using an efficiency term $\eta_{rad}^{tot}(f)$. To evaluate this efficiency, we first evaluate the field radiated by the antenna inside the lens using CST, and subsequently propagate the field to the plane of the pyroelectric detector using an in-house PO code [6] combined with TICRA GRASP [3]. The radiation efficiency is then found by taking the ratio of the power on the detector plane to the power generated in the PC gap, and is shown in Fig. 1(b).

Note that the radiation efficiency at the low end of the frequency spectrum is close to 0 because the strip-line acts as a transmission line at these frequencies [7]. The equivalent circuit for a PCA in transmission is shown in Fig. 2(a), and the procedure to numerically solve for the currents and voltages in the circuit can be found in [3]. The generator current is determined using the material parameters from [4] and an



(a) **(b)**

Fig. 2. Norton equivalent circuit for a (a) transmitting and (b) receiving PCA. The numerical evaluation of the currents and voltages is discussed in [3].

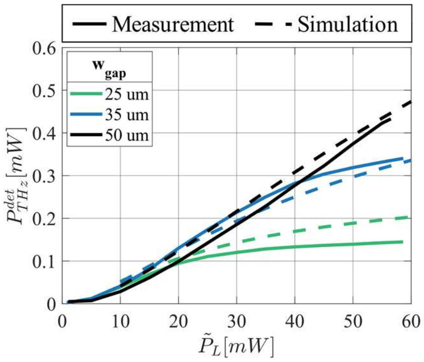


Fig. 3. Comparison between the measured [4] and simulated THz power arriving at the detector for different strip-lines with $w_{gap} = 25/35/50$ µm.

antenna resistance of $R_a = 80\,\Omega$, obtained from CST simulations. The procedure assumes a generator efficiency of $\eta_{generator}^{Tx} = 0.6$ when evaluating the PC current using the Norton equivalent circuit, which is the only fitting parameter that was used. The power at the detector plane can be found as:

$$P_{THz}^{det} = f_{rep} \int_{0.1THz}^{2THz} |I_{load}^{Tx}(f)|^2 R_a \eta_{rad}^{tot}(f) df\,. \quad (1)$$

The radiation efficiency and the PC current spectrum $I_{load}^{Tx}(f)$, are evaluated in a band from 100 GHz – 2 THz. This frequency range is selected because the modeling of the current density using the equivalent circuit model is no longer valid outside this frequency range. The simulated and detected power are shown in Fig. 3. The modelling procedure gives an excellent match with the measurements. As the saturation of the antennas is well predicted, the model can be used to design PCAs such that for a certain optical power, the antenna operates right before its saturation point, resulting in maximum radiated THz power.

III. Modeling of a Link Between a Strip-Line Transmitter and Bow-Tie Receiver

Apart from power measurements, [4] reports a measurement of a link between an InGaAs:Fe-based strip-line PCA emitter with a 50 µm gap-width and an InGaAs:Rh bow-tie receiver with a 20 µm gap. The antennas are coupled through two OAPs, as shown schematically in Fig. 4.

Through the procedure described in [3], we evaluate the stroboscopically sampled detector current. The Norton equivalent circuit for the receiver was evaluated using a generator efficiency of $\eta_{generator}^{Rx} = 0.8$, and using the material parameters given in [4]. The simulated spectrum of the detector

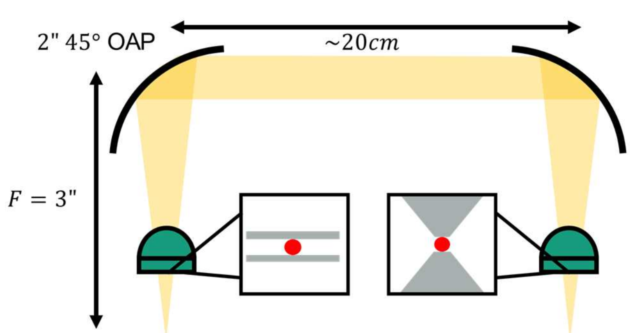


Fig. 4. Schematic overview of the link between the InGaAs:Fe strip-line emitter and the InGaAs:Rh bow-tie receiver measured in [4].

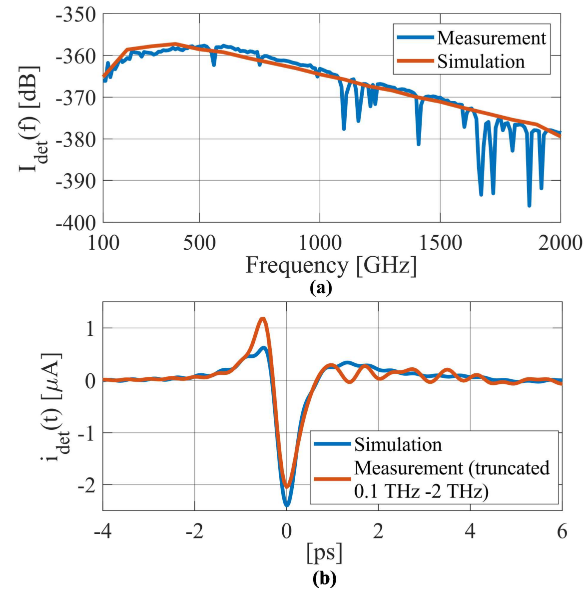


Fig. 5. Comparison between simulation and measurement of the (a) spectrum of the detected current, $I_{det}(f)$, and (b) the frequency-truncated time-domain data $i_{det}(t)$.

current is shown together with the measured spectrum in Fig. 5 (a). Again, the simulated spectrum closely matches the measured one.

As the simulations are only valid from 100 GHz – 2 THz, we truncate the measured TD pulse shown in Fig. 5(b) such that the match can be compared in a fair way.

IV. Summary

In this contribution, we demonstrate that the modeling procedure in [3] allows for accurate prediction of the radiated THz power from the InGaAs:Fe-based PCA transmitters from [4], as well as the detected current at the receiver when coupled with a transmitting antenna through a QO channel. The model predicts successfully the radiated THz power and detector current, and can be used for the design of a link-budget in imaging and sensing applications.

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