A 63-Pixel Plasmonic Photoconductive Terahertz Focal-Plane Array

Xurong Li#1, Mona Jarrahi#2

#Electrical and Computer Engineering Department, University of California, Los Angeles, USA
1xurongli@ucla.edu, 2mjarrahi@ee.ucla.edu

Abstract—We present a 63-pixel photoconductive terahertz focal-plane array based on arrays of plasmonic nano-antennas. The nano-antennas are designed to offer both broadband and high-sensitivity terahertz detection. A diffuser is used to efficiently focus the optical pump beam onto the active area of each pixel of the focal-plane array. The detected terahertz signal from each pixel is collected by a programmable FPGA-based readout circuit. We experimentally demonstrate more than a 60 dB signal-to-noise ratio and a 2 THz bandwidth for all of the pixels in the terahertz focal-plane array.

Keywords—terahertz focal-plane array, time-domain spectroscopy, nano-antenna.

I. INTRODUCTION

Rapidly developing terahertz imaging technologies have a broad range of applications including non-destructive quality control of industrial products, security screening, and medical diagnosis [1]–[10]. Pulsed terahertz imaging systems are of a particular interest since they offer spatial (both lateral and depth) and spectral information at the same time. Conventional pulsed terahertz imaging systems often use a single-pixel photoconductive antenna array and a one-dimensional mechanical scanning to capture an image. The mechanical scanning requirement significantly limits the image acquisition speed of these systems [11]–[13].

Two different approaches have been introduced to extend the single-pixel operation of pulsed terahertz imaging systems to multi-pixel operation. One approach is using a one-dimensional photoconductive antenna array and a one-dimensional mechanical scanning [14]. Despite offering shorter image acquisition times compared to single-pixel pulsed terahertz imaging systems, the speed of these imaging systems is still limited by the required one-dimensional mechanical scanning. In addition, the very small active area of the photoconductive antennas compared with the overall array size results in a severely inefficient use of the optical pump power. The other approach is utilizing conventional visible or infrared cameras for electro-optic terahertz detection [15]. However, the signal-to-noise ratio (SNR) of these imaging systems has been limited due to the relatively low terahertz intensity per pixel, which significantly reduces the electro-optic detection efficiency.

In this work, we present a photoconductive terahertz focal-plane array (FPA) with 63 pixels, which eliminates the need for any mechanical scanning in a pulsed terahertz imaging system, while maintaining high SNR levels. Each pixel consists of a plasmonic nano-antenna array, which is designed for an efficient interaction between the received terahertz field and the photocarriers generated by the optical pump beam. A diffuser is used to focus the optical pump beam onto the active area of each individual pixel, providing a highly efficient use of the optical pump beam. The output signals from the FPA pixels are collected by a programmable FPGA-based readout circuit. We experimentally demonstrate SNR levels above 60 dB and detection bandwidths exceeding 2 THz for all of the FPA pixels.

II. DEVICE ARCHITECTURE

Figure 1 shows the schematic diagram of the plasmonic photoconductive terahertz FPA. The FPA is fabricated on a low-temperature grown GaAs (LT-GaAs) substrate with a carrier lifetime of 0.3 ps. The LT-GaAs layer is epitaxially grown on a semi-insulating GaAs (SI-GaAs) substrate. Arrays of plasmonic nano-antennas on top of the substrate serve as broadband terahertz antennas and tightly confine the incident terahertz radiation at the tip-to-tip gap between the nano-antenna electrodes. The geometry of the nano-antennas is selected to excite surface plasmon waves in response to a TM-polarized optical pump beam [16], [17]. The excitation of surface plasmon waves results in a significant enhancement in optical pump intensity and photocarrier generation in close proximity to the nano-antenna electrodes, where terahertz field strength is maximized [18]–[25]. To further enhance the interaction between the terahertz field and the optical pump beam, a diffuser is used to project the optical pump beam in the form of parallel lines matching the active area of the plasmonic nano-antenna arrays. Compared to previously demonstrated terahertz detectors based on plasmonic nano-antenna arrays [21]–[23], which waste a considerable portion of the optical pump beam by the shadow metal stripes, this terahertz FPA is more power-efficient. The high spatial overlap between the photocarrier concentration and terahertz field results in a high output photocurrent from each pixel, which is the result of the photocarriers drifting under the terahertz field.

Fig. 1. Schematic diagram of the plasmonic photoconductive terahertz FPA.
A thin Si$_3$N$_4$ film covers the plasmonic nano-antenna arrays and serves as an anti-reflection coating, maximizing the optical transmission into the substrate. An array of shadow metal stripes on top of the Si$_3$N$_4$ layer blocks every other gap between the nano-antenna arrays to prevent the generation of photocurrent components with opposite polarities. The dark area under these shadow metal stripes is used to route the output photocurrent from each pixel to the FPA readout circuit.

III. DEVICE FABRICATION AND CHARACTERIZATION

The first prototype of the designed plasmonic photoconductive terahertz FPA consists of 9×7 pixels and covers a 2.43×1.68 mm$^2$ total area. Each pixel consists of 3 rows of 1500 plasmonic nano-antennas and covers an area of 270×240 μm$^2$. To fabricate the FPA, the plasmonic nano-antenna arrays are first patterned by electron-beam lithography, followed by deposition of Ti/Au (3/47 nm) and liftoff. Then, output traces and contact pads are formed using optical lithography, Ti/Au (20/180 nm) deposition and liftoff. Next, a 290-nm-thick silicon nitride layer is deposited using plasma-enhanced chemical vapor deposition. Finally, the shadow metals are patterned by optical lithography, Ti/Au (10/90 nm) deposition, and liftoff. The optical microscopy image of the fabricated terahertz FPA is shown in Fig. 3.

Figure 4 shows the block diagram of a time-domain spectroscopy setup used for characterizing the fabricated plasmonic photoconductive terahertz FPA. 135 fs-wide optical pulses with a central wavelength of 800 nm and repetition rate of 76 MHz are generated by a Ti:sapphire mode-locked laser. A large-area plasmonic photoconductive terahertz source [25] is used to generate terahertz pulses when pumped by the femtosecond optical pulses. Two convex terahertz lenses (Microtech Instruments, Inc. PL-60) are used to collimate and...
focus the generated terahertz beam onto the FPA. A diffuser (Holo/Or Ltd. ML-003-800-Y-A) is used to convert the optical pump beam from the Ti:sapphire laser into an array of parallel lines. An objective lens (Mitutoyo MY20X-824) is used to focus these parallel lines onto the FPA such that the line locations match the active area of the nano-antenna arrays. Optical alignment is optimized by maximizing the photocurrent of all of the FPA pixels. A total optical pump power of 200 mW is used for characterizing the FPA. A custom-made programmable FPGA-based readout circuit is used for data acquisition. 4 multiplexers (Analog Devices, Inc. ADG1206) controlled by an FPGA development board (Digilent Inc. Basys 3) are used to route the output of all of the FPA pixels to a transimpedance amplifier (FEMTO DLPCA-200) and lock-in amplifier (Zurich Instruments MFLI) sequentially, while recording the lock-in amplifier output signal.

![Fig. 4. Block diagram of the time-domain spectroscopy setup used for characterizing the fabricated plasmonic photoconductive terahertz FPA.](image)

The time-domain and frequency-domain responses of two selected pixels, one in the center and the other one at the corner of the FPA, are shown in Fig. 5. These results are obtained by capturing and averaging 12 time-domain traces. The ripples in the frequency-domain data (Fig. 5b) are due to multiple reflections of the terahertz pulse inside the GaAs substrate, which are also observed in the time-domain data (Fig. 5a). They can be eliminated by mounting the FPA on a silicon lens. The center pixel offers the strongest responsivity and SNR, because of the non-uniform distribution of the optical output lines from the diffuser and the objective lens. An SNR of 80 dB and a detection bandwidth of 3 THz is achieved at the center pixel, which is comparable to many commercially-available single-pixel terahertz time-domain spectroscopy systems. The SNR and detection bandwidth drop to 60 dB and 2 THz as we move from the center to the corner pixel of the FPA. To account for the non-uniform distribution of the optical pump beam, the output of each pixel is normalized according to the optical pump power it receives. To perform this normalization, the output photocurrent of each pixel in the presence of terahertz radiation is divided by its DC output photocurrent in the absence of terahertz radiation under a 20-mV bias voltage. Figure 5c shows the color plot of the FPA output after normalization, indicating a uniform response with less than a 20% variation across all of the 63 pixels. This 63-pixel output is captured without any mechanical scanning, showing the great potentials of the demonstrated FPA for boosting the image acquisition speed of pulsed terahertz imaging systems.

### IV. CONCLUSION

In summary, a 63-pixel plasmonic photoconductive terahertz FPA, composed of a two-dimensional array of plasmonic nano-antennas is demonstrated. The geometry of the nano-antennas is selected to provide a strong spatial overlap between the incident terahertz radiation and optical pump beam to maintain high SNR (> 60 dB) and broad detection bandwidth (> 2 THz) across all of the FPA pixels. The presented FPA eliminates the need for mechanical scanning in pulsed terahertz imaging systems and, therefore, reduces the image acquisition time of these systems significantly. The presented FPA architecture can be easily extended to provide a larger pixel count by fabricating a larger number of nano-antenna arrays over larger areas.

### REFERENCES


