Characterization of the THz Quasi-Optical Channel for the Measurement of the Power Radiated by Photoconductive Antennas

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Abstract—In this paper a rigorous electromagnetic characterization of the setup for measuring the THz power radiated by pulsed photoconductive antenna is discussed. Such characterization is expressed in terms of efficiencies which quantify how much power is lost in the coupling between the various components involved in the measurement setup. The conducted analysis highlights how such efficiencies affect the energy spectrum of the measured pulsed signal. Measurement results with two different detectors will be shown during the conference and will be compared against the power estimation obtained by a recently developed equivalent circuit model for photoconductive antennas. The proposed electromagnetic modeling allows us to effectively improve the design of THz time domain systems.

I. Introduction

MANY researchers have characterized the performances of Photo-Conductive Antennas (PCAs) [1]–[4] using measurements in the past. However, in most cases the analysis of the results was presented without having a characterization of the Quasi-Optical (QO) channel (which typically includes the lens antenna (PCA + lens), a chain of reflectors, and the detector). Such channels are typically extremely inefficient, causing the power detected to be smaller, in the order of tenths, than the one generated by the PCA. The lack of such quasi optical characterization for the channel typically renders impossible the calculation of how much power was actually generated by the source, giving rise to the wide spread use of arbitrary units. In this work two different measurement setups are discussed, prototypes of standard PCAs are presented, and the absolute powers generated by the PCAs, and their pertinent spectra have been measured. In order to deconvolve the impact of the quasi optical path, a dedicated accurate electromagnetic model for the channel has been developed, so that a complete power budget from the source to the detector has been characterized and completely validated by measurements.

The most commonly used geometries for PCAs have been chosen for the analysis: Auston-switch, bow-tie, and logarithmic spiral antennas. One prototype of each geometry has been manufactured, maintaining for all these sources the same geometrical gap dimensions, the semiconductor material, and the same optical and bias excitations. The power measurement setups were composed of an optical system that guides and collimates the laser beam, a QO channel, and a power detector. Two different power detectors have been used (and the specific features of both have been retained in the analysis): a cryo-cooled bolometer with a high sensitivity and fast response [5], and a calorimetric power meter with a lower sensitivity and a slower response [6]. The bolometer has been calibrated and the power meter has been characterized with the same commercially available source [7]. Excellent agreement between the detectors gives high confidence on the accuracy of the power measurements. Moreover, spectral measurements have been carried out by using a different setup where an Electro-Optic (EO) crystal paired with balanced photodiodes was employed to measure the time-domain signal and spectrum.

The estimation of the power budget of each antenna has been made by computing the energy spectrum generated using the circuit model developed in [8], and then propagating coherently the associated waves to the detectors. The comparative analysis of the performances of the different PCAs provides clear evidence of the major impact of the antenna properties of the sources. The relevant detected energy spectra of the devices is significantly affected by the direction, within the lens, in which the relevant THz power generated is launched.

II. PCA Prototype and Measurement Setup Description

Three different photoconductive antenna geometries have been manufactured, in order to measure their radiated power and compare it with the results derived by the equivalent circuit model discussed in [8]. The chosen antenna geometries are an Auston switch, a bow-tie, and a logarithmic spiral antenna. The three different devices were fabricated on the same semiconductor (LTG-GaAs) wafer. For the sake of compactness, in this work we report some results relevant only to the bow-tie antenna. Other results along with the ones relevant to the Auston-switch and the logarithmic spiral antennas will be discussed during the conference. The manufactured bow-tie antenna presents gap dimensions 10μm × 10μm, tapering angle 90°, and a total length of 2mm. The antenna chip was mounted on a Printed Circuit Board (PCB), gluing the bias pads on the two bias lines printed on the PCB by means a conductive silver glue. On the opposite side of the patterned antenna metalization, a silicon hyperhemispherical lens is placed.

The power measurements have been carried out using the two different measurements setups. Both setups were composed of the same optical and QO systems: the first one was used to drive and focus the laser excitation on the antennas' gap; whereas, the second one was used to focus the THz radiation emitted by the PCA onto the detector. The only differences between the setups were the two different power detectors used. The QO system was composed of two 90° off-axis parabolic reflectors. The first detector, used to perform the alignment procedure, was a cryo-cooled bolometer [5]. The calibration of the bolometer was performed by using an auto-calibrating absolute Power Meter [9] and a commercial photomixer [7], in order to derive the calibration factor to be used for converting the voltage readout of the lock-in amplifier in the measured power. The bolometer was used to perform the alignment of the antenna gap with the laser beam, as well as to measure the radiated power of the PCA prototypes. The second detector, used for the measurement, was a room temperature thermocouple based power meter [6], where the sensor is coupled with the QO system via a conical horn antenna WR-10.

III. Characterization of the Measurement Setup and Results

For sake of compactness, only the analysis of the power meter setup is shown in this section. The same analysis can be conducted for the bolometer setup. The antenna chip geometry have been simulated by an EM full-wave software, assuming the chip structure to radiate between free space and a semi-infinite dense dielectric medium, which simulates the presence of the dielectric silicon lens. The simulated radiation patterns of the antennas in the semi-infinite silicon medium have been used to compute the fields radiated by the dielectric lens of the prototypes via a Physical Optic (PO) approach.

By using the simulated radiation patterns from the lens, the power radiated by the lens has been computed as the integral of the radiated power density distribution outside the lens. The radiation efficiency of lens antenna η_l have been evaluated as the ratio between the power radiated by the lens and the power generated at the input port of the antenna at each frequency.

In order to analyze the behaviour of the QO system when it was fed by the PCA prototype, the electromagnetic behavior of the reflectors system has been simulated by means of a PO approach. The field used to illuminate the first reflector was the one estimated by the PO lens simulations. The power captured by the last reflector has been evaluated as the integral of the radiated power density distribution of the electromagnetic field impinging on the surface of the last reflector of the reflectors system. The reflectors system efficiency η_{rs} is defined as the ratio between the power captured by the last reflector and the power radiated by the lens at each frequency.

Finally, the coupling between the beam emerging from the last reflector and the detector has been simulated by a Method of Moment (MoM). The input electromagnetic field to the MoM was the one calculated by the simulation of the reflectors system. The power, impinging on the sensor at the end of the waveguide inside the detector, has been evaluated by integrating the power density distribution of the electromagnetic field travelling inside an infinite waveguide. The detector efficiency η_d for quantifying the coupling between the field focused by the reflectors system and the detector has been defined as the ratio between the power reaching the detector and the power captured by the last reflector at each frequency.

The product of the three discussed efficiencies determines the efficiency η_{qo} of the entire QO channel at each frequency.

The THz QO channel efficiencies are shown in Fig. 1. The measurement setup fed by the bow-tie presents a nearly flat total efficiency of about 20% over the entire operative band. In particular, it is evident that most of the power radiated by the antenna is lost in the QO channel between the source and the detector.

IV. Concluding Remarks

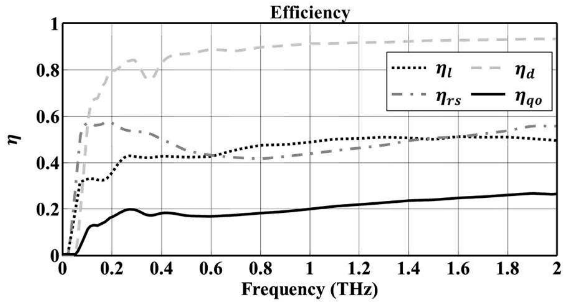

Fig. 1. Efficiency of the QO system: radiation efficiency of the lens antenna η_l (dotted line); reflectors system efficiency η_{rs} (dash-dotted line); detector efficiency η_d (dashed line); entire QO channel efficiency η_{qo} (solid line).

In this work, an electromagnetic model for the measurement setup of THz power radiated by PCAs on a large bandwidth is proposed. The system setup and the relevant coupling to the PCA radiated field is described in terms of its efficiency over the operative bandwidth. The results of the analysis have also been used to validate the equivalent circuit model introduced in [8].

The proposed electromagnetic model highlights that most of the power radiated by PCAs is lost in the QO channel that links source and detector. The quantification of such efficiencies open to the possibility of improving the performances of THz time domain systems, allowing to move their application from very short range to wider scenarios.

References

[1]. D. H. Auston and K. P. Cheung and P. R. Smith, "Picosecond photoconducting Hertzian dipoles," Appl. Phys. Lett., vol. 45, no. 3, pp. 284–286, Aug. 1984.

[2]. J. T. Darrow, X. C. Zhang, D. H. Auston, and J. D. Morse, "Saturation properties of large-aperture photoconducting antennas," IEEE J. Quantum Electron., vol. 28, no. 6, pp. 1607–1616, Jun. 1992.

[3]. M. Tani, S. Matsuura, K. Sakai, and S. Nakashima, "Emission characteristics of photoconductive antennas based on low-temperature-grown GaAs and semi-insulating GaAs," Appl. Optics, vol. 36, no. 30, pp. 7853–7859, Oct. 1997.

[4]. N. T. Yardimci, S. H. Yang, C. W. Berry, and M. Jarrahi, "High-power terahertz generation using large-area plasmonic photoconductive emitters," IEEE Trans. THz Sci. Technol., vol. 5, no. 2, pp. 223–229, Mar. 2015.

[5]. QMC Instruments Ltd., Cardiff, United Kingdom.

[6]. Virginia Diodes Inc., Charlottesville, Virginia, United States.

[7]. Toptica Photonics AG., Munich, Germany.

[8]. A. Garufo, G. Carluccio, N. Llombart, and A. Neto, "Derivation of an equivalent circuit for photo-conductive antenna," EuCAP 2016, European Conference on Antennas and Propagation, Davos, Switzerland, April 10th–15th, 2016.

[9]. Thomas Keating Instruments Ltd., Billingshurst, United Kingdom.