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A Tightly-Sampled Focal Plane Array in 22 nm CMOS with Integrated Direct-Detectors for Terahertz Imaging Applications

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***Abstract*— The design of a focal plane array (FPA) for imaging at sub-mm wavelengths generally is a trade-off between resolution and sensitivity. For maximum angular resolution, minimal spacing between FPA elements is desired, which leads to increased losses due to spillover and mutual coupling and therefore deteriorates the imaging sensitivity. This work presents the characterization of an ultra-wideband (200 GHz – 600 GHz) FPA with integrated direct-detectors, achieving a tight sampling of the focal plane by implementing overlapping of the feed elements, hence alleviating the penalty in aperture efficiency. The overlapping of the feed elements in implemented using a combination of a dual-polarized connected array configuration resembling a chessboard, and leaky-wave propagation in the CMOS stratification. The measured radiation patterns and aperture efficiency show <1dB agreement with simulations. Moreover, a beam spacing corresponding to a near diffraction-limited resolution is combined with a minimum cross-over level below 2 dB over the entire band, making this design a promising candidate for high-resolution terahertz imaging systems. To demonstrate the imaging capabilities of the chessboard array, a quasi-optical imaging setup was developed.**

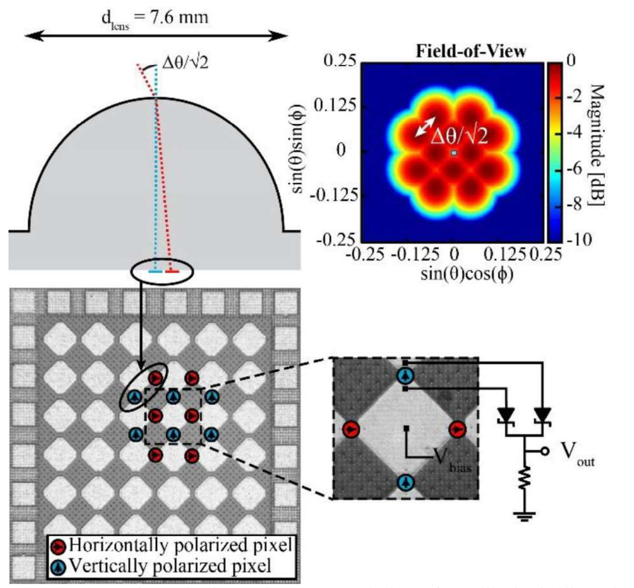

Fig. 1. Overview of 12-pixel THz imager consisting of an elliptical silicon lens and CMOS array with integrated direct-detectors.

I. INTRODUCTION

IMAGING at terahertz frequencies yields several advantages compared to mm wavelengths. First, the noise-equivalent power (NEP) of state-of-the-art antenna-integrated detectors indicates that fully-passive detection can be reached in the near future [1]. Secondly, resorting to shorter wavelengths automatically yields an improvement in the theoretically achievable resolution, as given by the diffraction limit.

To demonstrate the potential of direct-detection THz cameras for commercial applications, further improvement of the NEP is needed ($\leq 1pW/\sqrt{Hz}$), as well as large-scale focal plane arrays (FPA) to sample the field-of-view (FoV) with high angular resolution. In an FPA imager, high resolution is realized by having a small separation between the feed elements (i.e., pixels). Unfortunately, this compromises the NEP due to an increase in spillover and mutual coupling losses. As such, there is a clear trade-off between sensitivity and angular resolution.

This contribution covers the characterization and imaging demonstration of a previously presented FPA with integrated direct-detectors [2]. The FPA is operational from 200 GHz to 600 GHz and is implemented in 22 nm FD-SOI CMOS. The chessboard FPA configuration features overlapping of the feed elements, hereby achieving near diffraction-limited angular resolution in the middle of the band with an aperture efficiency similar to single-pixel designs [1,3].

II. CMOS-INTEGRATED CHESSBOARD FPA

The architecture of the FPA imager is shown in Fig. 1. It consists of the FPA with integrated, differential direct-detectors and it couples to a silicon, elliptical lens. The connected array consists of dipoles with a tapering angle 45°, resulting in a geometry which closely resembles a chessboard [2]. This self-complementary geometry implements two interleaved, orthogonally polarized arrays of which the respective feeds share the same dipoles and are therefore overlapping. Besides the overlap between the orthogonally polarized pixels, the effective area is also enhanced by utilizing the thin layer of SiO_2 between the antenna and the silicon lens within the CMOS stratification [3]. This enables the propagation of a wideband, non-resonant leaky-wave mode, hereby boosting the directivity of the feeds. The array configuration is designed to have a tight focal plane sampling, $d_f = \lambda/D$, at 400 GHz. Effectively, this reduces to $d_f = \lambda/(\sqrt{2}D)$ along the diagonal, resulting in near diffraction-limited angular resolution [4].

To measure the radiation patterns, the prototype was mounted on a 2D rotational stage and placed at 20 cm from standard 20 dB gain horn antenna connected to a WR2.2 frequency extender. The radiation patterns of multiple pixels were measured along four cuts, and interpolated to obtain 2D patterns, as is shown in Fig. 2(a). The aperture efficiency of the FPA imager has been determined through measurement of the system-level responsivity of the individual pixels of the array $\Re_{v,sys}$ in a procedure similar to [3]. The measured aperture efficiency is shown in Fig. 2(c), it is represented by the blue circles. It should be noted that this includes 2 dB of ohmic losses (in the CMOS stratification/metallization) and it is only 1 dB lower when compared to a previously demonstrated single-pixel imager [3], which has a similar directivity and was optimized for high aperture efficiency.

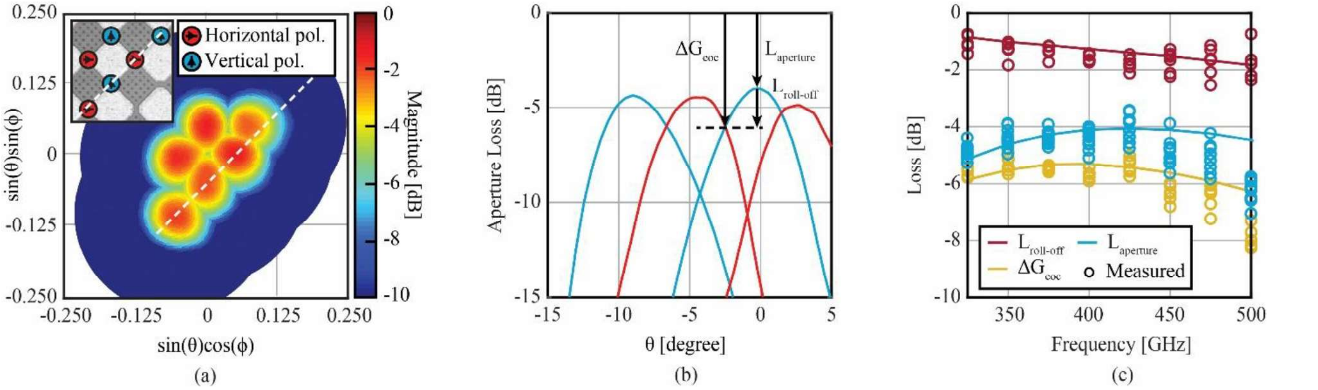

Fig. 2. Measured, interpolated radiation patterns normalized to the measured aperture efficiency, at 400 GHz of six of the active pixels within the array (a), the pattern along the diagonal in the 2D pattern and the definition of the ΔG_{eoc} (b), and the roll-off loss ($L_{roll-off}$), aperture loss ($L_{aperture}$) and ΔG_{eoc} as a function of frequency compared to simulations (c). Only the beam cross-over between diagonally adjacent pixels is considered

The difference in edge-of-coverage gain ΔG_{eoc}, which is the combination of aperture efficiency and roll-off between adjacent beams, as visualized in Fig 2(b), is a good metric to evaluate how well the array performs in the trade-off between aperture efficiency and angular resolution. By normalizing the measured beams to the measured aperture efficiency, the ΔG_{eoc} can be obtained from the magnitude at the beam cross-over. The result of this procedure for all (measured) diagonally adjacent beams is also shown in Fig 2(c) as a function of frequency, and indicates that the chessboard array achieves excellent angular resolution without paying a large penalty in terms of aperture efficiency. Consequently, the chessboard array design is very suitable for future commercial THz imaging systems.

I. Imaging Demonstration

To demonstrate the high resolution of the chessboard array in an imaging scenario, the quasi-optical (QO) setup [5] depicted in Fig. 3(a)-(b) was developed. Here, two plastic, hyperbolic lenses are used to collimate and refocus the beams of the source and detector in the imaging plane, respectively. This ensures a comparable coupling to all pixels in the FoV of the camera. By oversizing the beam of the horn with respect to that of the pixels in the image plane, the resolution (i.e., beamwidth) of the imaging setup, given by the two-way pattern in the image plane, remains identical to that of the pixels in the THz camera [5]. To minimize the additional coupling losses arising from the absence of a field match, the oversizing of the beam from the horn compared to that of the pixels had to be as small as possible. For this optimization, a mismatch of 0.5 dB between the directivity of the two-way pattern and the pixel patterns in the image plane was considered to be acceptable.

To sample the image plane using multiple pixels in the array, the beams corresponding to different pixels need to (virtually) originate from different locations on the primary focal plane (camera side) of the hyperbolic lens, such that they are redirected to different locations along the secondary focal (image) plane. Since all beams emerging from the silicon, elliptical lens originate from the same phase center, this lens had to be replaced by a silicon, hyper-hemispherical lens designed to have a virtual focal plane, as was described in [5]. The imaging demonstration is currently a work in progress, and results will be presented at the conference.

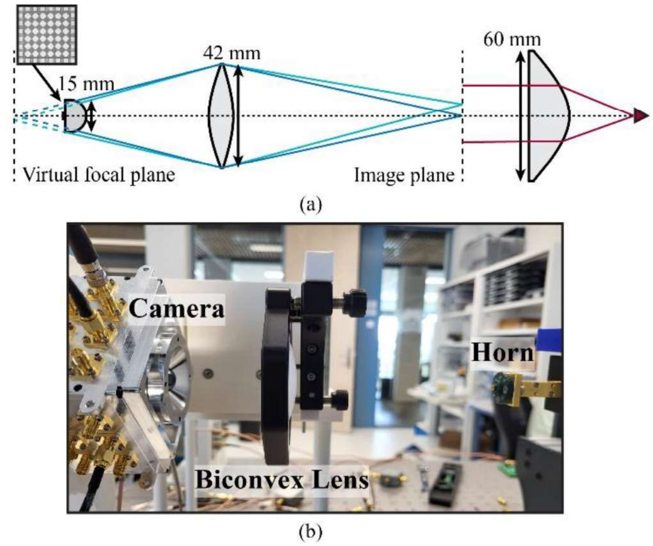

Fig. 3. Schematic of QO setup for demonstrating near diffraction-limited imaging (a), photograph of imaging setup, excluding the plastic, plano-convex lens (b).

References

[1] M. Andree, J. Grzyb, R. Jain, B. Heinemann, and U. R. Pfeiffer, “Broadband Modeling, Analysis, and Characterization of SiGe HBT Terahertz Direct Detectors,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 70, no. 2, pp. 1314–1333, 2022.

[2] S. L. van Berkel, E. S. Malotaux, B. van den Bogert, M. Spirito, Cavallo, A. Neto, and N. Llombart, “High resolution passive THz imaging array with polarization reusage in 22nm CMOS,” in *2019 44th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, 2019, pp. 1–2.

[3] S. van Berkel et al., "Wideband Modeling of CMOS Schottky Barrier Diode Detectors for THz Radiometry," in *IEEE Transactions on Terahertz Science and Technology*, vol. 11, no. 5, pp. 495-507, Sept. 2021, doi: 10.1109/TTHZ.2021.3085137.

[4] S. van Berkel, O. Yurduseven, A. Freni, A. Neto, and N. Llombart, “THz imaging using uncooled wideband direct detection focal plane arrays,” *IEEE Transactions on Terahertz Science and Technology*, vol. 7, no. 5, pp. 481–492, 2017.

[5] M. Hoogelander, S. van Berkel, E.S. Malotaux, M. Alonso-delPino, M. Spirito, A. Neto, D. Cavallo, N. Llombart, "Diffraction-Limited Imaging Demonstration using a Silicon Integrated Array at Terahertz Frequencies," *2022 47th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz)*, Delft, Netherlands, 2022, pp. 1-2.