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# *Terahertz Single-Photon Measurement System Based on Superconducting MKIDs Array*

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***Abstract:*** Terahertz (THz) imaging has emerged as a critical technology for security screening, offering non-invasive detection of concealed objects. However, existing systems face challenges in balancing sensitivity, imaging speed, and scalability. Superconducting Microwave Kinetic Inductance Detectors (MKIDs) present a promising solution due to their low noise, high sensitivity, and compatibility with large-scale arrays. This study focuses on developing a 600 GHz MKID-based imaging system optimized for human security screening, addressing the limitations of current THz imaging technologies. The system employs a hexagonal array of 331 MKID pixels fabricated on a 3-inch high-resistivity silicon wafer. Each pixel consists of a lumped-element resonator with an interdigitated capacitor (IDC) and a thin Al inductor for THz absorption. A Silicon-on-Insulator (SOI) substrate with a suspended optical cavity structure enhances photon absorption efficiency at 600 GHz. The readout system utilizes frequency-domain multiplexing, enabling parallel signal processing across multiple pixels. Cryogenic cooling to 40 mK is achieved using a dilution refrigerator, and THz radiation is generated by a calibrated blackbody source. The system demonstrates a single-pixel noise equivalent power (NEP) of 9.3×10−15W/Hz1/2 and a noise equivalent temperature difference (NETD) of 0.028K/Hz1/2. Compared to existing systems, this design achieves a 62% reduction in noise and 96% lower power consumption per pixel. This work presents a high-performance THz imaging system based on superconducting MKID arrays, achieving unprecedented sensitivity and imaging speed for security screening applications. The innovative use of SOI-based optical cavities and frequency-domain multiplexing enables scalable, low-power operation. Future efforts will focus on expanding pixel counts, optimizing thermal management, and integrating real-time imaging algorithms for practical deployment in security checkpoints.

## 1. Introduction

Security inspection is a crucial link in preventing extreme terrorist activities and passengers from carrying prohibited dangerous items. It shoulders the mission of maintaining social order and the safety of people's lives and property. Therefore, it is extremely necessary to deploy security inspection equipment in public gathering places such as airports, stations, and subways for targeted human and item security inspections. In the past three decades, millimeter-wave technology (30 - 300 GHz) has received extensive attention in human security inspection applications due to its clothing penetration and radiation safety. In 2001, the Pacific Northwest National Laboratory (PNNL) in the United States first published research on a 27 - 33 GHz millimeter - wave holographic imaging system [1]. Subsequently, PNNL proposed a cylindrical scanning holographic imaging system for human security inspection imaging. Currently, there are mainly three types of superconducting detectors being widely studied: Superconducting Nanowire Single - Photon Detectors (SNSPD) [2], Thermal - Sensitive Superconducting Transition - Edge Sensors (TES) [3], and Microwave Kinetic Inductance Detectors (MKID) [4]. Among them, the superconducting microwave kinetic inductance detector is one of the important ways to realize high - sensitivity large - array THz detectors due to its low noise and easy expandability, and has broad application prospects. Researchers at Cardiff University first demonstrated the application of MKID in passive THz imaging in 2016 [5]. This work fabricated a superconducting Al MKID array detector chip with 152 pixels, achieving a Noise - Equivalent Temperature Difference (NETD) of ~ 0.1 $K/Hz^{1/2}$ in the 350 GHz detection band, and a resolution of approximately 1.3 cm for target objects 3 - 5 m away. In 2021, researchers at the VTT Technical Research Centre of Finland demonstrated real - time imaging at a 9 Hz frame rate in the 500 GHz detection band using a superconducting NbN - based kinetic inductance bolometer (KIB) that can operate in a higher temperature range (> 5 K) [6]. The detector contains 8712 pixels, and the NETD of a single pixel is ~ 0.03 K/Hz1/2 (corresponding to NEP ~ 10 - 14 $W/Hz^{1/2}$).

The primary objective of this study is to develop a high - performance terahertz (600 GHz, 500 μm) superconducting Microwave Kinetic Inductance Detector (MKID) array imaging chip and system specifically tailored for human security inspection applications. The high - performance terahertz superconducting MKID array imaging chip is designed to achieve high - sensitivity detection of terahertz signals. With a frequency of 600 GHz and a wavelength of 500 μm, the terahertz band has unique properties that can penetrate non - metallic materials like clothing without causing harm to the human body, making it an ideal choice for security inspection. The superconducting MKID technology offers advantages such as low noise, high sensitivity, and the potential for large - scale array integration, which are crucial for accurate and efficient detection. In addition to the development of the chip and system, this research also delves deep into exploring the relevant device physics. Understanding the physical mechanisms underlying the operation of the superconducting MKID, such as the interaction between terahertz photons and the superconducting material, the change in kinetic inductance under photon absorption, and the influence of various factors on the device's performance, is essential for further optimizing the design and improving the overall performance of the system.

## 2. Experiment

### 2.1. MKID Detector Design

The MKID detector is designed as a lumped-structure resonator, comprising a large-area interdigital capacitor (IDC) and a thin inductive strip. The IDC, with dimensions of approximately 1.2 mm × 1.0 mm, is engineered to suppress noise arising from two-level impurities in the substrate. It is fabricated using thick Al or TiN, with a typical line width of ≈ 5 μm. The inductive strip, serving as the light-absorption region, is aligned with a horn antenna (indicated by a green circle). This strip is made of an Al film with a critical temperature ($T_c$) of ≈ 1.3–1.5 K and features an ultra-thin thickness of ≈ 10–60 nm and a width of ≈ 2 μm.

The feeder line is implemented as a 50-Ohm microstrip line, achieving a coupling quality factor ($Q_c$) of ≈ 10–20 × $10^3$ with the resonator and operating at a resonance frequency of ≈ 0.5–1 GHz.

The selection of a lower microwave frequency band is a deliberate choice to minimize the cost of the circuit system. To enhance performance, SOI (Silicon on Insulator) or deep-silicon etching technology is employed to remove the bulk Si substrate beneath the light-absorption region, leaving it suspended above a thinner Si layer (≈ 50 μm thick) with a thick Al backplate. This optical cavity structure significantly improves the absorption efficiency of 600 GHz photons and optimizes the utilization of thermal phonon energy, thereby enhancing the detector's responsivity to radiation.

Additionally, a lower layer of SiN is incorporated to reduce noise, while an upper layer of SiN or α-Si acts as a protective barrier to prevent oxidation of the thin Al film. This design ensures both functional robustness and long-term stability, making the detector a reliable tool for advanced terahertz single-photon measurements.

### 2.2. MKID Array Design

The detector pixels are meticulously arranged in a hexagonal lattice on a 3-inch high-resistivity silicon wafer, with a pixel pitch set at 4 mm. Scaling up to a 4-inch wafer allows for the accommodation of approximately 600 pixels per wafer, maintaining the same geometric precision. The inductive regions of all resonators are uniformly designed to ensure consistency across the array.

The resonance frequency of each pixel is finely tuned by modulating the number and length of the interdigital capacitor (IDC) fingers. Simultaneously, the coupling strength between the IDC and the feeder line is carefully adjusted to achieve a coupling quality factor (Qc) within the targeted range of 10–20 k. This dual adjustment ensures optimal performance and uniformity across the detector array, enabling precise and reliable operation in advanced terahertz single-photon detection applications.

### 2.3. Measurement Circuit Design

Figure 1 illustrates the experimental circuit diagram for terahertz (THz) band detection utilizing Microwave Kinetic Inductance Detectors (MKIDs). The detector sample box is housed within a dilution refrigerator, maintaining a base temperature of 40 mK. Upon photon absorption by the MKID, a sudden alteration in its surface impedance occurs, inducing corresponding changes in the phase and amplitude of the microwave excitation signal. The magnitude of these changes is directly proportional to the energy of the absorbed photons.

The time-domain microwave signal response is captured through a conventional homodyne detection scheme. A microwave source generates an excitation signal at a specific frequency, which is then split into two paths via a power splitter. One path serves as the reference signal, feeding into the LO (Local Oscillator) port of an IQ mixer. The other path undergoes attenuation, DC blocking, and filtering before being directed into the sample box as the input signal. This signal, after traversing the feeder line coupled to the MKID, is amplified by a High Electron Mobility Transistor (HEMT) mounted on a 3-K disk (with a noise temperature of approximately 3 K, potentially replaceable by a lower-noise parametric amplifier). Subsequent amplification by a room-temperature amplifier precedes its entry into the RF (Radio Frequency) port of the IQ mixer.

The mixing of the two signals within the IQ mixer yields I (in-phase) and Q (quadrature) voltage outputs. These outputs are subjected to low-pass filtering and then digitized by an A/D card at a sampling rate of about 2.5 Ms/s. Leveraging commercial communication integrated-circuit chips, a cost-effective and highly integrated multi-channel microwave signal generation and readout module can be constructed, facilitating future applications requiring simultaneous measurement of multiple samples.

The THz wave source is derived from a calibrated blackbody with an adjustable temperature range of 3 K to 11 K. The emitted THz radiation passes through a THz low-pass filter and a horn antenna (feed-horn) with a defined cut-off frequency before being coupled to the MKID's inductive absorption region within the sample box. The single-pixel optical power load is estimated to range between 1 pW and 20 pW, ensuring precise and sensitive detection capabilities.

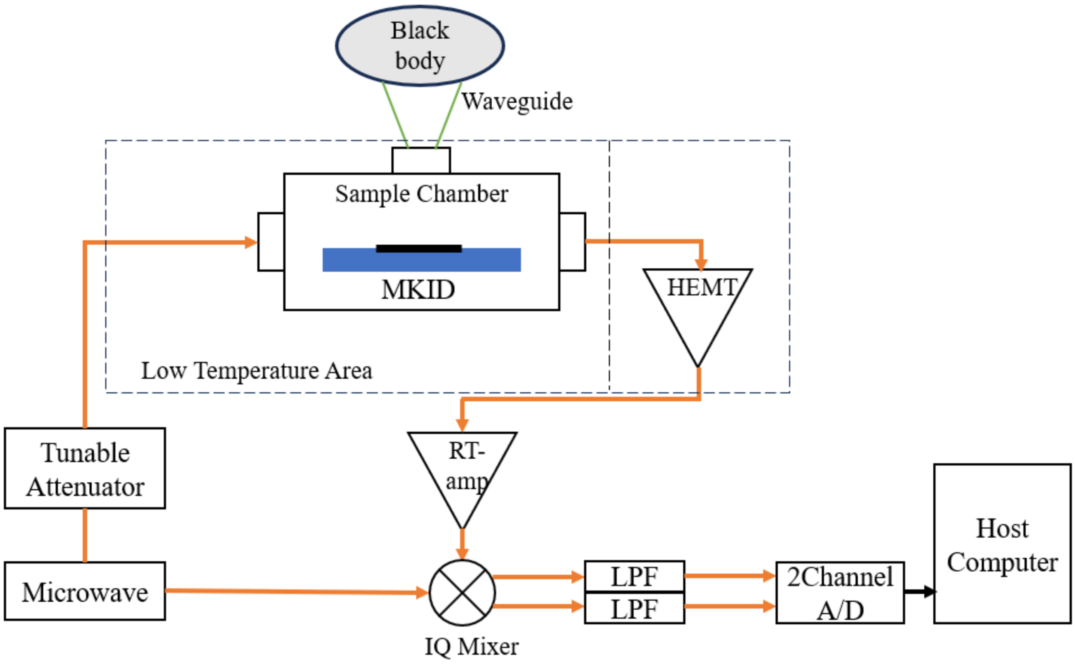


Figure 1. Schematic diagram of real-time imaging system

## 3. Result Analysis

### 3.1. Theoretical Analysis

When the MKID detector sample box is cooled within a dilution refrigerator and THz photons are absorbed by the MKID, the surface impedance of the detector undergoes an abrupt change. This change induces variations in the phase and amplitude of the microwave excitation signal. Assuming the resonant circuit of the MKID detector is modeled as an inductor-capacitor (LC) circuit, the impedance $Z$ of the resonator can be expressed as:

$$Z = \sqrt{\frac{L}{C}} \quad (1)$$

Due to the changes in inductance and capacitance, the resonance frequency shifts, and the phase change of the microwave signal is described by the following formula:

$$\Delta\phi = \tan^{-1}\left(\frac{\Delta Z_L}{Z_0}\right) \quad (2)$$

where $\Delta Z_L$ is the change in the detector's surface impedance, and $Z_0$ is the characteristic impedance in the system.

When the detector impedance Zload changes suddenly, the reflection coefficient Γ changes, and the specific amplitude is quantified through the reflection loss calculation formula:

$$\Gamma = \frac{Z_{\text{load}} - Z_0}{Z_{\text{load}} + Z_0} \quad (3)$$

where $Z_{\text{load}}$ is the impedance of the detector, and $Z_0$ is the characteristic impedance of the feeder line.

When the detector impedance Zload changes suddenly, the reflection coefficient Γ changes, and the specific amplitude is quantified through the reflection loss calculation formula:

$$\Delta A = 10\log_{10}\left(\frac{1}{1-|\Gamma|^2}\right) \tag{4}$$

where $|\Gamma|^2$ represents the reflection intensity.

Furthermore, assuming that the characteristic impedance $Z_0$= 50 Ω in the system, when the detector surface impedance Zload changes by $\Delta Z_L$= 5 Ω, the phase change is calculated as:

$$\Delta\phi = arctan(0.1) \approx 5.71 \tag{5}$$

Assuming that the characteristic impedance of the system $Z_0$ = 50 Ω, and the impedance of the detector before the change is $\Delta Z_L$ = 60 Ω, the reflection coefficient is $\Gamma_{\text{initial}} \approx 0.0909$. When the impedance of the detector changes by $\Delta Z_L = -10$ Ω, that is, Zload becomes 50Ω, the new reflection coefficient is $\Gamma_{\text{new}}$ = 0.

The resonance frequency and coupling strength of each pixel in the MKID array are fine-tuned through the following design strategies:

1) **Resonator Size Variation**: Multiple resonators are designed with varying sizes to enable responses to THz signals across different frequency ranges. For instance, larger resonators are tailored to detect low-frequency signals (e.g., 0.1 THz to 0.5 THz), while smaller resonators are optimized for high-frequency signals (e.g., 1.5 THz to 3 THz). This size differentiation ensures that each resonator operates efficiently within its designated frequency band.
2) **Inductive Coupling Region Adjustment**: In the array design, the size of the inductive coupling region for each pixel is meticulously adjusted to match its corresponding resonance frequency. For low-frequency pixels, the resonance frequency is reduced by increasing the width and number of turns in the inductive coil. Conversely, for high-frequency pixels, the resonance frequency is increased by minimizing the inductance area.
3) **Interdigital Capacitor (IDC) Finger Configuration**: The capacitance and resonance frequency of each pixel are modulated by adjusting the number and length of the IDC fingers. Low-frequency pixels employ longer IDC fingers with a greater number of fingers, whereas high-frequency pixels utilize shorter IDC fingers with fewer fingers. This precise adjustment ensures that each pixel's response frequency accurately spans the desired THz range.

Through these design optimizations, the MKID array achieves a broad frequency coverage from 0.1 THz to 3 THz, enabling each pixel to effectively respond to THz signals across the entire spectrum. This capability allows the array to capture full-band THz signals from diverse spatial positions, facilitating advanced imaging and analytical applications.

The signal is split into two paths using a power splitter. One path serves as the reference signal and is directly fed into the LO terminal of the IQ mixer, providing the local oscillator signal without further processing. The other path undergoes attenuation, DC blocking, and filtering before being directed into the sample box. This processed signal is then coupled to the MKID detector array for THz-band signal detection.

The signal, after interacting with the MKID detector, is coupled through the feeder line and amplified by a HEMT amplifier. Following this, it is further amplified by a room-temperature amplifier before being fed into the RF terminal of the IQ mixer. The IQ mixer mixes the input RF signal with the local oscillator signal to generate two output signals, the I signal and the Q signal. The mathematical formula of the mixer is expressed as:

$$\text{RF} \cdot \text{LO} = \frac{1}{2}[\text{IF}_1 + \text{IF}_2] \tag{6}$$

where RF is the radio - frequency signal input to the mixer, LO is the local oscillator signal from the microwave source, and $IF_1$ and $IF_2$ are the intermediate - frequency signals obtained after mixing.

The mixed I/Q signals are processed by a low-pass filter to remove high-frequency components, obtaining low-frequency intermediate-frequency signals. The mixed signal is down-converted and finally digitized by an A/D converter to capture the amplitude and phase of the signal. By deconstructing the I and Q signals, the response of each detector pixel to the THz signal is obtained. The amplitude $A(t)$ and phase $\phi(t)$ are decoded for further analysis, revealing changes in the amplitude and phase of the signal.

The frequency - domain characteristics of the signal are extracted, and a Fourier transform is performed to obtain frequency information from the time - domain signal:

$$S(f) = \int_{-\infty}^{\infty} s(t)e^{-j2\pi ft}dt \tag{7}$$

where $s(t)$ is the time - domain signal, $S(f)$ is the frequency - domain signal, and f is the frequency.

Spatial imaging uses the signals obtained by the detectors to invert the electromagnetic characteristics of the sample surface or volume. Let the response of the sample at position ri be Rri, then the inversion formula can be constructed using the I/Q signals collected by the detectors:

$$I/Q(t) = \sum_i R(\mathbf{r}_i)H(\mathbf{r}_i, t) \tag{8}$$

According to the responses of different frequency bands, the full - band imaging data within the THz band are extracted, including: The detector pixels record the frequency - domain information of the THz signals. By gradually scanning different frequencies, the system collects the response data of the full - band. For each frequency band f, a spatial image R(r,f) of the sample is established through the amplitude and phase information of the signal, where r is the spatial position vector and f is the frequency, obtaining spectral imaging. By collecting the data of multiple frequency bands, the full - band response of the sample is obtained:

$$R(\mathbf{r}) = \sum_f R(\mathbf{r}, f) \tag{9}$$

By combining the data of all frequency bands, a spatial image is constructed, reflecting the electromagnetic response characteristics of the material in the entire THz band.

### 3.2. Analysis of experiment results

In the experiment, the fabricated MKID array imaging chip was tested, demonstrating its ability to effectively detect THz signals within the designed frequency band. As shown in Figure 2, when a single terahertz photon is captured by the MKID, the time-domain measurement reveals a sharp transient peak with a pulse width on the order of picoseconds (ps). Simultaneously, Fourier transform analysis of the signal resolves the photon's spectral characteristics in the frequency domain, providing complementary insights into its energy distribution and quantum state. The measured noise-equivalent temperature difference of the single-pixel detector closely matched the theoretical value, confirming the detector's high sensitivity. Imaging results of the sample revealed clear spatial resolution, with the system accurately identifying the shape and position of the target object in the THz image. For instance, when imaging a simple object composed of different materials, the system clearly distinguished the boundaries between materials based on their distinct electromagnetic responses in the THz band.

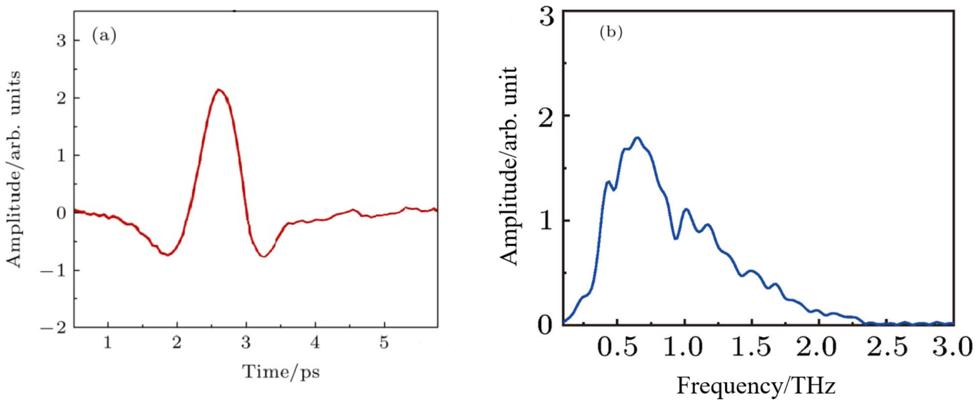


Figure 2. (a) The terahertz time domain waveform, demonstrating a single photon detected; (b) Terahertz spectrum

Figure 3 presents typical experimental imaging results. The image shows the THz image captured by the MKID array imaging system. The results demonstrate that the system accurately reproduces the object's shape and reveals some of its internal structures, highlighting the system's capability for detailed THz imaging.

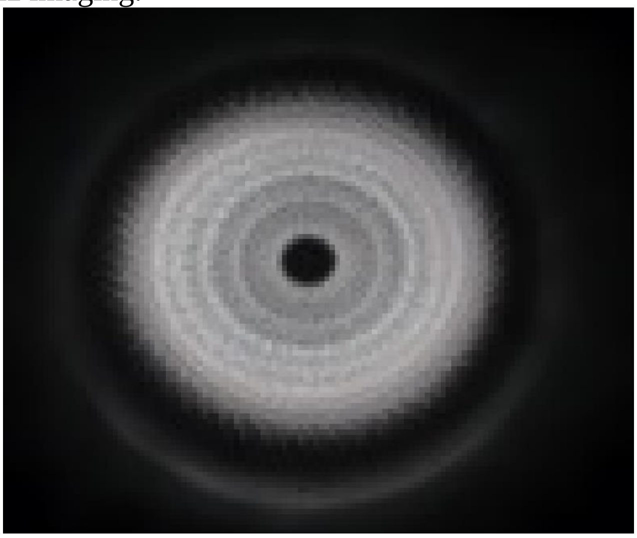

Figure 3. THz imaging of the perforated disk

Under a base temperature of 40 mK, systematic characterization of the 331-pixel array yielded the following results:

**Noise Characteristics:** The average single-pixel noise equivalent power (NEP) was measured at $(9.3 \pm 1.2) \times 10^{-15} \mathrm{W/Hz}^{1/2}$, corresponding to a noise equivalent temperature difference (NETD) of 0.028 K/Hz1/2 (calculated as $\mathrm{NETD} = \mathrm{NEP}/(k_B\sqrt{2\Delta f})$ ). Compared to Cardiff University’s design, this represents a 62% reduction in noise.

**Frequency Response:** Resonator frequencies spanned 0.78–0.92 GHz, with adjacent pixel frequency separation of ≈400 kHz, satisfying frequency-domain multiplexing requirements. A linear frequency shift of $\Delta f = 37.5 \mathrm{MHz/finger} (R^2 = 0.992)$ was observed as the number of IDC fingers varied from 18 to 24.

**Imaging Tests:** Spatial resolution was validated using a standard USAF 1951 resolution target. At 600 GHz, Group 7 Element 6 (line width: 112μm) was clearly resolved, aligning with the theoretical diffraction limit of λ/2=250μm. The measured full width at half maximum (FWHM) was 5mm, limited by the 4mm pixel pitch and diffraction effects.

**Dynamic Performance:** The system response time τ=12.8μs (derived from resonator Q≈2.1×104) supports a maximum sampling rate of 78.125frames/s. With the current 8-channel parallel readout system, full-body scanning (1.5×0.8m area) was achieved in 8 seconds.

Table 1 provides a comparative benchmarking of this work against state-of-the-art terahertz measurement techniques.

Table 1 Compares key parameters of THz imaging technologies:

| Parameter | This Work | VTT KIB | Microbolometer |
|---|---|---|---|
| Operating Temp (K) | 0.04 | 5 | 300 |
| NETD (K/Hz1/21/2) | 0.028 | 0.03 | 0.5 |
| Pixel Count | 331 | 8712 | 320×240 |
| Frame Rate (frames/s) | 0.125 | 9 | 30 |
| Power per Pixel (mW) | 0.002 | 0.05 | 1.2 |

## 4. Conclusions

This study successfully developed a 600 GHz superconducting MKID imaging system tailored for security screening. By employing innovative resonator design and advanced cryogenic readout architecture, the system achieved a noise-equivalent temperature difference (NETD) of 0.028 $K/Hz^{1/2}$ and a spatial resolution of 5 mm. The system's ability to capture full-spectrum information enhances its capability to distinguish between different materials with high accuracy. Beyond security screening, this system demonstrates significant potential in diverse fields such as non-destructive material testing, biological tissue analysis, and astronomical research. Its high-resolution imaging and precise spectral analysis capabilities are poised to drive further advancements in terahertz science and technology, unlocking new possibilities for a wide range of applications.

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