Ultra-sensitive Balanced Receivers for Terahertz Sensing and Imaging

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***Abstract*— This report gives a brief overview of the outcomes of the project "Ultra-Sensitive Balanced Receivers for Terahertz Sensing and Imaging". This project seeks to investigate, develop, and demonstrate a quasi-optical, planar balanced hot-electron mixer/receiver system with broad RF bandwidth and ultrahigh sensitivity for terahertz (THz) imaging applications. The research activities and results including the investigation of broadband balanced mixer circuit, nano-scale hot-electron bolometer mixers, tunable THz antennas (for realizing tunable mesh filters) are presented in this report.**

***Index Terms*— Receivers, broadband antennas, balanced mixer, quasi-optical configuration, hot-electron bolometer, tunable antenna.**

I. Introduction

HETERODYNE THz detection has been proven a powerful tool in radio astronomy, remote sensing, security screening, spectroscopy, and medical diagnostics [1]. Mixers based on superconducting Hot-Electron Bolometers (HEBs) are widely used for terahertz (THz) sensing and detection owing to their advantages of high sensitivity, low noise, and low local oscillator (LO) power requirement. However, single-element HEB mixers may suffer from noise introduced by LO injection. Balanced mixers have potential to achieve lower noise temperature because of their capability to suppress the thermal noise and AM noise from the LO injection. Balanced waveguide HEB mixers have been reported recently, but waveguide mixers tend to have relatively narrow RF bandwidth, such that multiple mixers are needed for multi-band operations. Alternatively, we propose a quasi-optical balanced receiver employing broadband sinuous antenna and superconducting HEB devices, that is expected to provide both broadband operation (superior to waveguide mixers) and higher sensitivity (superior to single element mixers).

In addition to the ultra-sensitive broadband receivers, a frequency-tunable THz filter is also essential in realizing a multiband receiver front-end. THz filters based on metal mesh array, microelectromechanical systems (MEMS), and graphene metamaterials have been intensively studied, however, most of these filters cannot be tuned, which hinders their applications in multiband receiver systems. In this project, a prototype tunable annular-slot antenna (ASA), which can be used for realizing tunable mesh filters, has been demonstrated. A THz tunable mesh filter was proposed based on the tunable antenna elements. Simulation results for a G-band tunable mesh filter shows that a broad tuning range (e.g., over one octave) and high tuning speed can be expected.

Finally, in order to fully characterize the performance of the ultrasensitive multiband balanced receiver front-end, a cryostat RF testing system has been designed and constructed.

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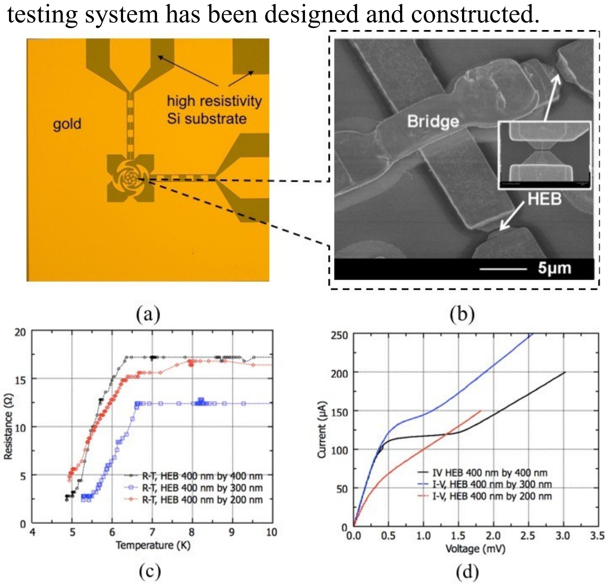

Fig. 1. (a) Optical picture of the fabricated balanced mixer circuit; (b) SEM picture of the air-bridge and nano-scale HEB devices. (c) R-T curves and (d) I-V curves for HEB devices with a length of 400 nm and width ranging from 200 nm to 400 nm.

II. Project Outcomes

The objective of this project is to investigate, develop, and demonstrate a quasi-optical, planar balanced hot-electron mixer/receiver system with broad RF bandwidth and ultrahigh sensitivity. Since the launch of the project in 2011, the first phase of the research activity has been focused on the design, fabrication and characterization of the THz broadband quasi-optical balanced mixer circuit, which has been accomplished before the application of the MTT-S graduate fellowship and resulted in a conference paper awarded the student paper prize in Asia Pacific Microwave Conference (APMC) [2]. Since then, the focus has been to develop the device processing technique for integrating and fabricating nano-scale superconducting niobium HEB mixers [3]. The HEB mixers were fabricated from superconducting niobium thin films. In order to achieve higher device performance, niobium thin film sputtering processes have been optimized, and high quality niobium thin films with critical temperature

(T_c) of 7.8 K and residual resistivity ratio (*RRR*) value of 2.3 have been fabricated. To achieve an impedance matching between the mixers and sinuous antenna, the dimensions of the HEB devices were designed based on the thin film sheet resistance and antenna embedding impedance. A novel polyamide/resist bi-layer photo-lithography process has been developed, permits the direct integration of two HEBs and an air-bridge into planar antennas to form a balanced mixer configuration as shown in fig. 1 (a) and (b). Nano-scale HEB devices have been fabricated employing electron-beam lithography (EBL) and reactive-ion etch (RIE) techniques. As shown in fig. 1 (c) and (d), device DC characterization results including resistance-temperature (R-T) and current-voltage (I-V) curves indicate that nano-scale HEB devices with T_c up to 6.1 K have been successfully fabricated.

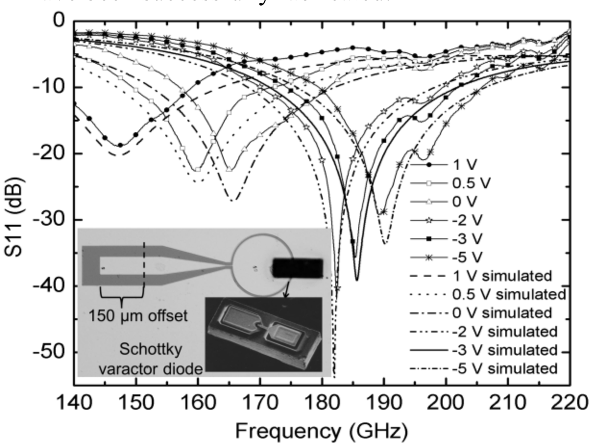

Fig. 2. (a) Measured and simulated return loss for the tunable ASA. Inset: micrograph of the fabricated tunable ASA circuit.

In order to achieve multiband receiver operation, electronically tunable THz mesh filters are needed at the receiver front-end. A prototype tunable annular-slot antenna (ASA), which can be used for realizing tunable mesh filters, has been developed and characterized [4], [5]. As shown in fig. 2 (inset), this single tunable ASA was loaded with a high speed Schottky varactor diode as tuning element. Measurement at G-band (140-220 GHz) has shown a frequency tuning range of nearly 50 GHz by varying the voltage bias of the Schottky varactor diode from -5 V to 1 V. This approach enables the development of a variety of tunable/reconfigurable THz circuits and components including tunable mesh filters, reconfigurable detectors and spectral-resolved focal-plane imaging arrays. A THz tunable mesh filter based on the tunable antenna elements was designed and simulated. Simulation result for the G-band tunable mesh filter shows that a broad tuning range (e.g., over one octave) and high tuning speed can be expected by employing the circuit and device techniques for single tunable ASA.

To fully characterize the performance of the balanced receiver front-end, RF measurements of conversion gain and noise temperature for single HEB mixers, balanced mixers and the entire receiver system need to be performed at multiple frequency bands in cryostat. As shown in fig. 3 (a) and (b), a quasi-optical testing block was designed and machined using oxygen-free copper for both single mixer and balanced mixers testing. A cryostat RF measurement system based on a liquid helium cooled open cycle infrared dewar was designed and constructed as shown in fig. 3 (c) (single IF chain). This cryogenic dewar allows the sample to be mounted onto a 4.2 K cold surface without direct contact with the cryogenic liquid. A THz window was installed for applying RF/LO signals to sample from the external of the dewar. The cryostat IF chain for mixer noise temperature measurement has been designed and installed. The RF measurement for the balanced mixers is still ongoing.

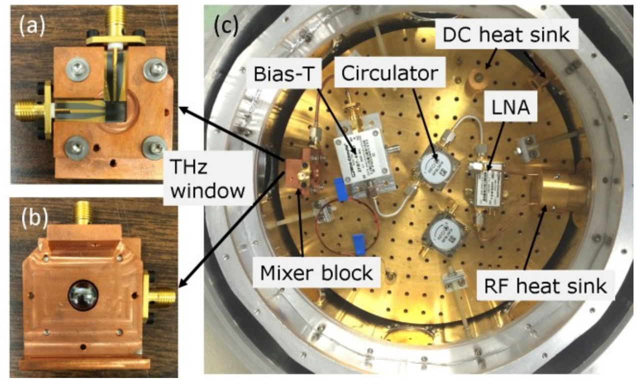

Fig. 3. (a) Back view and (b) front view of the quasi-optical balanced mixer testing block; (c) HEB mixers testing setup (single IF chain) in a cryostat open cycle dewar.

III. Conclusion and Future Work

In this report, we give a brief overview of the outcomes for the project "Ultra-Sensitive Balanced Receivers for Terahertz Sensing and Imaging". Prototype broadband balanced mixer circuits with monolithically integrated nano-scale HEB devices have been successfully fabricated. A tunable THz annular-slot antenna has been demonstrated at G-band, which enables the development of tunable mesh filters for receiver multiband operation. A cryostat measurement system has been designed and constructed for balanced mixer RF characterization. The RF measurement including mixer conversion loss and noise temperature for the entire balanced receiver system will be performed soon at multiple frequency bands.

Receiving the MTT-S graduate fellowship was really encouraging. In the next future, I plan to seek postdoctoral position to develop independent research capability in this field.

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