

CMOS terahertz imaging pixel with a small on-chip antenna

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Abstract – We propose a Si-CMOS terahertz image sensor to resolve the lack of low-cost and small-size detectors. The imager chip consists of an imaging pixel array and column ADCs. The imaging pixel consists of an on-chip antenna and an amplifier acting as envelope detector. The pixel used a microstrip patch antenna for receiving THz waves. However, these antennas' narrow bandwidth and large ground-plane size cause major problems. A low-resistivity Si substrate degrades the gains of planar antennas apart from the microstrip patch antenna. We introduce an on-chip folded-slot antenna to reduce the pixel size and prevent gain degradation due to the Si substrate. The antenna has a broader bandwidth and higher gain than conventional on-chip slot antenna. The folded-slot antenna has about a 0-dBi gain at 0.85 THz and a broader bandwidth than the microstrip antenna in the 0.85 to 1 THz frequency region. The measured results for the THz image sensors with the integrated folded-slot antennas will be reported in near future.

I. Introduction

The terahertz-frequency region (100 GHz – 10 THz), namely, between millimeter waves and far-infrared light waves, has attracted much attention owing to its wide range of applications, such as wireless communications and sensors. Terahertz waves can pass through many kinds of materials, such as plastics, fabrics, and paper, revealing characteristics that cannot be seen by visible light. In addition, so-called fingerprint spectra in the terahertz frequencies can identify hazardous materials [1]. However, the lack of low-cost and small-size microelectronics that generate sufficient power and detect faint signals (often called the “THz gap”) is one of the major obstacles preventing terahertz applications from coming into wide use in our daily lives [2]. In the microelectronics community, terahertz detection outperforms terahertz generation.

Detection methods are generally divided into two methods, coherent (heterodyne) detection and incoherent (direct) detection. Although heterodyne detection achieves higher sensitivity than direct detection, it requires a local oscillator and mixer that are difficult to construct with today's technology, even if a sub-harmonic scheme is used. For that reason, direct detection has been used. Fabrication of THz direct detectors has primarily relied on specialized technologies such as Schottky diodes [3], bolometers [4], and high-electron-mobility transistors (HEMT) [5]. Many of these technologies require additional process steps to make them compatible with CMOS technologies [6].

To solve this problem, we propose a Si-CMOS detector. The advantages of Si-CMOS process technology are low cost and high integration with readout electronics and on-chip signal processors. We have been developing a Si-CMOS imaging pixel, which has shown good responsivity to THz waves [7]. The imaging pixel uses a microstrip patch antenna to receive THz waves. However, the antennas' narrow bandwidth and large ground-plane size cause major problems. A low-resistivity Si substrate degrades the gains of planar antennas such as conventional slot and dipole antennas apart from the microstrip antenna. In this paper, we introduce a folded-slot antenna as an on-chip antenna to reduce the pixel size and prevent gain degradation due to the Si substrate. We will focus on the design of the on-chip folded-slot antenna.

II. Architecture of the THz imager

Fig. 1 shows the block diagram of our proposed imager chip and imaging pixel. The imager chip consists of a 16×16 pixel imaging array and 256 column ADCs. The imaging pixel consists of an on-chip antenna and cascode amplifier with a

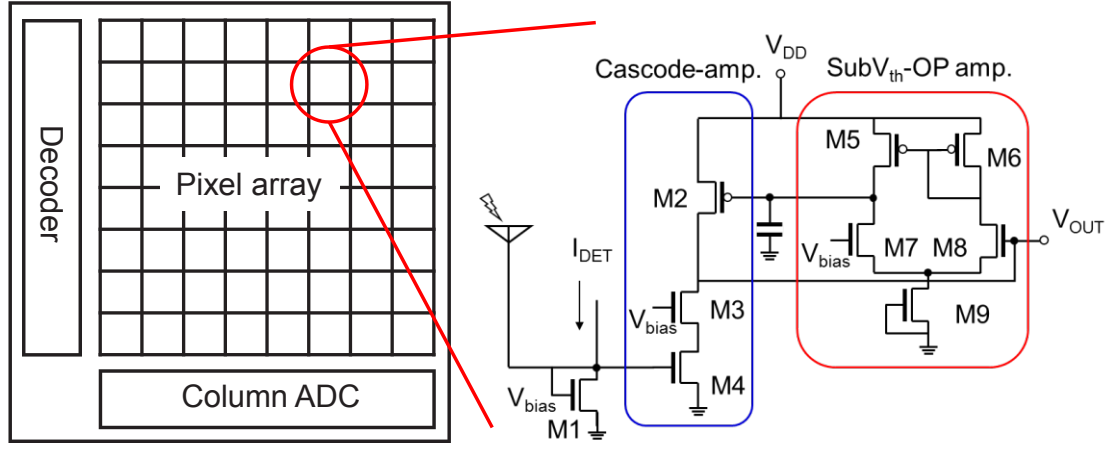


Figure 1. Schematic of image sensor and imaging pixel.

subthreshold-biased operational amplifier (subVth-OP amp). The THz detection is based on nonlinearity of the nMOSFET in the cascode amplifier biased near the threshold voltage. Since the subVth-OP amp, in the sub-threshold region, operates very slowly with a large time constant, the feedback operation is established only at DC and very low frequencies. The feedback circuit operates as a high-pass filter in the detector. Therefore, the detector has no DC offset by using the subVth-OP amp as a feedback circuit [8].

We measured THz imaging pixels fabricated with 180-nm CMOS process [7]. The peak responsivity at 0.915 THz was 51.9 kV/W. The measured noise-equivalent power (NEP) was 358 pW/Hz^{1/2} for 31-Hz sampling. By increasing the sampling rate, NEP of 42 pW/Hz^{1/2} is expected to be obtained at 100 kHz. The detector draws about 3 μ A from a power supply (V_{dd}) of 1.5 V.

III. Design of antenna

Fig. 2 shows the fabricated pixel. At a size of 215 μ m \times 215 μ m, it was larger than the wavelength in the Si substrate at a target frequency of around 1 THz. Thus, a smaller pixel could take advantage of the spatial resolution due to short wavelengths in the THz frequency. To make the pixel smaller, we attempted to reduce the on-chip antenna size. The fabricated pixel employed a microstrip patch antenna for receiving THz waves. However, these antennas' narrow bandwidths and large ground plane sizes cause major problems. Generally, the size of ground plane should be larger than the patch size by 0.2 \times wavelength [9]. On the other hand, a low-resistivity Si substrate degrades the gains of on-chip planar antennas such as conventional slot and dipole antennas apart from the microstrip patch

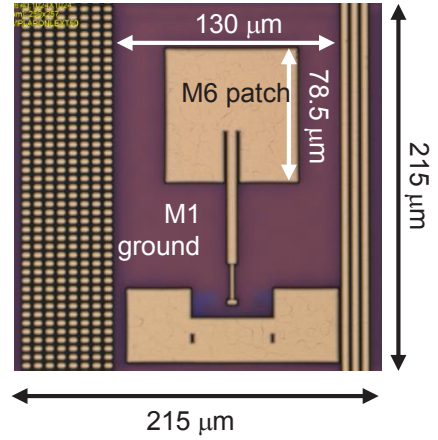


Figure 2. Die photograph of fabricated imaging pixel.

antenna with the ground plane acting as the substrate shielding.

To reduce the antenna size, we introduce a folded-slot antenna [10] as an on-chip antenna, while keeping the antenna gain. Embedding the antenna to the SiO₂ layer can prevent the gain degeneration due to the Si substrate because folded-metal acts as electric shielding. Fig. 3 shows the geometry view of the designed on-chip folded-slot antenna for the THz imaging pixel. Using the CMOS 6-layer metal process, the metal was folded from the top-layer metal (M6) to the bottom-layer metal (M1) through via holes. A 96- μ m-long, 2.39 μ m-wide slot was made on the top-layer metal. The thickness of top-layer metal was 2.39 μ m. The antenna size was 106 μ m \times 45 μ m, which was smaller than the previous microstrip patch antenna. The width of via hole area was 2 μ m.

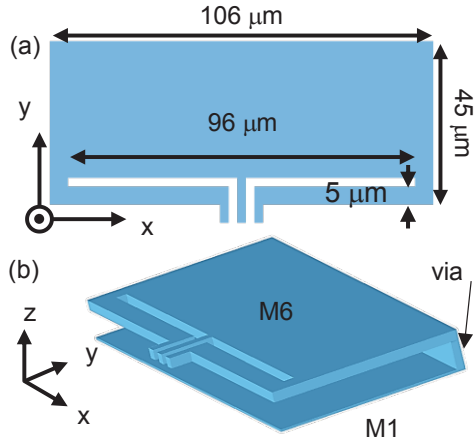


Figure 3. (a) Top and (b) perspective views of folded-slot antenna.

We simulated the antenna using an electromagnetic field simulator (Keysight Technologies, EMPro). The size of the simulation area in xy plane was $200 \mu\text{m} \times 200 \mu\text{m}$ (\sim pixel size). The substrate was $300 \mu\text{m}$ thick. The distance between the antenna and an absorbing boundary was $300 \mu\text{m}$. Fig. 4 compares the simulated gain characteristics of the microstrip patch antenna,

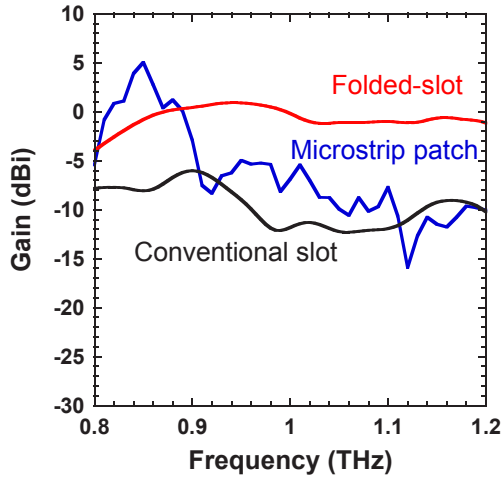


Figure 4. Simulated gains of microstrip, conventional slot, and folded-slot antennas.

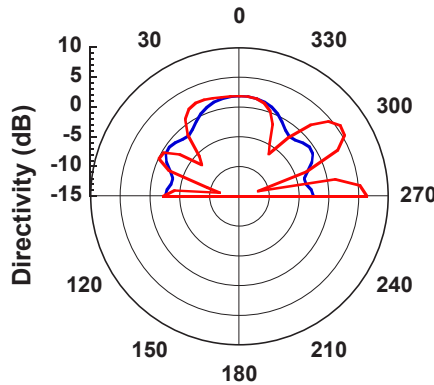


Figure 6. Simulated directivity of the folded-slot antenna.

conventional slot antenna, and folded-slot antenna. While the microstrip patch antenna had a 5-dBi gain at 0.85 THz, the folded-slot antenna had a gain of about 0 dBi at the same frequency. Although the gain of the folded-slot antenna was smaller than that of the microstrip antenna, it had a broader bandwidth from 0.85 to 1 THz. Furthermore, the advantage of the folded-slot antenna over the conventional slot antenna was clearly demonstrated.

Fig. 5 shows the electric field distributions at the antenna resonant frequencies of 0.660 THz and 0.885 THz for the conventional slot (a) and the folded-slot (b) antennas, respectively. The folded-metal suppressed the power leakage to the Si substrate and enhanced the power radiated into the air. Fig. 6 shows the directivity of the folded-slot antenna at 0.885 THz. The main lobe was directed to the z -axis. When a pixel array is formed, the directivity of the arrayed antennas may be changed from that of the isolated antenna shown in Fig. 6. The directivity of arrayed antennas was calculated by

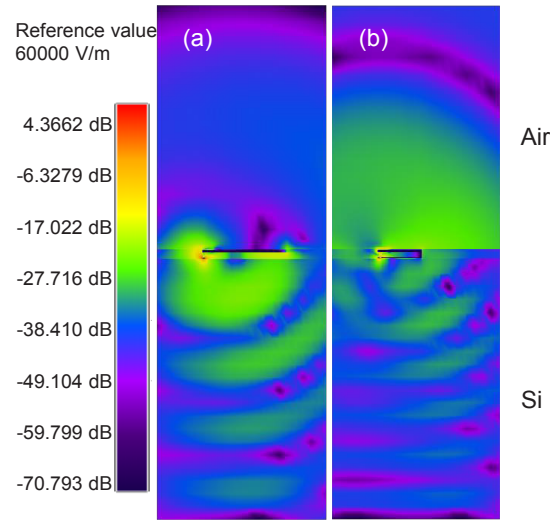
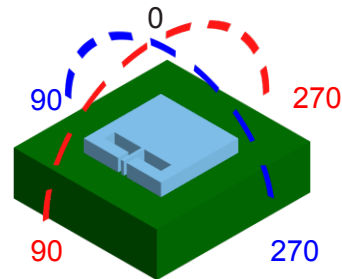


Figure 5. Electric field distributions in xz plane of (a) conventional and (b) folded slot antennas.



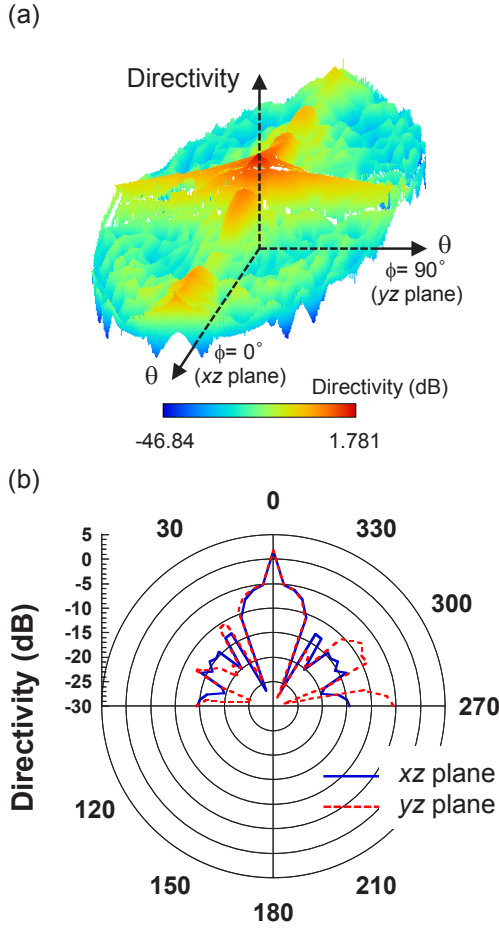


Figure 7. Simulated directivity of arrayed antennas. (a) Birds-eye view. (b) In xz and yz planes.

multiplying the array factor for a 16×16 array. Fig. 7 shows the calculated results. The directivity in the z direction increased compared with that of the isolated antenna.

IV. Conclusion

By introducing the folded on-chip slot antenna, we successfully reduced the size of imaging pixel, while maintaining the antenna gain. The designed antenna achieved about a 0-dBi gain at 0.85 THz, and a broader bandwidth than the microstrip antenna in the 0.85 to 1 THz frequency region. The improved on-chip antenna will bring the advantage of spatial resolution due to short wavelengths in the THz frequency region.

Acknowledgments

This work was partially supported by the Ministry of Internal Affairs and Communications of Japan / Strategic Information and Communications R&D Promotion Programme (MIC/SCOPE) #151301001 and the VLSI Design and Education Center (VDEC),

University of Tokyo in collaboration with Cadence Design System, Inc. and Keysight Technologies Japan, Ltd.

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