Biological testing with terahertz focal-plane imaging based on a slot metamaterial sensor

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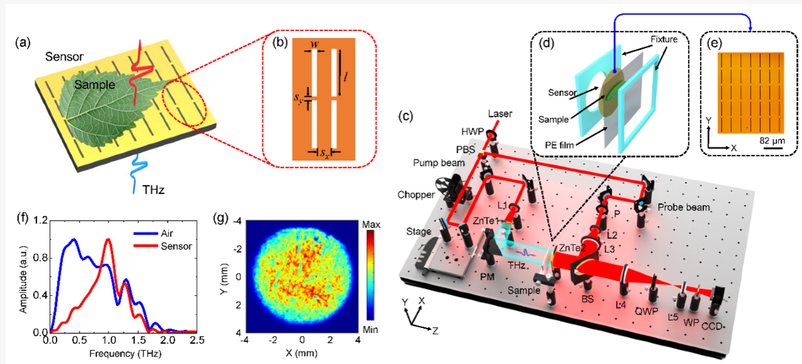
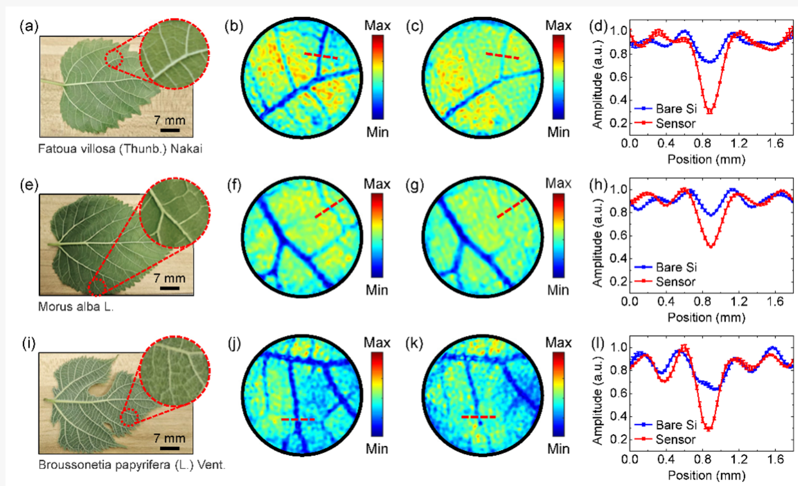
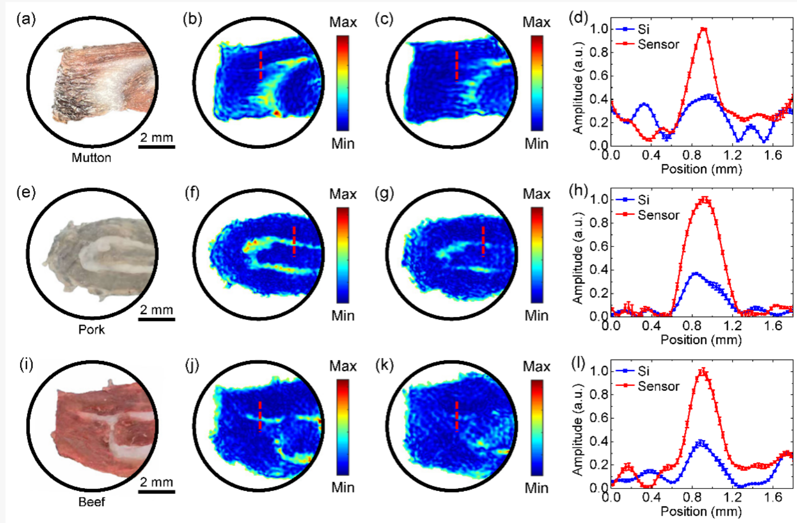


Schematic illustration of the THz focal-plane imaging system based on a slot metamaterial sensor.[



Comparison of THz imaging results of plant leaves obtained using the metamaterial sensor and a bare silicon substrate.

Terahertz (THz) radiation, located between the microwave and infrared regions of the electromagnetic spectrum, possesses unique properties such as low photon energy and strong sensitivity to water molecules. These characteristics make THz waves particularly attractive for biological sensing and non-destructive testing. In recent years, metamaterials—engineered structures with tailored electromagnetic responses—have been widely employed in THz biosensing due to their ability to generate strong localized field enhancement. By significantly amplifying the interaction between THz waves and biological samples, metamaterial-based sensors have demonstrated substantial improvements in detection sensitivity. Despite these advantages, most metamaterial-enhanced THz imaging systems rely on point-by-point scanning approaches. While such methods can provide enhanced signal contrast, they are inherently time-consuming and therefore impractical for large-area imaging or high-throughput biological analysis. This trade-off between imaging efficiency and enhancement capability remains a critical bottleneck in the field. To address this challenge, a slot-array metamaterial sensor was introduced into a THz focal-plane imaging system, thereby integrating metamaterial-induced field enhancement with parallel imaging acquisition. This strategy enables high-contrast imaging while dramatically reducing experimental time. Furthermore, by incorporating deep learning–based image processing techniques, the image quality and tissue differentiation performance were further enhanced. The proposed approach establishes an efficient and data-driven solution for THz biological testing, combining physical field enhancement with intelligent computational analysis.



Comparison of THz imaging results of animal tissues obtained using the metamaterial sensor and the bare Si substrate.

In this study, a THz focal-plane imaging platform based on a slot-array metamaterial sensor was developed, enabling rapid and high-contrast detection of biological tissues.

1. Integration of Metamaterial Enhancement with Focal-Plane Imaging
A slot-array metamaterial sensor resonant at 1.0 THz was designed and fabricated. Numerical simulations show that the structure generates pronounced localized electric-field enhancement at the resonance frequency, leading to a sensitivity improvement of up to 3.9 times. In experiments, biological samples were placed in intimate contact with the metamaterial surface, ensuring that the enhanced near-field region effectively interacted with the tissues. This configuration enables highly sensitive detection of subtle variations across different tissue regions.

2. The significant improvement of image contrast
Compared with a bare silicon (Si) substrate, the metamaterial sensor substantially strengthens the THz field–sample interaction, resulting in an approximately threefold increase in image contrast. This improvement was consistently validated in both plant and animal tissue samples. For three different plant leaves, THz amplitude images acquired using the metamaterial sensor clearly resolved primary veins, secondary veins, and mesophyll regions. In contrast, images obtained on a bare Si substrate failed to distinguish fine secondary veins. Cross-sectional profile extraction and statistical analysis further confirmed that the image contrast was enhanced by nearly a factor of three using the metamaterial sensor. A similar enhancement was observed in animal tissues, including mutton, pork, and beef samples. Under metamaterial-enhanced conditions, attenuation differences between adipose and muscle tissues became significantly more pronounced, leading to clearer structural delineation. Equally important, the focal-plane imaging configuration dramatically improved acquisition efficiency. Data collection time was reduced from approximately one day in traditional raster-scanning systems to less than 30 minutes, greatly enhancing the practicality and applicability of THz imaging technology.

3. Neural Network–Assisted Fine Tissue Segmentation

To further improve image quality, a multilayer perceptron (MLP) neural network model was implemented for automated tissue classification. Each pixel was represented by a 128-dimensional equivalent attenuation parameter (EAP) spectrum, serving as the input feature vector for the model. For both plant and animal tissue datasets, the classification accuracy reached 98%. After threshold segmentation and connected-component post-processing, tissue boundaries became more distinct and background noise was effectively suppressed. The contrast-to-noise ratio (CNR) showed a marked improvement compared with raw amplitude images. This data-driven framework not only enhances image contrast but also exploits the rich spectral information embedded in THz signals, enabling more refined tissue characterization. By integrating metamaterial-enhanced sensing with intelligent neural-network analysis, this work demonstrates a synergistic fusion of advanced electromagnetic design and computational imaging, paving the way for efficient, high-sensitivity THz biological diagnostics.

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Keywords: terahertz, metamaterial sensor, biosensing, focal-plane imaging, deep learning

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The research team is affiliated with the Key Laboratory of Terahertz Optoelectronics, Ministry of Education, Capital Normal University, and has long been committed to the development of THz imaging technologies and metamaterial-based devices. The first corresponding author, Prof. Xinke Wang, is a Professor and Ph.D. Supervisor in the Department of Physics at Capital Normal University. He received his Ph.D. degree in optics from Harbin Institute of Technology and joined Capital Normal University in 2011. His research focuses on THz pulsed imaging and THz metasurface devices. As corresponding author, Prof. Wang has published more than 40 peer-reviewed papers in leading journals, including Light: Science & Applications, Advanced Optical Materials, Optics Letters, Optics Express, and Applied Physics Letters. He has presided over six national and municipal research projects, and obtained four Chinese invention patents and one US invention patent. He has received three research awards and, over the past five years, has delivered more than ten invited talks at major national and international conferences.

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CN 51-1811/O4
Contact Us: oet@ioe.ac.cn
Twitter: @OptoElectronAdv (https://twitter.com/OptoElectronAdv?lang=en)
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