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Diffraction-Limited Imaging Demonstration using a Silicon Integrated Array at Terahertz Frequencies

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Abstract— **In this contribution we will present the diffraction-limited imaging capabilities of a focal plane array (FPA) of antenna-coupled direct-detectors at submillimeter wavelengths. The FPA prototype is a tightly sampled, 12-pixel array that was developed in a 22 nm CMOS technology and it covers a band from 200 GHz to 600 GHz. A quasi-optical (QO) setup was developed to actively illuminate this FPA in order to perform imaging with $> 40\,dB$ SNR. The resulting images will be the first that have diffraction-limited angular resolution at these wavelengths, which demonstrates that this FPA design can be very attractive for future passive THz imaging applications.**

Index Terms — **Diffraction-limited resolution, Silicon integrated array, direct-detection, antenna-coupled detector, QO imaging system, submillimeter-wave imaging, broadband antenna, THz imaging.**

I. Introduction

A truly passive, silicon integrated terahertz (THz) camera operating at room temperature would be very attractive for different applications in the security and automotive industries due to its potential for low power consumption, compactness and low-cost. Unfortunately, the current state-of-the-art direct-detection THz imagers require either active illumination [1] or cryogenic cooling [2], [3] to overcome the noise injected by the detector and thus to achieve a sufficient signal-to-noise ratio (SNR). These solutions, unfortunately, significantly increase both system complexity and cost.

The remaining work towards a prototype that is more viable for commercial applications is split into two ways: On the one hand, the noise-equivalent power (NEP) at room temperature of passive THz cameras must improve in order to achieve a sufficient SNR. On the other hand, the pixels in the focal plane of the camera should be spaced very tightly to achieve diffraction-limited angular resolution, which yields the highest possible image quality. For an incoherent imaging scenario, the pixel spacing needs to be $d_f = 0.5\lambda F/D$ in order for the imager to be diffraction-limited, which is defined by an angular separation of $\Delta\theta_{lim} = \lambda/(2D)$ between the different beams and related to having a beam cross-over level of -0.7 dB [4]. The current state-of-the-art implies that one either has to accept that the QO system will suffer from high spillover losses [2], [3], or has to resort to mechanical scanning mechanisms [5], [6] in order to compensate for the under-sampling of the focal plane.

Recently, we developed a tightly sampled, 12-pixel imager operational between 200 – 600 GHz and integrated in a commercial 22 nm CMOS technology. This prototype uses a dual-polarized connected array of leaky-wave antennas in order to realize overlapping of the feeds in the focal plane [7]. In the middle of the operational band, the horizontally and vertically polarized pixels are diagonally separated $d_f = \frac{1}{2}\sqrt{2}\lambda F/D$,

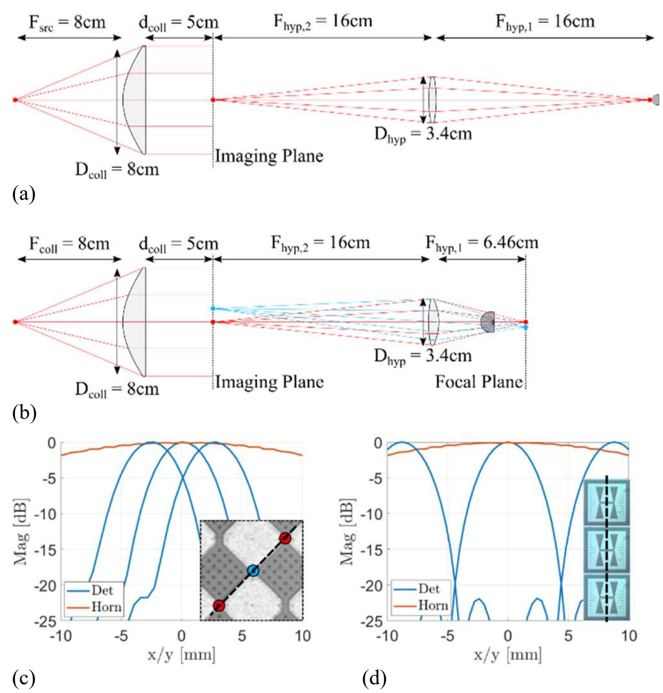

Fig. 1. Imaging setup for single pixel (a) and multi-pixel (b) cameras, the electric field in the imaging plane for three diagonally adjacent pixels of the multi-pixel (c) vs. that of a theoretical array of single-pixels (d).

which provides a fully- or even over-sampled ($d_f < 0.5\lambda F/D$) condition at lower frequencies in the operational band. This enables, for the first time, the demonstration of diffraction-limited imaging at THz frequencies.

In this contribution we will demonstrate the imaging resolution of this multi-pixel imager compared to a previously presented single-pixel camera [8]. Both prototypes have similar radiation patterns and employ the same direct-detector architecture. The single-pixel prototype was fully characterized and the frequency-averaged system NEP was reported to be $90\ \text{pW}/\sqrt{\text{Hz}}$ [8]. Since this does not suffice for passive imaging, a coherent, active source was used to illuminate the detectors and a QO setup was developed to achieve a high SNR.

II. Quasi-Optical Setup For Diffraction-Limited Imaging using a Coherent Source

Two QO setups were designed to test the imaging capabilities of the single- and multi-pixel prototypes. They are composed by the detector on one end, a coherent source on the other end, and the imaging plane in the middle, as is shown in Fig. 1a-b.

The single-pixel detector is integrated with a silicon, elliptical lens of 7.6 mm in diameter, whereas the multi-pixel camera is equipped with a silicon, hyper-hemispherical lens

[10] in order to allow for scanning of the imaging plane. Since the phase center of an elliptical lens antenna is located at the tip of the lens, irrespective of the feed location in the focal plane, the radiation from a feed located anywhere in the focal plane would be refocused to the center of the imaging plane by the QO setup. A hyper-hemispherical lens, on the other hand, transforms the fields of the FPA elements in such way that they appear to be generated by a virtual source located on a unique point in its focal plane, which is displaced $F_V = D_{hemi}/2n$ behind the tip of the lens.

A large diameter of the hemi-hemispherical lens gives more symmetric patterns and decreases the scanning angle [10], which in turn results in smaller scan losses. The performance of this lens was analyzed using an in-house Physical Optics (PO) tool [11], which led to the conclusion that a lens diameter of 15 mm ($20\lambda_0$ at 400 GHz) can provide good imaging performance.

Both QO imaging setups are designed to have a half-power beamwidth (HPBW) in the imaging plane of the source antenna that is considerably larger (i.e. six times) compared to that of the detector, as is shown in Fig 1c-d. This is necessary in order to have the image resolution be determined by only the patterns of the detector, rather than by the two-way pattern [9]. Note that the ratio of HPBWs should be designed such that the resolution of feeds displaced from the FPA center are also decoupled from the resolution of the source. Plastic (HDPE) lenses are employed to respectively refocus and collimate the beams of the detector and source. This achieves the desired spot sizes while also maximizing the coupling between the two antennas. The main performance metrics of the proposed QO systems at 400 GHz are summarized in Tab. 1. The definition of the stated field match loss between the detector ($\vec{E}_{det}$) and source ($\vec{E}_{src}$) patterns in the imaging plane S is given in the equation below.

$$\eta_{field\ match} = \frac{\left| \iint_S \vec{E}_{det} \cdot \vec{E}_{src} \, dS \right|^2}{\iint_S \left|\vec{E}_{det}\right|^2 dS \iint_S \left|\vec{E}_{src}\right|^2 dS} \qquad (1)$$

The SNR of both imaging setups has been be calculated using the previously measured NEP from the single pixel detector and the estimated losses of the array and QO systems as shown in Tab 1. The result (assuming a standard integration time of 1s) is shown in Fig. 2. It can be concluded that the images created using both prototypes can have an SNR above 40 dB over the entire operational band of the THz source. This SNR will be more than sufficient to demonstrate the diffraction-limited imaging capabilities of this novel array architecture.

The field patterns of three diagonally adjacent pixels in the imaging plane at 400 GHz are shown in Fig. 1c. The patterns show a very low beam cross-over level and indicate diffraction-limited resolution at the lower end of the operational band. A comparison to the patterns in the imaging plane of a (virtual) array of single-pixel detectors (see Fig. 1d) demonstrates the major improvement in imaging resolution that is achieved by the array design employed in the multi-pixel camera.

The multi-pixel prototype has already been fabricated and assembled. Measurements are currently being carried out and the results will be presented at the conference.

TABLE. I. FIELD COUPLING IN THE IMAGING PLANE AT 400GHZ

Performance Summary	Single-Pixel	FPA $\Delta d_f = 0$	FPA $\Delta d_f = 1.5 d_f$
QO Setup Reflection + Spillover + Ohmic Loss	1.8 dB	1.3 dB	1.3 dB
Field Match Loss	13.9 dB	15.3 dB	16.7 dB
HPBW	4 mm	4mm	4mm

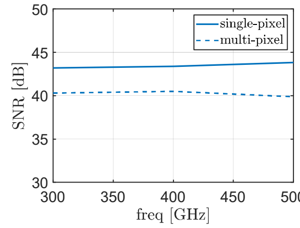

Fig. 2. SNR using the QO setup for the single- and multi-pixel detectors

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