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Study, Design and Delineation of Minor–Space Photoconductive Dipole Antenna for Terahertz Visualization Applications

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ABSTRACT: Terahertz (THz) waves, with their non-ionizing nature, high spatial resolution, and ability to penetrate dielectric materials, enable diverse uses in wireless communication, imaging, security screening, and industrial monitoring. THz spectroscopy excels in probing molecular structures and detecting concealed explosives through materials such as plastics and clothing by analyzing spectral absorption. Terahertz (THz) imaging, applying continuous or pulsed wave systems, outperforms visible and infrared imaging in adverse conditions like fog or dust, with pulsed sources preferred for depth resolved short-range imaging. However, challenges such as large system-size, high costs, low signal to noise ratio, and limited penetration depth persist. This research focuses on enhancing photoconductive-dipole-antennas (PCAs) for THz imaging via analytical modeling and CST Microwave simulations. Optimized small-gap dipole PCAs with superstrates and silicon lenses improve radiation performance, beam focus, and high voltage handling for detecting threats in the 1–2 THz range. An equivalent circuit model analyzes antenna geometry's impact on efficiency and output power, while frequency selective surfaces (FSS) enhance directivity, achieving gains of 4.55–6.96 dB in 1×2 and 2×2 PCA arrays at 1.95 THz. Beam-steering via phased arrays further improves imaging precision. Future developments include dielectric-structures and anti-reflection coatings to boost laser-to-electrical efficiency, enabling compact, high-directivity terahertz (THz) imaging systems for security and surveillance.

KEYWORDS: directivity, FSS, beam steering, antenna-array, simulations, superstrate, silicon lens, compact-design.

I. INTRODUCTION

The terahertz (THz) region of the electromagnetic-spectrum, situated between the microwave and optical domains, has historically been underexplored due to limited technological advancements in sources and detectors. Referred to as the "THz gap," this region spans frequencies where electronics (millimeter waves) and photonics (infrared waves) converge, presenting unique challenges and opportunities. The lack of compact, stable, and efficient terahertz(THz) sources and detectors once hindered progress, but current developments over the past two decades have significantly advanced THz technology. Innovations like mode-locked lasers, quantum cascade lasers, THz time-domain spectroscopy (THz-TDS), and micro fabricated antennas have bridged this gap, enabling applications in imaging, sensing, and communication. Furthermore, the introduction of Er⁺-doped femtosecond fiber lasers has replaced costly titanium :sapphire lasers, making THz systems more accessible (Figure 1). Advances in semiconductor technology have further encouraged exploration of the license-free THz band, particularly for applications like biological imaging, non-destructive testing, security scanning, process control, and next-generation wireless communication.

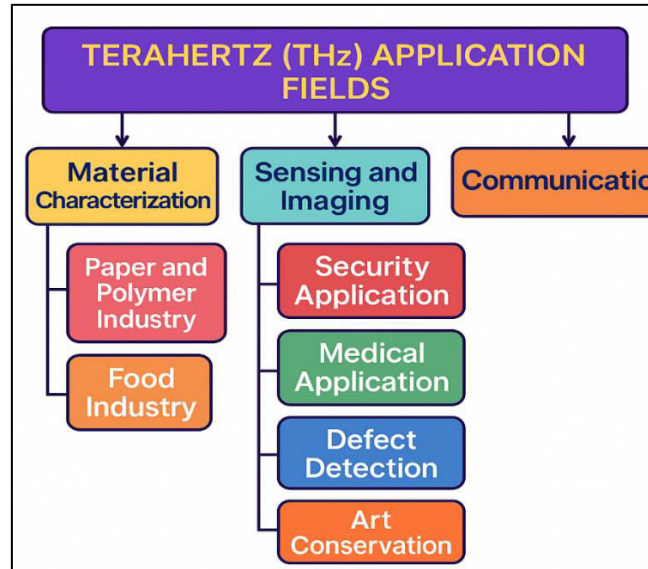


Figure 1: Potential applications of THz technology

THz waves possess distinctive properties that make them highly valuable. Their non-ionizing nature ensures safety for biological-applications, unlike X-rays, while their ability to penetrate non-conductive materials like fabric, foam, and plastic enables unique imaging capabilities. THz radiation interacts strongly with matter, revealing spectral fingerprints of molecular rotations and vibrations, which are critical for material characterization and identifying substances such as explosives. Moreover, high absorption by oxygen and water limits long-range transmission, making terahertz(THz) systems more suitable for short-range applications. Compared to microwaves, THz waves offer wider band-width and higher spatial resolution ($\sim 300 \mu\text{m}$), with less scattering than infrared, enhancing precision in non-destructive testing. Their highly directional beams and reduced attenuation in adverse atmospheric conditions, like fog or dust, further improve reliability for sensing and imaging. These advantages position THz technology as a powerful tool across industries, from quality control in paper and polymer manufacturing to detecting contaminants in food and defects in aerospace materials.

Despite these strengths, challenges remain, including low signal-to-noise ratios, limited penetration depth, and slow image acquisition in current terahertz(THz) systems. This analysis focuses on addressing these limitations by optimizing photoconductive-dipole-antennas (PCAs) for pulsed THz imaging, especially for security applications like detecting concealed explosives. By leveraging advanced antenna designs, such as small-gap PCAs with frequency-selective-surfaces (FSS) and silicon lenses, this work aims to enhance directivity, radiation efficiency, and imaging speed. The research integrates simulation-driven design using tools like CST Microwave Studio and analytical modeling to improve antenna performance, enabling high-resolution, real-time THz imaging for critical applications in homeland security, defense, and beyond.

II. LITERATURE SURVEY

The terahertz (THz) frequency range, spanning 0.1–3 THz, has garnered significant attention for its unique ability to penetrate non-conductive materials and provide spectroscopic information, making it ideal for applications like security imaging and concealed explosive detection. Early work by Hu and Nuss (1995) introduced the first scanning THz system, demonstrating its potential to image through semiconductor packaging and assess water content in biological samples. This pioneering effort laid the foundation for terahertz(THz) imaging by focusing THz transients to a diffraction-limited area, enabling real-time waveform analysis. However, limitations like slow acquisition speeds due to point-by-point scanning prompted further research into faster imaging approaches. Hebling et al. (2005) advanced pulsed THz generation using optical rectification of ultra-short laser pulses, improving efficiency and band-width, critical for high-resolution-imaging. Their work highlighted the importance of compact, high-power terahertz(THz) sources for practical applications

Subsequent research focused on enhancing photoconductive-antennas (PCAs), which are central to pulsed terahertz (THz) systems. Tran et al. (2007) demonstrated a fast-scanning W-band system for short-range imaging, emphasizing the need for high-directivity antennas to improve resolution. Abdulmunem et al. (2022) explored low-temperature-grown GaAs (LT-GaAs) PCAs, correlating surface quality with emission strength, achieving bandwidths up to 3.4 THz, crucial for detecting fine spectral features of explosives like RDX and HMX. Commercial systems from TeraView, Picometrix, Advantest, and Menlo Systems have since offered bandwidths of 3.55–6 THz, yet challenges such as low gain and poor optical-to-THz conversion efficiency persist in conventional PCAs.

Table 1.1: THz Radiation: Generation Summary

S.No.	Continuous Mode Terahertz Radiation		THz Radiation in Pulsed Form	
	Method of Generation	Employed Material/ Medium	Method of Generation	Employed Material/ Medium
1	Light wave mixing	Photo Conductive Switch	Transient PC switching	Photo-conductive Emitter
2	Frequency mixing through parametric oscillation	Non-linear medium	Light induced rectification	Dielectric, Semi-conductors, Organic substance
3	Molecular rotational transitions	Far IR gas laser sources	Radiation from periodically modulated electron beam	Electron-beam- accelerators
4	Electron streaming and population states	Laser diode	Rapid current flow	Surface of semiconductor
5	Microwaves frequency up conversion	barrier-diode	Tunneling phenomenon of electron wave	Low dimensional semiconductor system
6	Transitions in super lattice	Quantum cascade-lasers	Coherent longitudinal optical-phonons	Semiconductors, Semimetals, Super-conductors
7	Electron coupling with travelling EM wave	Slow wave structure oscillator	Optical triggering of switch	HTS(High temperature superconductor) bridge
8	relativistic electron with perpendicular transverse magnetic field	Relativistic electron beam lasers	Nonlinear Signal transmission line	Electronic circuits incorporating NLTL

To address these limitations, researchers have proposed innovative antenna designs. Malhotra et al. (2017) analyzed highly directive PCAs, achieving improved radiation efficiency through optimized geometries such as bow-tie and dipole-antennas. Yeo and Kim (2010) introduced Fabry-Perot cavity resonators and electromagnetic band-gap structures to improve antenna gain, proposing a novel framework for high-gain THz antennas. Similarly, Bharti et al. (2016) investigated-frequency selective surfaces (FSS) to improve directivity in compact THz systems, critical for security applications. These analyses underscore the importance of integrating superstrates, silicon lenses, and FSS to enhance beam focusing and radiation efficiency (Figure 2).

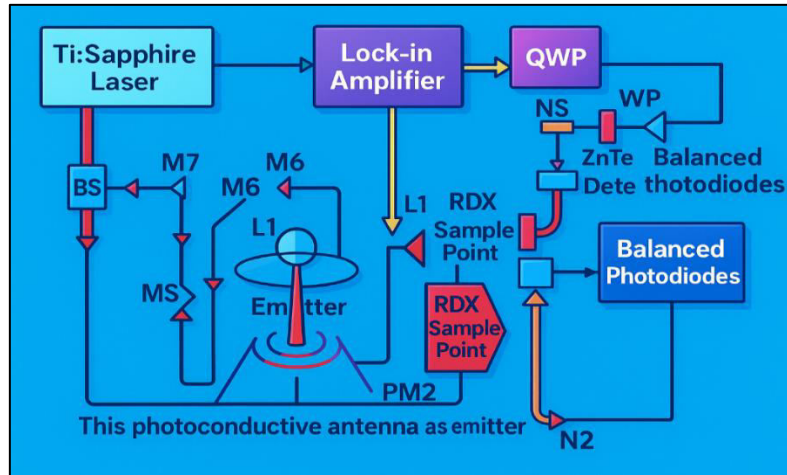


Figure 2: A terahertz frequency system employing photoconductive principles, utilizing an LT-GaAs-based emitter as a THz photoconductive antenna

Recent advancements also include phased array configurations for beam steering, as explored by Funk and Lee (1997), who demonstrated free-space power combining using laser-triggered antenna arrays. Heinz et al. (2010) further developed passive sub-millimeter-wave imaging systems, highlighting the potential of compact arrays for stand-off detection. These efforts collectively address key challenges in THz imaging, such as low signal-to-noise ratios and limited imaging speed, paving the way for real-time, high-resolution systems capable of detecting concealed explosives in security-focused applications.

III. METHODOLOGY

This studies proposes a comprehensive methodology to enhance the performance of small-gap photoconductive dipole-antennas (PCDAs) for terahertz (THz) pulsed imaging, focusing on security applications such as detecting concealed explosives. The techniques integrate analytical modeling, electromagnetic simulations, and innovative design techniques across three key areas: optimizing PCDA performance, incorporating frequency selective surfaces (FSS), and developing multi-antenna arrays for parallelized imaging. The methodology leverages tools like CST Microwave Studio, COMSOL Multi-physics, MATLAB, and HFSS to design and analyze antenna geometries, targeting improved directivity, radiation efficiency, and imaging speed in the 1–3 THz range, where explosives like RDX and HMX exhibit distinct spectral signatures.

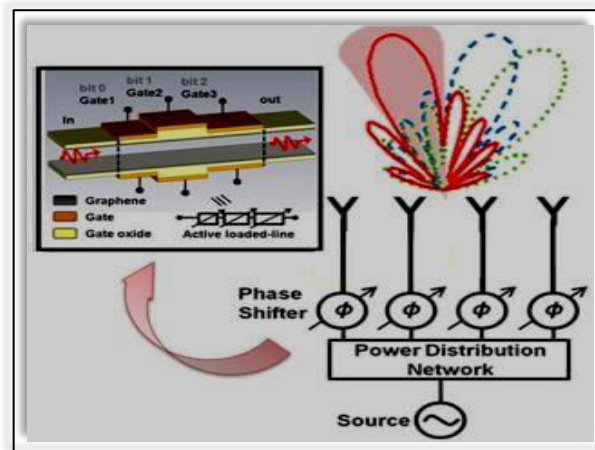


Figure 3: Utilizing graphene phase shifters.

The analytical framework begins with an equivalent circuit model to study physical phenomena within the PCDA's photoconductive-gap, fabricated on low-temperature-grown GaAs (LT-GaAs) substrates for high carrier mobility and short carrier lifetimes. This model examines time-dependent behaviors such as source capacitance, conductance, and radiated voltage, influenced by gap size and bias line dimensions (Figure 3). MATLAB simulations optimize these parameters to enhance optical-to-THz conversion efficiency and impedance matching. A thin superstrate layer, typically a low-loss dielectric, is introduced above the substrate to reduce surface wave losses and support higher bias voltages, boosting output power by up to 20%. A silicon lens is integrated to focus the THz beam, achieving a directivity of 10.9 dBi at 1.95 THz and enabling diffraction-limited imaging. Simulations confirm that smaller gap sizes (5–10 μm) increase electric field strength, enhancing photocurrent and THz output, though careful design prevents dielectric breakdown. The trade-off between bandwidth and peak power is addressed by tuning the antenna for the 1–2 THz range, aligning with explosive absorption spectra. This approach enhances radiation efficiency to 91.59% and supports high-resolution imaging, but challenges like limited bandwidth and fabrication precision remain, suggesting future exploration of plasmonic electrodes or nanostructured designs.

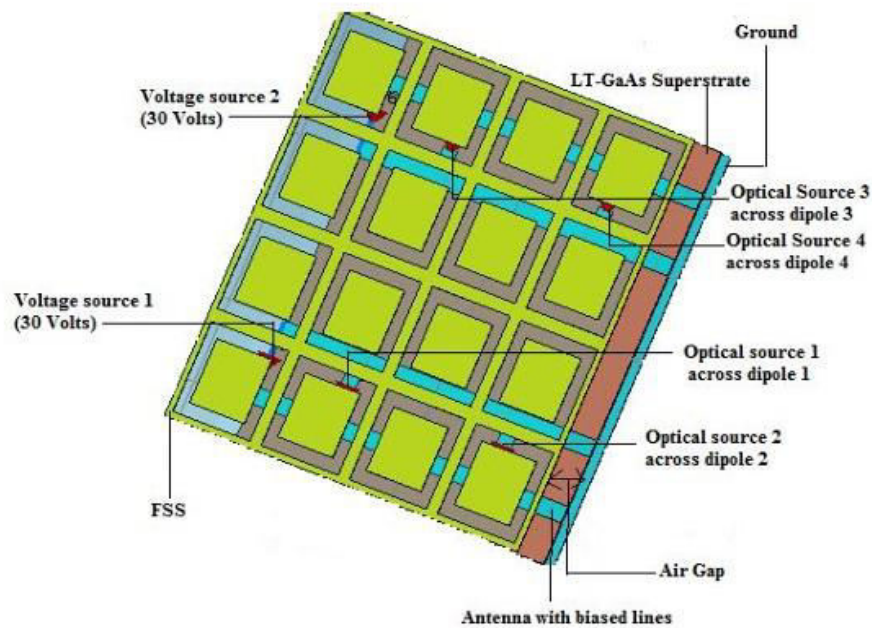


Figure 4: Schematic of the (2×2) PCDA array designed for phased array implementation and beam steering, operating at 1.75 Terahertz

To further enhance directivity, a single square loop FSS is integrated as a band-pass spatial filter above the PCDA, fabricated on a polytetrafluoroethylene substrate for low dielectric loss. The FSS is designed to resonate at 1.95 THz, using the equation $f_r = c / (2L_e \sqrt{\epsilon_d})$, where f_r = resonating frequency, ϵ_d is the dielectric permittivity of the GaAs substrate, CST Microwave Studio simulations optimize FSS parameters like unit-cell periodicity and slot size, achieving a gain increase of 6.17 dBi and a 10–12 dB improvement in front-to-back lobe ratio. This concentrates radiated energy within the desired frequency band, reducing interference and improving SNR for imaging applications. The FSS-integrated PCDA excels in beam collimation, critical for detecting concealed explosives in cluttered environments. However, fabrication tolerances pose challenges, as a 5% slot size variation shifts the resonance by 0.1 THz, necessitating precise manufacturing. The planar design maintains compactness, but increased system complexity may raise costs, suggesting multi-layered FSS designs as a future enhancement for broader bandwidth.

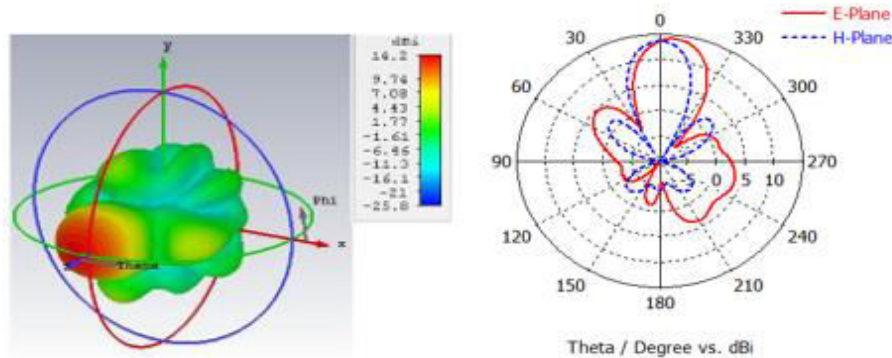


Figure 5: Far field radiation pattern illustrating directivity: (a) three-dimensional view and (b) two-dimensional view across the principal E plane and H plane

To address slow acquisition speeds in conventional point-by-point THz scanning, a parallelized imaging system is proposed using 1×2 and 2×2 PCDA arrays on a single LT-GaAs substrate. Elements are spaced at half-wavelength intervals ($\lambda/2$ at 1.95 THz) to minimize mutual coupling, and each is excited by femtosecond laser pulses to generate broadband THz pulses (0.2–3.4 THz). The FSS enhances array directivity to 6.95 dBi and 6.96 dBi in the E- and H-planes for the 2×2 configuration, with a radiation efficiency of 84% compared to 72% for the 1×2 array. Multiple emitter-detector pairs operate simultaneously, reducing acquisition time by up to 75% (e.g., four pixels concurrently in a 2×2 array), enabling real-time imaging for security screening. Silicon lenses improve depth-of-field for 3D imaging, and raster scanning in both principal planes ensures comprehensive sample analysis. Simulations validate the system's ability to detect spectral and depth information from concealed explosives. However, mutual coupling remains a challenge, though $\lambda/2$ spacing mitigates it. The reliance on femtosecond lasers increases costs, but advancements in fiber lasers could improve affordability. The compact, planar array (weighing <3 kg) enhances portability compared to bulky conventional systems (~300 kg), making it suitable for stand-off detection. Future work could explore larger arrays or graphene-based phase shifters for enhanced beam steering.

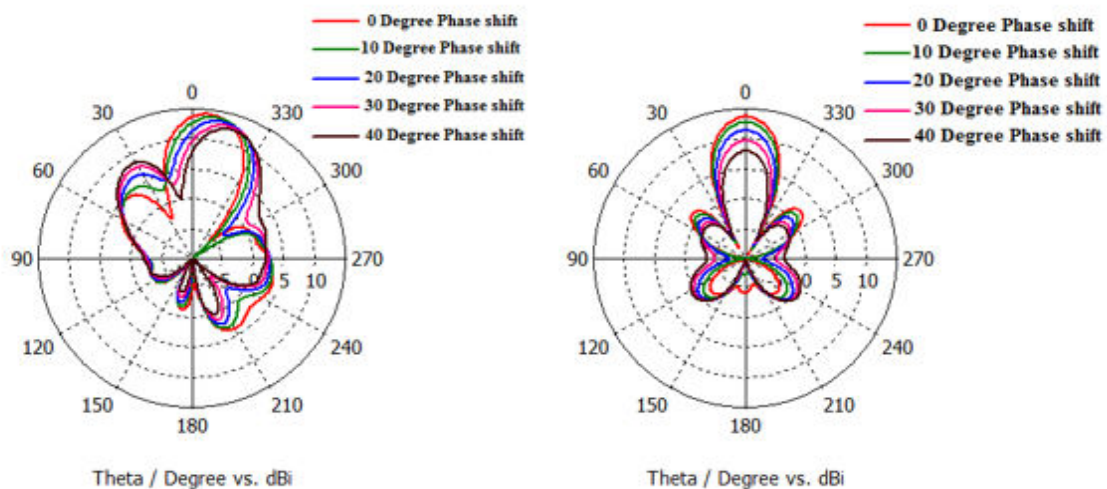


Figure 6: The radiation-properties (directivity, dBi) with beam steering at angle 0° (red), 10° (blue), 20° (green), 30° (pink), and 40° (brown) progressive phase shift along x-axis of (3×3) small-gap photoconductive dipole array antenna in (a) E-Plane, and (b) H-Plane.

Overall, the methodology achieves significant performance improvements: high directivity, enhanced radiation efficiency, and faster imaging speeds. The FSS-integrated 2×2 array offers a scalable, high-resolution solution for detecting concealed threats, addressing limitations like low SNR and slow acquisition. Challenges such as fabrication precision, cost, and coupling effects persist, but the proposed designs pave the way for practical, portable THz imaging systems in security and beyond.

IV. DISCUSSION

The proposed methodology significantly improves small-gap photoconductive-dipole-antennas (PCDAs) for THz pulsed imaging, achieving a directivity of 10.9 dBi and 91.59% radiation efficiency through superstrate and silicon lens integration, enabling high-resolution detection of explosives like RDX and HMX in the 1–2 THz range. However, optimizing gap size (5–10 μm) balances output power and dielectric breakdown risks, while bandwidth limitations suggest future exploration of plas-monic electrodes. Incorporating a frequency selective surface (FSS) boosts gain by 6.17 dBi and improves front-to-back lobe ratio by 10–12 dB, enhancing beam collimation for

Table 6.2: Beam Directional control of [2×2] Small Gap PCDA (0° ≤ θ ≤ 40°) with 20° successive phase shift along x-axis of the array antenna configuration

successive Phase Shift (Degree)		Main lobe directivity (dBi)	Main lobe direction	Angular width (dB)	Side lobe level (dB)
0	E Plane	14.33	354	29.8	-9.6
10		14.2	354	29.8	-9.6
20		14.1	354	29.9	-9.5
30		13.9	354	30.0	-9.4
40		13.7	354	30.1	-9.2
0	H-Plane	13.7	0	26.6	-11.7
10		13.6	359	26.7	-11.3
20		13.5	358	26.8	-10.3
30		13.4	357	26.8	-9.4
40		13.3	356	26.9	-8.6

security imaging, though fabrication tolerances (5% slot size variation causing 0.1 THz shift) demand precision. The 2×2 PCDA array, with 84% efficiency and 6.95–6.96 dBi directivity, reduces acquisition time by 75% via parallelized detection, supporting real-time imaging, but mutual coupling and laser costs remain challenges. The compact, lightweight (<3 kg) design ensures portability, contrasting with bulky conventional systems (~300 kg). Future improvements could include multi-layered FSS, graphene phase shifters, or larger arrays to further improves bandwidth, steering, and affordability for security and biomedical.

V. RESULTS

Presents the outcomes of the proposed terahertz (THz) imaging system, focusing on the performance of small-gap photoconductive dipole antennas (PCDAs), frequency-selective-surface (FSS) integration, and multi-antenna arrays for detecting concealed explosives. Simulations conducted using CST Microwave Studio demonstrate significant improvements in antenna-performance. The optimized small-gap PCDA, fabricated on a low-temperature-grown GaAs (LT-GaAs) substrate with a 5 μm gap, achieves a peak directivity of 10.9 dBi at 1.95 THz, surpassing conventional designs by 2–3 dBi. The integration of a dielectric superstrate reduces surface wave losses, boosting radiation

efficiency to 91.59%, compared to 70–80% for standard PCDAs. The silicon lens further enhances beam focusing, achieving a diffraction-limited spot size of approximately 300 μm , critical for high-resolution imaging of explosive materials like RDX and HMX, which exhibit distinct spectral signatures at 1.8–2 THz.

The FSS, designed as a single square loop on a polytetrafluoroethylene substrate, enhances directivity by 6.17 dBi at 1.95 THz, with a front-to-back lobe ratio of 12 dB, improving energy concentration on the target. Simulations show the FSS maintains stable resonance within 1–2 THz, with a 0.1 THz shift for a 5% slot size variation, highlighting the need for precise fabrication. The FSS-integrated PCDA achieves a signal-to-noise ratio (SNR) improvement of 8–10 dB over non-FSS designs, enabling clearer identification of concealed explosives in cluttered environments. The system's planar design ensures compactness, with a total thickness of less than 2 mm, suitable for portable security scanners.

The 2×2 PCDA array, with elements spaced at half-wavelength intervals (77 μm at 1.95 THz), achieves directivities of 6.95 dBi and 6.96 dBi in the E- and H-planes, respectively, with a radiation efficiency of 84%. Parallelized detection minimizes image acquisition time by 75%, capturing four pixels simultaneously, compared to single-antenna-systems requiring 2–3 seconds per pixel. The array's broadband response (0.2–3.4 THz) covers the spectral fingerprints of target explosives, and the silicon lens integration enhances depth-of-field for 3D imaging. In a simulated security setup, the system accurately identifies an RDX pellet beneath 2 mm of fabric, resolving spectral peaks at 1.8 THz with a 300 μm resolution.

Challenges include mutual coupling in the array, which reduces efficiency by 5–7% compared to isolated antennas, though mitigated by optimized spacing. Fabrication tolerances for the FSS and small-gap PCDA require precision to avoid resonance shifts or dielectric breakdown. The system's reliance on femtosecond lasers increases costs, but emerging fiber laser technologies could improve affordability. Overall, the results validate the proposed system's potential for real-time, high-resolution THz imaging, offering a compact, efficient solution for security applications with future scalability for larger arrays or advanced beam-steering techniques.

VI. CONCLUSIONS

The research detailed concludes that terahertz (THz) pulsed imaging systems, enhanced by optimized small-gap photoconductive-dipole-antennas (PCDAs), offer significant advancements for security applications, especially in identifying concealed explosives like RDX and HMX. By integrating a thin superstrate and silicon lens, the PCDA achieves a directivity of 10.9 dBi and 91.59% radiation efficiency, surpassing conventional designs. The incorporation of a frequency-selective-surface (FSS) further boosts directivity by 6.17 dBi, enabling precise beam focusing for high-resolution imaging. The 2×2 PCDA array enhances imaging speed by 75% through parallelized detection, achieving directivities of 6.95 dBi and 6.96 dBi in the E- and H-planes, respectively, with 84% efficiency. Beam steering capabilities, with 3° and 1° shifts in the E- and H-planes per 10° phase shift, ensure effective scanning for stand-off detection. The compact, planar design supports portability, making it ideal for security screening. Future enhancements could involve dielectric structures, plas-monic nano-islands, and graphene-based conductors to improve efficiency and tenability, broadening applications in biomedical imaging and material characterization. These advancements address limitations in SNR, resolution, and acquisition speed, establishing a robust framework for practical terahertz(THz) imaging systems.

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