A Leaky Enhanced Photo-Conductive Connected Array for Broadband Generation of THz Power

Bueno , J.; Huiskes, M. ; Zhang, H.; Sberna, P.M.; Llombart, N.; Neto, A.

DOI
10.1109/IRMMW-THz50927.2022.9895896

Publication date
2022

Document Version
Final published version

Published in
Proceedings of the 2022 47th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz)

2022 47th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz) | 978-1-7281-9427-1/22/$31.00 ©2022 IEEE | DOI: 10.1109/IRMMW-THz50927.2022.9895896

A Leaky Enhanced Photo-Conductive Connected Array for Broadband Generation of THz Power

J. Bueno[1,*], M. Huiskes[2], H. Zhang[2], P. M. Sberna[2], N. Llombart[2], and A. Neto[2]
[1] Electronic Circuits and Architectures Group, Delft University of Technology, Delft, The Netherlands
[2] Tera-Hertz Sensing Group, Delft University of Technology, Delft, The Netherlands
j.buenolopez@tudelft.nl

***Abstract*—Photoconductive antennas are devices that provide power up to THz frequencies at a relatively low cost. However, the power radiated by each antenna is typically quite low and arrays have been proposed to increase it. In this paper we present the design of a leaky enhanced array architecture that surpasses the state of the art as it operates efficiently for frequencies up to 1THz, without excessive complications in the manufacturing. This architecture is compared with a 'standard' array, showing a broader bandwidth and a higher emitted detected signal.**

I. Introduction

PHOTOCONDUCTIVE antennas (PCAs) are a combination of semiconductor materials driven by optical laser sources and THz antennas, where the optically excited semiconductor functions as antenna feed over large bandwidths, reaching THz frequencies. The development of these PCAs has enabled a broad variety of applications for THz technology since they provide power at THz frequencies [1-7]. However, the power radiated by a single PCA source has historically been limited [8] mainly by two factors: i) The maximum biasing voltage applied to the semiconductor material, which leads to the disablement of the PCA if voltage breakdown of the material is exceeded; ii) The maximum laser power applied to the device since the radiated power saturates for high laser powers [9], which limits the available THz power of the PCA [10]. In order to overcome this problem, a photoconductive connected array source (PCCA), which was presented for the first time in [11], is proposed. The first characterization of this device gave the unprecedented ~1mW of power, with very clean simulated beam patterns and spectrum.

II. Membrane Based Array Design

The design in [11] operates extremely well for frequencies up to 650 GHz. The upper frequency limit to the performance would emerge evidently as a loss in the radiated spectrum. The limit to the higher operating frequency was due to the excitation of the array by means of commercially available micro lenses of diameter $D = 100\ \mu m$. For inter-element period of $d_x = d_y = D = 100\ \mu m$ an array designer, unexperienced with connected arrays, would have expected the maximum frequency of operation associated to the grating lobe free radiation in the dense dielectric ($\sqrt{\epsilon} \approx 3.45$) to be 870GHz, corresponding to $D = \lambda^d_{870GHz}$. However, the maximum useful frequency was 650GHz, with the inter-element period $D = 0.47\ \lambda^d_{650GHz}$ due to a poor impedance match. It was shown in [12] that the introduction of an electrically small air gap will increase both the impedance match and grating free bandwidth for these arrays. The design in [11] has been modified with the addition of an air gap between the PCCA and the lens, which pushes the active impedance drop to higher frequencies, effectively increasing the operational bandwidth. The introduction of the air gap has a minimal minimal effect on the radiation patterns at lower frequencies but the grating lobes are greatly reduced at higher frequencies. This can be explained by the fact that the leaky-wave excited due to the air-gap increases the directivity of the embedded element patterns, leading to less radiation in the direction of the grating lobes. An air gap of 10μm is found to be the best trade-off for this design. All the simulated performance can be found in Fig. 1.

III. Fabrication and Measurements

The fabrication of the PCCAs, the one with (bulk) and the one without air gap (membrane), is similar. They are both fabricated on the same 3" diameter and 625um thick semi-insulating (SI) single-crystalline GaAs wafer. A multilayer consisting of an 0.2um thick GaAs, an 0.4um thick $Al_{0.75}Ga_{0.25}As$ and a 2um thick LT-GaAs is deposited by Molecular Beam Epitaxy (MBE) on the front side of the SI-GaAs. The only difference between the processing of the two

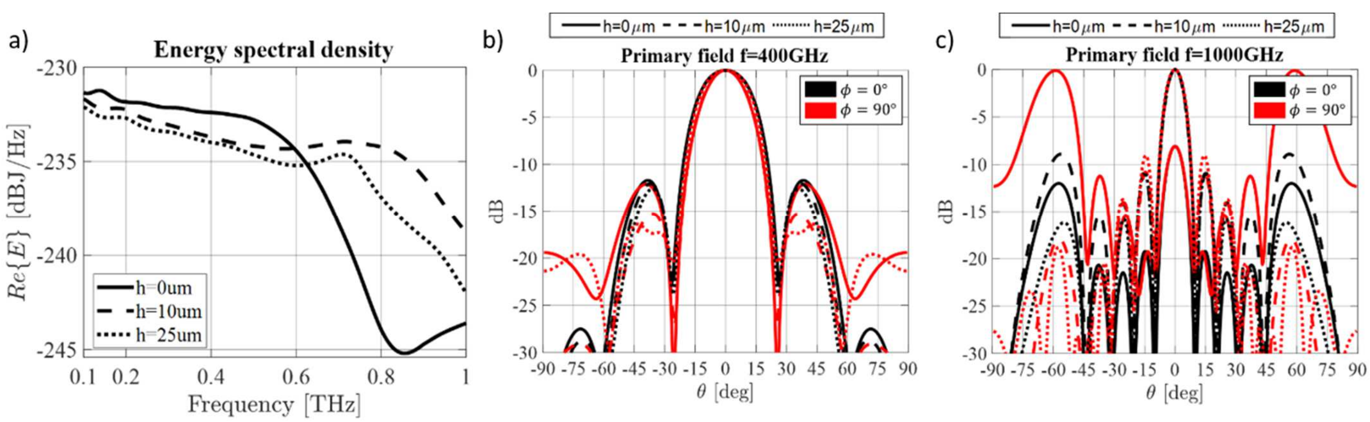

Fig. 1. a) Spectra radiated in the dielectric lens by a connected array for three different dielectric stratification, stepping the air gap between the connected array and the lens for h=0, 10 and 25μm. b) Normalized radiation patterns in the lens at 400GHz. c) Normalized radiation patterns in the lens at 1THz.

arrays that the processing of the PCCA on the bulk substrate and the one on the membrane is that the back of the wafer is locally etched behind the PCCA so the remaining suspended LT-GaAs becomes the membrane. A full description of the fabrication process is discussed in [13]. To create the 3D structure required for the operation of the PCCA, we use a very similar assembly to the one used by Garufo et al. [11]. The alignment and the gluing procedure is identical since the same setup is used. We use two different lenses, one flat Si lens for the PCCA on the bulk substrate and the other one with a protrusion. This protrusion will go inside the cavity on the back of the PCCA and assure that the air gap has the correct dimension. A micro-lenses array made of polymer-on-glass is used to distribute and focus the laser beam into each gap of the 5x5 dipole array. The micro-lenses array is placed on the other side of the PCCA, on an specially machined edge of the sample holder at a distance equal to the focal length of the micro-lenses array. A sketch of the PCCAs is shown in Fig. 2a.

We use a commercial system TERA K15 available from Menlo Systems (https://www.menlosystems.com/), with ad hoc modifications, to characterize the spectrum of the PCCAs. The standard TERA K15 transmitter (TX) is replaced by the PCCAs under investigation, which are fed by the free space 390cm optical delay path. The TX PCCA is biased to a fixed voltage. We use the receiver (RX) from the TERA K15 to measure the frequency response. This receiver is an Auston switch fed by in-fiber optical pulses (Fig. 2b). All details about this setup can be found in [9]. The -3dB diameter of the laser beam impinging the micro-lenses array is 500µm along the two orthogonal axis. The micro-lenses array is illuminated with a laser power of 100mW, from which approximately 30mW is absorbed by the PCCA. Both arrays are biased with 20V in total (4V per gap). The time domain signal of the PCCAs is acquired and transformed to frequency response via a Fourier transform (Fig. 2c and 2d). The grating lobe is clearly suppressed in the array with the 10µm gap and it receives a much higher signal.

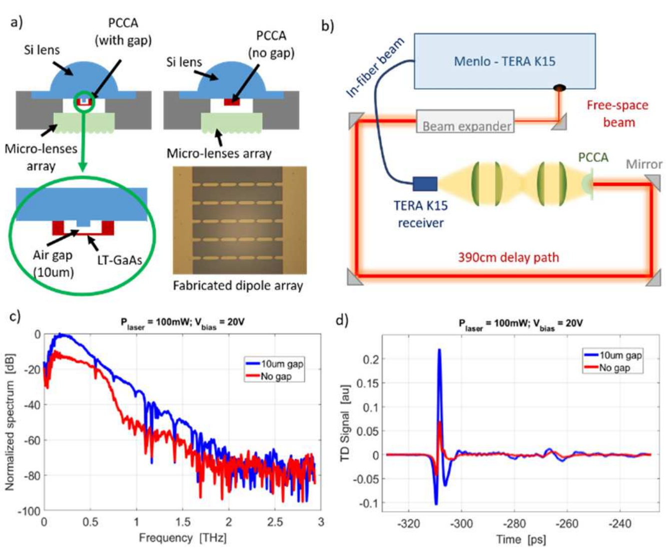

Fig. 2. a) Sketch of the PCCAs under investigation (not to scale). b) Schematic of the measurement setup. c) Measured frequency response of the PCCA with no air gap (red) and with a 10µm gap (blue). d) Measured signal response of the PCCA with no air gap (red) and with a 10µm gap (blue).

IV. Discussion and Conclusions

This work presented a novel connected antenna array for power generation in the THz spectrum. The array on one side exploits connected array elements to achieve high mutual coupling and consequently enlarge the bandwidth in the lower portion of the spectrum. On another side it is "leaky enhanced", as it is manufactured on a thin membrane to realize an air cavity to push the grating lobes to beyond 1THz frequencies. The simulation results and the preliminary measurements are extremely promising, as the air gap introduced between the PCCA and the lens supresses the grating lobes (roader frequency band) and the detected signal is significantly higher.

Acknowledgments

This work has been supported by the ERC starting grant, Lens Antenna Arrays for Coherent THz Cameras (LAA-THz-CC, 639749).

References

[1] S Preu, G. H. Dohler, S. Malzer, A. Stohr, V. Rymanov, T. Gobel, E. R. Brown, M. Feiginov, R. *Gonzalo, M. Beruete, and M. Navarro-Cia,* "Principles of THz generation" *in Semiconductor Terahertz Technology: Devices and Systems at Room Temperature Operation,* G. Carpintero, E. G.-H. noz, H. L. Hartnagel, and A. V. R. S. Preu. Eds. John Wiley & Sons, pp. 3-68 (2015)

[2] P. Jepsen, D. Coole, and M. Koch, "Terahertz spectroscopy and imaging modern techniques and application", *Laser and Photonics Reviews,* vol. 5, no 1, pp. 124-166, (2011)

[3] M. Hangyo, M. Tani, T. Nagashima, H. Kitahara, and H. Sumikura, "Spectroscopy and imaging by laser excited terahertz waves", Plasma and Fusion Research, vol. 2, pp. S1020:1–7 (2007)

[4] J. F. Federici, B. Schulkin, F. Huang, D. Gary, R. Barat, F. Oliveira,and D. Zimdars, "THz imaging and sensing for sefurity applications, explosives, weapons and drugs", Semiconductor Science and Technology, vol. 20, no. 7, pp. S266–S280 (2005)

[5] P. H. Siegel, "Terahertz technology in biology and medicine," IEEE Transactions on Microwave Theory and Techniques, vol. 52, no. 10, pp. 2438–2447 (2004)

[6] D. Mittleman, Ed., Sensing with Terahertz Radiation, *ser. Springer Series in Optical Sciences*. Springer-Verlag Berlin Heidelberg, vol. 85 (2003)

[7] J. W. Bowen, "Towards terahertz communications - systems requirements," *in Terahertz Sources and Systems*, R. E. Miles, P. Harrison, and D. Lippens, Eds. Springer Netherlands, pp. 269–283 (2001)

[8] N. Llombart and A. Neto, "THz time-domain sensing: The antenna dispersion problem and a possible solution," *IEEE Transactions on Terahertz Science and Technology*, vol. 2, no. 4, pp. 416–423, (2012)

[9] A. Fiorellini-Bernardis, P. M. Sberna, J. Bueno, H. Zhang, N. Llombart, and A. Neto, "Time Domain Modelling of Pulsed Photo Conducting Sources. Part II: Characterization of a LT GaAs Bow Tie Antenna", *submitted to IEEE Transactions on Antennas and Propagation* (unpublished)

[10] J. T. Darrow, X. C. Zhang, D. H. Auston, and J. D. Morse, "Saturation properties of large-aperture photoconducting antennas", *IEEE Journal of Quantum Electronic*s, vol. 28, no. 6, pp. 1607–1616, (1992)

[11] A. Garufo et al., "A Connected Array of Coherent Photoconductive Pulsed Sources to Generate mW Average Power in the Submillimeter Wavelength Band", *IEEE Transactions on Terahertz Science and Technology*, vol. 9, no. 3, pp. 221-236 (2019)

[12] D. Cavallo and A. Neto, "A Connected Array of Slots Supporting Broadband Leaky Waves", *IEEE Transactions on Antennas and Propagation,* Vol. 61, No. 4 (2013)

[13] P. M. Sberna, J. Bueno, A. Fiorellini-Bernardis, H. Zhang, N. Llombart and A. Neto, "Fabrication and characterization of leaky wave photo-conductive antennas for higher power fiber-based THz time domain systems", in preparation (unpublished)