Dimensioning Photoconductive Connected Array Sources to Maximize the Radiated Power

Huiskes, Martijn; Bueno, Juan; Llombart, Nuria; Neto, Andrea

DOI
10.1109/IRMMW-THz57677.2023.10299142

Publication date
2023

Document Version
Final published version

Published in
Proceedings of the 2023 48th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)

2023 48th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz) | 979-8-3503-3660-3/23/$31.00 ©2023 IEEE | DOI: 10.1109/IRMMW-THz57677.2023.10299142

Dimensioning Photoconductive Connected Array Sources to Maximize the Radiated Power.

Martijn Huiskes[1], Juan Bueno[2], Nuria Llombart[1], and Andrea Neto[1]
[1]Tera-Hertz Sensing Group, Microelectronics Dept., Delft University of Technology, Delft, The Netherlands
[2]Electronic Circuits and Architectures Group, Microelectronics Dept., Delft University of Technology, Delft, The Netherlands

***Abstract*— Photoconductive antennas (PCAs) are used for imaging and sensing applications because of their ability to radiate short pulses with large bandwidths in the THz regime. The characterization of PCAs has previously been done using a time-domain Norton equivalent circuit. Thanks to a recent contribution, the size of the excited photoconductive area of PCAs that results in an impedance match with the antenna can be determined analytically using only the available optical power and the material parameters of the photoconductor. Through the impedance matching, the radiated THz power is maximized. These insights are used for the dimensioning of a wide-band photoconductive connected array to be used in the low THz band, excited by a high power laser (~1W).**

I. INTRODUCTION

A large bandwidth PCA system would allow for radar systems with a depth resolution in the order of a millimeter [1]. The radiated power by PCAs has however been limited in the past, mainly due to limited available laser power, the use of low-efficiency dispersive antennas and saturation effects [2]-[4]. Several arrays have been proposed in the past to distribute the active PC area over multiple elements. These arrays however usually rely on electrically short- or resonant elements, making it difficult to efficiently match the element impedances to the impedance associated to the feeding gaps over a broad band. Garufo et al. introduced the photoconductive connected array (PCCA) concept [4]. Connected arrays are intrinsically broadband, and the distribution of the active PC area keeps the size of the feeding gaps small in terms of the THz wavelength. PCCAs can therefore be used to efficiently radiate the generated PC power with minimal dispersivity.

Previously, an extensive characterization of PCAs has been done in transmission [5], resulting in a time-domain Norton equivalent circuit. In a recent contribution, some of the authors derived an analytical approximation for the internal resistance of a Norton equivalent circuit in Frequency Domain (FD). The FD circuit was previously verified with power measurements of a bow-tie antenna [6]. It is found that the saturation of the radiated power from PCA sources is related to the impedance match between the antenna and generator. In this work, the simplified FD circuit model is used to design the next generation PCCA sources driven by high power lasers (~1W). The size of the active PC area is determined such that a good impedance matching with the generator impedance is obtained. Furthermore, we predict the radiated THz power for a certain available laser power and applied bias field. Finally, we discuss several trade-offs concerning the connected array dimensions.

II. PCA IMPEDANCE MATCHING & RADIATED POWER

Generally when one wants to increase the radiated THz power of a PCA, both the laser intensity and/or the bias voltage can be increased. The bias voltage is limited by the dielectric breakdown of the material. The laser power is limited by the maximum available laser power and cost of commercial sources. These limitations make careful design of PCAs necessary to obtain a significant radiated power. To this end, we consider the equivalent FD Norton circuit model shown in Fig. 1(a). The circuit consists of a current generator $I_{impr}(f)$, an internal generator load $Z_{int}(f)$, and a load representing the antenna. The load representing the antenna is here assumed to be a frequency-independent radiation resistance R_a, which is an accurate approximation in the case of electrically long broadband antennas [5]. The FD current through the load and through the generator are denoted by $I(f)$ and $I_{int}(f)$ respectively. The evaluation of the currents in the circuit is discussed in [5],[6].

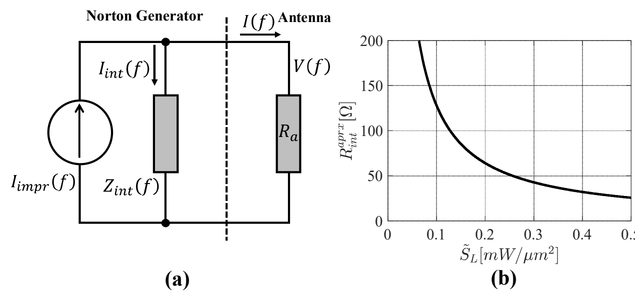

Fig. 1. (a) Norton equivalent circuit in transmission in FD. (b) Approximate generator impedance vs the laser intensity $\tilde{S}_L$, evaluated using Eq. 1.

When one considers the FD Norton circuit, the maximum power transfer occurs when $\Re\{Z_{int}(f)\} = R_a$. The generator impedance is dependent on the optical excitation, the applied bias field $\vec{E}_{bias}$ and the antenna impedance. A good impedance match between the generator and antenna impedance, when excited with the maximum available optical power, is important to maximize the achievable THz power. In a recent contribution [6], it was highlighted that the generator impedance mainly depends on the optical excitation, leading to an approximate equation for $Z_{int}(f)$:

$$Z_{int}(f) \approx R_{int}^{aprx} = \frac{1}{\tilde{S}_L}\frac{2}{\mu_{dc}\left[q_e\dfrac{T}{hf_c}\right]}\frac{(\tau_c+\tau_s)}{(\tau_c-\tau_s)}, \qquad (1)$$

where $\tilde{S}_L = \tilde{P}_L^{abs}/A_{PC}$, $\tilde{P}_L^{abs}$ is the power absorbed in the PC material, A_{PC} is the total active PC area, μ_{DC} is the electron mobility, q_e the electron charge, T and f_c the laser repetition rate and center frequency, h the Planck constant, and τ_c and τ_s the electron recombination and scattering time respectively.

The intensity $\tilde{S}_L$ can be chosen such that the approximated generator impedance R_{int}^{aprx} (Fig. 1(b)) matches the antenna resistance R_a. To see whether this matching condition results in the maximum radiated THz power for a certain available laser power, one can evaluate the radiated THz power for varying A_{PC} while keeping $\tilde{P}_L^{abs}$ constant. This way $\tilde{S}_L$ is effectively varied to change the generator impedance. An example of the normalized generated THz power as a function of the laser intensity for $R_a = 90\Omega$ is shown in Fig. 2(a). The PC material assumed is LT-GaAs with $\mu_{DC} = 210\ cm^2/Vs, \tau_c = 300fs, \tau_s = 8fs$, which is excited with a pulsed laser with a carrier frequency $f_c = 385THz$ and repetition rate $T = 12.5ns$. Fig. 2(a) shows that $R_{int}^{aprx} = R_a$ when the intensity is set to $\tilde{S}_L = 0.142mW/\mu m^2$ resulting roughly in the maximum radiated power and a good impedance match (Fig. 2(b)) until about $600GHz$, where one can in principle further tweak $\tilde{S}_L$ to shape the spectrum of the generated THz power.

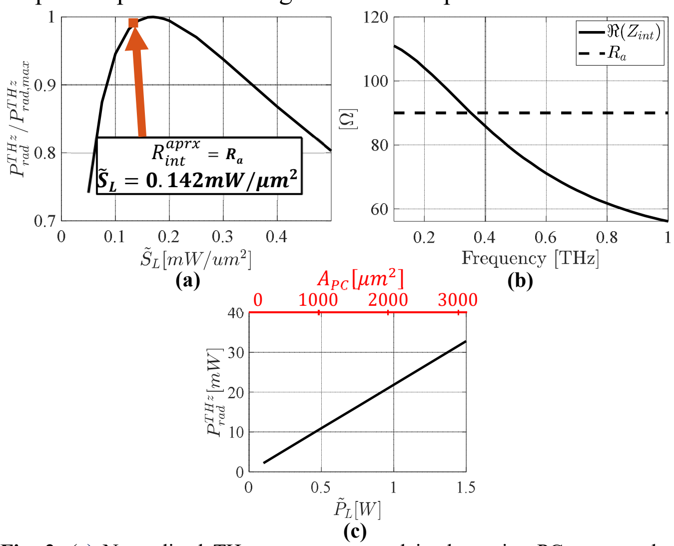

Fig. 2. (a) Normalized THz power generated in the active PC area vs the intensity of the laser. The laser power is fixed, and the intensity is varied by changing the active PC area. (b) Generator impedance and (c) generated THz power using LT-GaAs, $\tilde{S}_L = 0.142mW/\mu m^2$, an applied electric bias field of $|\vec{E}_{bias}| = 10.67V/\mu m$ and $R_a = 90\Omega$. Note that in all cases the power is evaluated from $0.1THz - 1THz$

The envisioned transmitter is excited by a laser with an average power $\tilde{P}_L$ of at least 0.5W. The absorption efficiency is $\eta_{abs} = 0.59$, taking into account both reflections on the interface between LT-GaAs and air as well as the absorption in the LT-GaAs ($2\mu m$ thick). Furthermore, a laser spillover efficiency of $\eta_{SO}^{laser} = 0.5$ is assumed. The total PC area needed for an absorbed laser power of $\tilde{P}_L^{abs} = \eta_{abs}\eta_{SO}^{laser}\tilde{P}_L$ can then be found as $A_{PC} = \tilde{P}_L^{abs}/\tilde{S}_L$. One can without further simulations find the generated THz power using the Norton model. Fig. 2(c). shows the generated THz power P_{rad}^{THz} as a function of the laser power. To achieve these high power levels, the design of a broadband antenna array is crucial, which is discussed in the next section.

III. PCCA Dimensions

A schematic representation of a connected dipole array is shown in Fig. 3. The connected array with $N \times N$ elements and array period d placed on a photoconductor is used as feed to a silicon lens. The laser beam is distributed and focused onto the

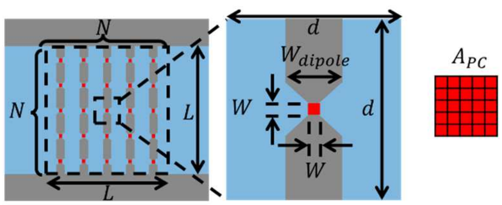

Fig. 3. PCCA geometry presented in [4]. The blue material represents the photoconductor (LT-GaAs), and the grey material represents metal. The red squares represent the PC feeding gaps, of which the areas sum up to A_{PC}.

dipole PC feeding gaps of area $W \times W$ by a lens array. In this work, only the connected array design is considered. The total active PC area (area of all the feeding gaps combined) needed for a certain available laser power is found from $\tilde{S}_L$ under the condition $R_{int}^{aprx} = R_a$. An estimate of the antenna resistance is thus needed to choose an appropriate $\tilde{S}_L$. For a well-designed connected array with air on the bottom and a silicon lens on top (neglecting the thin PC material), the active element impedance is around $r_a \approx 90\Omega$. "Well-designed" in this case means:

i. The gap size $W \ll \lambda_d^{THz}$

ii. The array period $d \leq \lambda_{eff}^{THZ}/2$ to avoid grating lobes and undesired mutual coupling effects.

iii. The size of the array should be $L \gtrsim \lambda_d^{THz}$

Here λ_d^{THz} is the wavelength of the THz radiation inside the silicon lens and $\lambda_{eff}^{THz} = \lambda_0^{THz}/\epsilon_{r,eff}$ is the effective wavelength between silicon and air with $\epsilon_{r,eff} = \sqrt{(\epsilon_r^{si} + \epsilon_r^{air})/2}$. For an operational bandwidth between $0.1THz - 1THz$, this means roughly that: $W \ll 90\mu m$, $d \lessapprox 60\mu$m and $L_x \gtrsim 1mm$.

The size of the gaps for a certain $\tilde{P}_L^{abs}$ is dependent on the number of elements used (Fig. 4(a)). The gap size should be chosen based on fabrication tolerances and the accuracy of the alignment to the lens array that focuses the laser power on the feeding gaps. In Fig. 4(b), the periodicity required to achieve a certain array size L is given as a function of N.

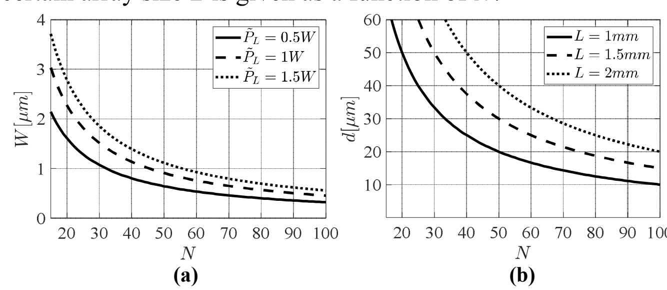

Fig. 4. (a) Size W of the feeding gaps of the connected array as a function of the number of elements N along a single direction (b) Array periodicity d as a function of N for different array sizes .

IV. Summary

A design procedure for PCCA antennas is presented in this paper. Using an array excited by 1W of average laser power would result in ~20mW of generated THz power. To achieve these unprecedented power levels, we would roughly need both the PC gap-width and the array period to be smaller by at least a factor two compared to the state of the art PCCAs [4].

V. References

[1]. A. F. Bernardis, *et al.*, "Signal to Noise Ratio Budget of a Pico-Seconds Pulsed Radar System for Stand-Off Imaging," *IRMMW-THz*, 2019.

[2]. N. Llombart and A. Neto, "THz Time-Domain Sensing: The Antenna Dispersion Problem and a Possible Solution," in *IEEE Trans. THz Sci. Technol.*, vol. 2, no. 4, pp. 416-423, July 2012.

[3]. J. T. Darrow, X. . -C. Zhang, D. H. Auston and J. D. Morse, "Saturation properties of large-aperture photoconducting antennas," in *IEEE Journal of Quantum Electronics*, vol. 28, no. 6, pp. 1607-1616, June 1992.

[4]. A. Garufo *et al.*, "A Connected Array of Coherent Photoconductive Pulsed Sources to Generate mW Average Power in the Submillimeter Wavelength Band," in *IEEE Trans. THz Sci. Technol*, vol. 9, no. 3, pp. 221-236, May 2019.

[5]. A. Neto, N. L. Juan and A. Freni, "Time-Domain Modelling of Pulsed Photoconducting Sources—Part I: The Norton Equivalent Circuit," in *IEEE Tran. Antennas Propag.*, vol. 71, no. 3, pp. 2527-2535, March 2023.

[6]. H. Zhang, *et al.,* "Analytical Expression for the Generator Resistance of Pulsed Photoconductive Antennas," *EuCAP*, 2023.