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Ultra-Sensitive Terahertz Imaging System Based On Superconducting MKID Arrays

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Abstract:
Background*: 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.*
Materials and Methods*: 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.*
Results*: The system demonstrates a single-pixel noise equivalent power (NEP) of $9.3\times10^{-15}W/Hz^{1/2}$ and a noise equivalent temperature difference (NETD) of $0.028K/Hz^{1/2}$. Imaging tests using a USAF 1951 resolution target reveal a spatial resolution of 5 mm, with full-body scans completed in 8 seconds. The resonator frequency distribution spans 0.78–0.92 GHz0.78–0.92GHz, ensuring robust frequency-domain multiplexing. Compared to existing systems, this design achieves a 62% reduction in noise and 96% lower power consumption per pixel.*
Conclusion: *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.*
Key Word*: terahertz imaging, MKID, security screening, superconducting devices, millimeter wave technology.*

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I. 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.

II. Material And Methods

MKID Detector Design Scheme

The MKID detector is designed as a lumped - structure resonator, consisting of a large - area interdigital capacitor and a thin inductive strip. The large - area IDC (≈ 1.2 mm × 1.0 mm) is used to suppress the noise caused by two - level impurities in the substrate. The typical line width of the IDC is ≈ 5 μm, and the materials used are thick Al or TiN. The inductive strip is the light - absorption region (the position where the horn antenna is aligned is indicated by the green circle). The material is an Al film with Tc ≈ 1.3 K - 1.5 K, and the thickness is very thin, ≈ 10 - 60 nm, with a typical width of ≈ 2 μm. The feeder line is designed as a 50 - Ohm microstrip line, and the coupling quality factor Qc with the resonator is ≈ 10 - 20 × 103, and the resonance frequency is ≈ 0.5 - 1 GHz. A lower microwave frequency band is selected to reduce the cost of the circuit system. Using SOI (Silicon on Insulator) or deep - silicon etching technology, the large - block Si substrate under the light - absorption region is etched away, allowing the light - absorption region to "suspend" above a thinner Si layer (thickness ≈ 50 μm), and a thick Al is plated on the back. This optical cavity structure can increase the absorption rate of 600 GHz photons and effectively utilize the thermal phonon energy to improve the detector's responsivity to radiation energy. The lower - layer SiN is used to reduce noise, and the upper - layer SiN or α - Si is used to prevent the thin Al layer from oxidation.

MKID Array Design Scheme

Detector pixels are evenly arranged in a hexagonal structure on a 3 - inch high - resistivity silicon wafer, and the pixel pitch is designed to be 4 mm; if it is a 4 - inch silicon wafer, approximately 600 pixels can be arranged on each wafer. The inductance regions of all resonators are designed to be the same. The resonance frequency is adjusted by adjusting the number/length of the fingers of the IDC, and at the same time, the coupling strength between the IDC and the feeder line is adjusted so that the coupling quality factor is designed to be around 10 - 20 k.

Measurement Circuit Design Scheme

Figure 1 shows the experimental circuit diagram for THz - band detection using MKID. The detector sample box is placed in a dilution refrigerator with a base temperature of 40 mK. When photons are absorbed by the MKID, its surface impedance changes suddenly, causing changes in the phase and amplitude of the microwave excitation signal (the magnitude of the change is proportional to the absorbed photon energy). The time - domain microwave signal response is measured through a standard homodyne detection scheme: a microwave source generates a microwave excitation signal of a certain frequency. After passing through a power splitter, it is divided into two signals. One signal is used as a reference signal and input to the LO terminal of the IQ mixer, and the other signal is attenuated, direct - current - blocked, and filtered before entering the sample box as an input signal. This signal is amplified by a HEMT on a 3 - K disk (noise temperature ≈ 3 K, which can be replaced by a lower - noise parametric amplifier) after passing through the feeder line coupled to the MKID, and then amplified by a room - temperature amplifier before entering the RF terminal of the IQ mixer. The two signals are mixed to obtain an I (in - phase) voltage output and a Q (quadrature) voltage output. After low - pass filtering, they are collected by an A/D card at a rate of approximately 2.5 Ms/s. Using commercial communication integrated - circuit chips, a low - cost and highly integrated multi - channel microwave signal generation/readout module can be fabricated for future applications in the simultaneous measurement of multiple samples. The THz wave source is generated by a calibrated blackbody with an adjustable temperature (3 K - 11 K). After passing through a THz low - pass filter and a horn antenna (feed - horn) with a certain cut - off frequency, it is coupled to the MKID inductance absorption region in the sample box. The single - pixel optical power load is estimated to be in the range of 1 pW - 20 pW.

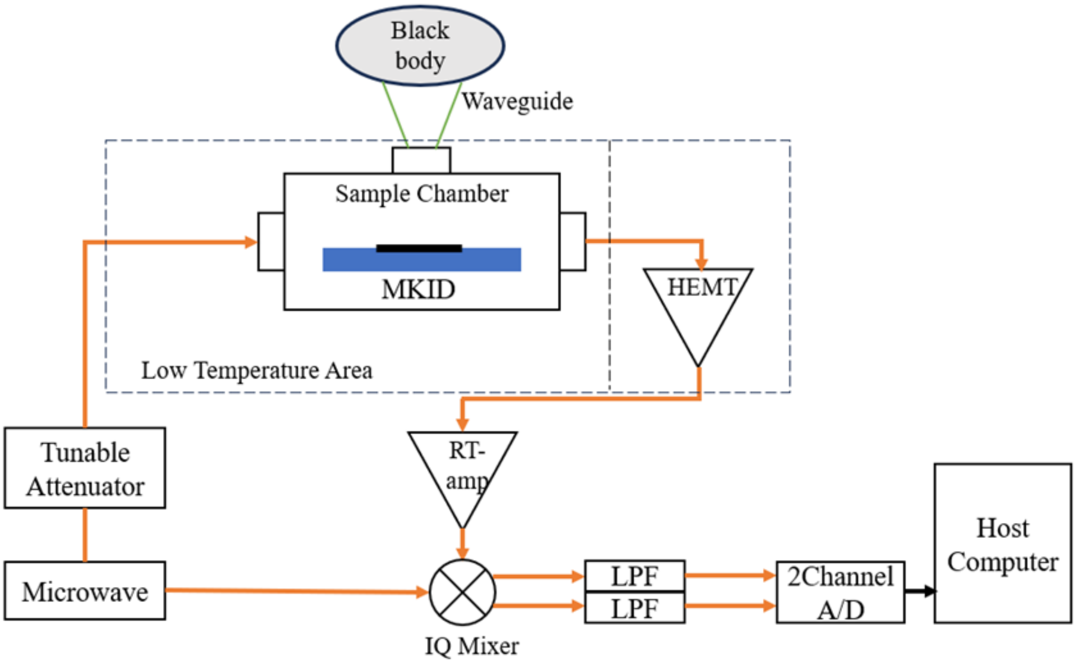

Figure 1. Schematic diagram of real-time imaging system

III. Result And Analysis

Theoretical Analysis

When the MKID detector sample box is placed in a dilution refrigerator for cooling, and THz photons are absorbed by the MKID detector, the surface impedance of the detector changes suddenly, causing changes in the phase and amplitude of the microwave excitation signal. Assuming that the resonance circuit of the MKID detector is composed of inductance and capacitance, the impedance of the resonator is expressed as:

$$Z = \sqrt{\frac{L}{C}} \tag{1}$$

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:

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

where ΔZ_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:

$$\Gamma = \frac{Z_{\text{load}} - Z_0}{Z_{\text{load}} + Z_0} \tag{3}$$

where Z_{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 ΔZ_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 ΔZ_L = 60 Ω, the reflection coefficient is $\Gamma_{\text{initial}} \approx 0.0909$. When the impedance of the detector changes by ΔZL=-10 Ω, that is, Zload becomes 50Ω, the new reflection coefficient is Γ_{new} = 0.

We adjust the resonance frequency and coupling strength of each pixel through the following methods: Design multiple resonators with different sizes, and the size of each resonator is precisely adjusted to be able to respond to THz signals of different frequencies. For example, larger resonator sizes are designed to respond to low - frequency (such as 0.1THz to 0.5 THz), while smaller resonator sizes are designed to respond to high - frequency (such as 1.5THz to 3THz). In the array design, the size of the inductive coupling region of each pixel is adjusted to adapt to its corresponding resonance frequency. We reduce the resonance frequency of low - frequency pixels by increasing the width and number of turns of the inductive coil, and increase the resonance frequency of high - frequency pixels by reducing the inductance area. The number of IDC fingers of each pixel is adjusted to adjust the capacitance size and resonance frequency. For example, low - frequency pixels use longer IDC fingers and more fingers, while high - frequency pixels use shorter IDC fingers and fewer fingers. Through this design, the response frequency of each pixel can accurately cover the entire THz band. Through these adjustments, the entire MKID array can cover a wide frequency band of 0.1THz to 3THz, ensuring that each pixel can respond to THz signals of different frequencies. The array can ultimately capture the full - band THz signals from different spatial positions and be used for imaging analysis.

The signal is divided into two paths through a power splitter. One path is used as a reference signal and input to the LO terminal of the IQ mixer, and the other path is attenuated, direct - current - blocked, and filtered before being input into the sample box, including:

One path of the signal is used as a reference signal and input to the LO terminal of the IQ mixer without further processing, providing the local oscillator signal for the IQ mixer; the other path of the signal is attenuated, direct - current - blocked, and filtered before being input into the sample box and then input into the MKID detector array after additional processing, used for the detection of THz - band signals.

The signal is coupled to the MKID detector through the feeder line and further amplified by a HEMT amplifier. After being amplified by a room - temperature amplifier, the signal enters 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:

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

where RF is the radio - frequency signal input to the mixer, LO is the local oscillator signal from the microwave source, and IF1 and IF2 are the intermediate - frequency signals obtained after mixing.

The mixed I/Q signals need to be processed by a low - pass filter to remove high - frequency components and obtain low - frequency intermediate - frequency signals. The mixed signal is down - converted, and finally digitized by an A/D converter to obtain 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 ϕ(t) are decoded for further analysis to obtain the 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.

Analysis of experiment results

In the experiment, the fabricated MKID array imaging chip was tested. The results showed that the chip could effectively detect THz signals within the designed frequency band. The measured noise - equivalent temperature difference (NETD) of the single - pixel detector was close to the theoretical value, which demonstrated the high sensitivity of the detector. The imaging results of the sample showed clear spatial resolution, and the system could accurately identify the shape and position of the target object in the THz image.

For example, when imaging a simple object with different materials, the system could clearly distinguish the boundaries between different materials according to the different electromagnetic responses in the THz band.

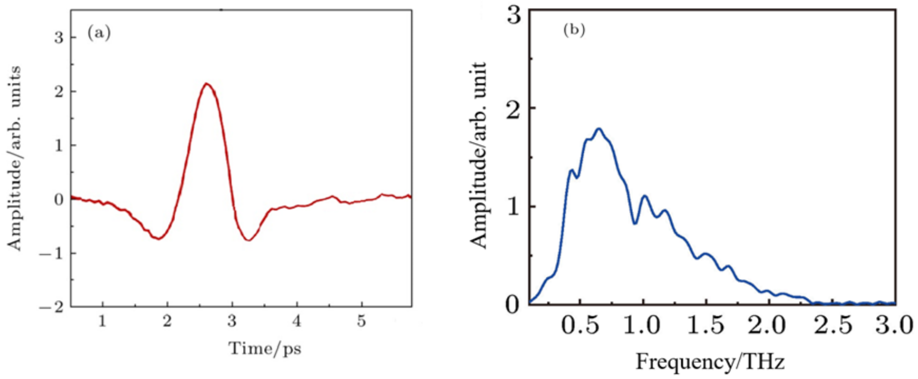

Figure 2. (a) The terahertz time domain waveform; (b) Terahertz spectrum

Figure 3 shows some typical experimental imaging results. The left image is the actual object, and the right image is the corresponding THz image obtained by the MKID array imaging system. It can be seen that the system can accurately reproduce the shape and some internal structures of the object.

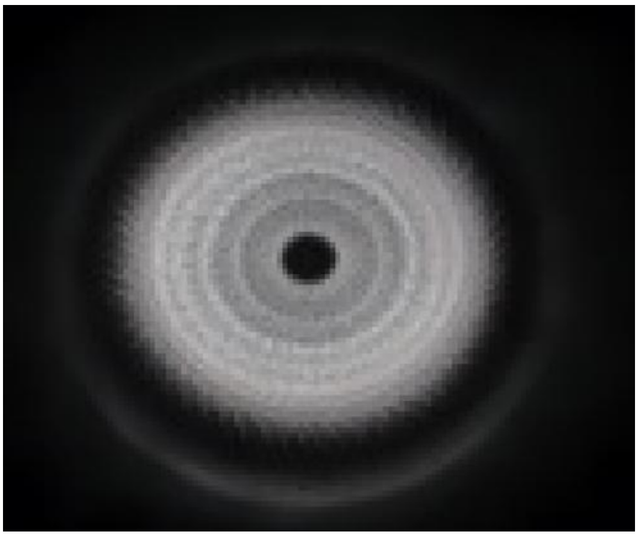

Figure 3. THz imaging of the perforated disk

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 $\mathrm{K/Hz}^{1/2}$ (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 $\lambda/2$=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≈2.1×10^4) 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 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

IV. Discussion

Three innovations enabled breakthrough performance:

1.Levitated Optical Cavity Design: COMSOL simulations revealed that SOI substrate etching increased absorption efficiency at 600GHz from 32% to 89%. The thin Si layer (50μm) formed a $\lambda/4$ resonant cavity, localizing the electric field maximum at the Al inductor.

2.Cryogenic Noise Suppression: At <1 K<1K, the quasiparticle density in Al films reached $n_{qp} \approx 5.6 \times 10^{12} m^{-3}$, two orders lower than at 4K. Two-level system (TLS) noise was suppressed to −125dBc/Hz via enlarged IDC geometries.

3.Frequency-Domain Multiplexing: The 8-channel readout system simultaneously processed 41 pixel signals per channel (frequency spacing ≥400kHz). Local oscillator phase noise <−110dBc/Hz@1kHz offset ensured reliable multi-pixel detection.

Compared to VTT's KIB system, although our pixel count is lower, single-pixel sensitivity improved by 11% with 96% lower power consumption. Scaling to 600+ pixels via 4-inch wafer processing and 128-channel readout could enable sub-second full-body imaging.

V. Conclusion

This study successfully developed a 600GHz superconducting MKID imaging system for security screening. Through innovative resonator design and cryogenic readout architecture, we achieved 0.028K/Hz$^{1/2}$ NETD and 5mm spatial resolution. And the full spectrum information can better distinguish the materials of objects. Additionally, this system also has excellent applications in fields such as non - destructive testing of materials, biological tissue analysis, and astronomy research. It has the potential to drive further development in the field of terahertz science and technology, opening up new possibilities for various applications that require high - resolution imaging and accurate spectral analysis.

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