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Terahertz SIS Detectors for Space Applications

Shiwei Dong, Zhongbo Zhu, Ying Wang
National Key Laboratory of Space Microwave Technology
China Academy of Space Technology (Xi'an)
Xi'an, China
lldsw@126.com

***Abstract*—Many terahertz systems have been put forward and some of them even find ways in space. Radio astronomy is the most prospective domain where terahertz SIS detectors are employed. Fundamental of SIS is introduced and the detection system is overviewed. Some typical systems are depicted working in space with special requirements.**

Keywords-terahertz; SIS; radio astronomy; space

I. INTRODUCTION

Although terahertz (THz) gap has been existed for long, THz wave science and technology is expected to become one of the key fields of the 21st century [1]. As more and more researches are being carried out all around the world, much has been achieved in this field. Many terahertz systems have been put forward and some of the even find their way in space application.

The lack of good emission and detection techniques and devices has limited the development of terahertz technology. But still many prospective candidates have been explored [2-6]. Terahertz detectors will play an important role in many domains, such as radio astronomy and atmospheric research. So they are studied from various ways. Superconducting-Insulator-superconducting (SIS) is a main kind of terahertz detectors [6,7].

This paper is organized as follows. Fundamental is introduced in section II. SIS heterodyne detection systems are addressed in section III. In section IV a few typical systems are depicted working in space with special requirements.

II. FUNDAMENTAL OF SIS

Since a superconductor exhibits an energy gap of magnitude 2Δ, a quasi-particle with an energy $|E| < \Delta$ with respect to the Fermi energy in the superconductor on the left cannot tunnel into the right superconductor. Therefore no current can flow until the voltage is large enough for the quasi-particles to overcome the gap. At this voltage, the infinite densities of states are aligned, causing a steep current rise. From this voltage on the current increases approximately linear with voltage since the density of states also falls off rapidly to its normal state value for energies $|E| > \Delta$. The energy gap of Nb at 4.2 K is about 1.4 meV, therefore the "gap voltage" 2Δ = 2e at which the current rise occurs is 2.8 mV.

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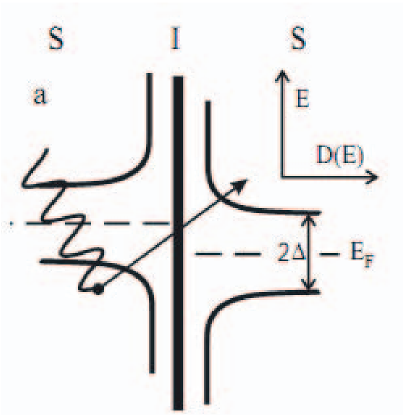

Figure 1. Energy band diagram of the SIS structure with an applied voltage.

A simple way to understand the concept of heterodyne mixing is to consider a non-linear element with a current-voltage performance as $I(V) = V^2$. Let's define the radiation and local oscillator signals as $V_{sig}(t) = V_S sin\omega_S t$ and $V_{lo}(t) = V_{LO} sin\omega_{LO} t$. Both signals imposed on the non-linear element, the resulting current is given by the following equation,

$$I(t) = V_{LO} sin\omega_{LO} t + V_S sin\omega_S t + V_{LO} V_S sin(\omega_{LO} - \omega_S)t + V_{LO} V_S sin(\omega_S - \omega_{LO})t \quad (1)$$

The terms including $(\omega_{LO} - \omega_S)$ and $(\omega_S - \omega_{LO})$ appear at the IF output.

In theory, an SIS junction serves as a mixing instrument until it is no longer nonlinear in light of the radiation. When the voltage modulation applied by the impinging signal is larger than the voltage nonlinearity of the SIS junction, it no longer mixes. Nb junction will in principle operate as a mixer up to 1400 GHz, twice the gap frequency of Nb. When the frequencies go beyond 1400 GHz, the superconductor material has to be replaced by those with larger energy gaps and therefore larger voltage nonlinearity, such as NbN. In fact NbN SIS junctions have been reported operating at up to 2.6 THz.

III. SIS HETERODYNE DETECTION SYSTEMS

SIS tunnel junctions have been in use since 1979 for their unequaled nonlinearity and low leakage current. The junction consists of two superconducting layers separated by an oxide layer of a few atoms thick, through which a current can flow via quantum mechanical tunneling of electrons. The superconductor commonly used is niobium, with a

superconducting transition temperature of 9.2 K. The major advantage is the sensitivity, which is unbeaten so far. Limitations are mainly posed by the large intrinsic capacitance, which calls for impedance matching methods which can introduce large absorption losses. The LO power required is much smaller than for Schottky diodes, enabling compact lightweight LO supplies for space applications. A further disadvantage is that the device needs to be cooled to 4 K to become superconducting and sufficiently nonlinear. This poses an upper limit on the lifetime in space operations.

Since the SIS consists of two superconductors separated by an insulator, an intrinsically large capacitance is formed which tends to shunt the incoming high frequency signal. To overcome this capacitance, an impedance transformation is used to convert the junction impedance with the large capacitive part to the real impedance of the probes. This is done with a transmission line technique. Obviously the larger the RF bandwidth is, the better. Since the bandwidth depends on the impedance mismatch, the junction area is chosen as small as practically possible to decrease the capacitance.

The SIS heterodyne detection system is as shown in Fig. 2. It always consists of quasi-optic components, a local oscillator, an SIS mixer, a digital signal processor and a cryostat.

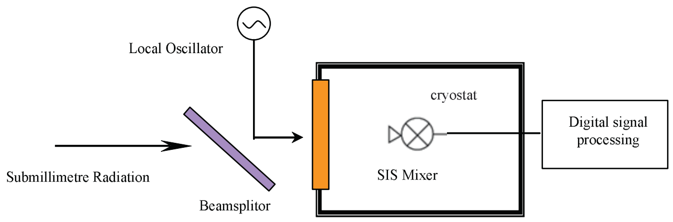

Figure 2. SIS heterodyne detection system.

Quasi-optic components are used to guide and focus terahertz wave. The beam-splitter, for example, can let through the radiation wave and reflect the local oscillator wave and guide both waves to the SIS mixer. There are several technologies of terahertz source for the local oscillator, such as up-conversion of microwave sources, gas laser, backward-wave oscillator, quantum-cascade laser (QCL) *etc.* Up-conversion is typically achieved using a chain of GaAs Schottky diode multipliers after a Gunn or impact ionization avalanche transit-time (IMPATT) diode. QCL technology is another promising way in space terahertz systems [8]. The digital signal processor is employed to sample the IF signal and analyze the power spectrum. The cryostat provide low temperature environment for the SIS junction.

IV. SIS Detectors for Space Application

The most prominent application of terahertz is sub-millimeter wave radio astronomy [8]. Spectrum of many interstellar molecules are located at terahertz band, some of examples are listed in Table I. Observing these spectrum man can carry research on the formation of planets, evolution of the galaxy and son on.

Some ground–based radio telescopes have been built around the world, such as ALMA and KOSMA. To cancel atmospheric absorption and get higher sensitivity, terahertz radio astronomy telescope has been advised to be mounted on space platform. Herschel, the fourth cornerstone of Horizon 2000 program of European Space Agency (ESA), was launched on May 14, 2009, as shown in Fig. 3. HIFI, the Heterodyne Instrument for the Far Infrared aboard as shown in Fig. 4, will be employed to study evolution of galaxies and star and planet formation by terahertz detection.

TABLE I. Spectrum of Interstellar Molecules

Interstellar Molecules	Frequency
O_2	487.249 GHz
N_2O	552 GHz
H_2O	556.936 GHz
HCl/ClO/HOCl	640 GHz
CO/CS	1 THz

Figure 3. Herschel space astronomy observatory.

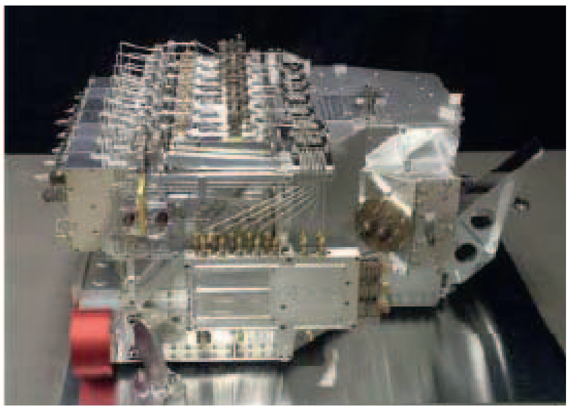

Figure 4. HIFI on Herschel.

HIFI is the Heterodyne Instrument for the Far Infrared led by SRON, Groningen, The Netherlands [9-11]. HIFI instrument consists of five major sub-systems. The focal-plane sub-system comprises the focal-plane unit (FPU) inside the cryostat. The local oscillator sub-system comprises the local oscillator unit (LOU) located on the outside of the cryostat. A wide-band spectrometer (WBS) consists of a pair of 4 GHz-wide Acoustics-Optical Spectrometers. A high-resolution

spectrometer (HRS) consists of a pair of auto-correlator spectrometers. An instrument control unit (ICU) within the SVM interprets commands from the satellite tele-command system, controls the operation of the instrument, and returns science and housekeeping data to the satellite telemetry system.

The mixers at the heart of the Focal Plane Unit largely determine the instrument's sensitivity. For this reason, the mixer technologies used in each band have been selected to yield the best possible sensitivity. In particular, a range of Superconductor-Insulator-Superconductor (SIS) mixer technologies are being used in the lowest 5 frequency bands (covering 480 - 1250 GHz).

HIFI band 5 mixers use Nb/AlN/NbTiN junctions normal metal wire and Nb ground planes on sapphire substrates with an integrated twin slot antennas shown in Fig. 5. The mixer devices are integrated in a quasi-optical mount with a 5 mm diameter lens. Receiver temperatures have consistently been under 1000 K in air without correction for windows, beam splitters or atmospheric attenuation.

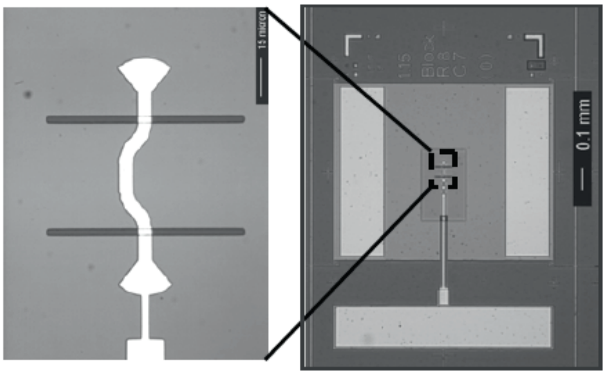

Figure 5. SIS device and an expanded view of the twin junction twin slot mixer circuit.

Atmosphere physics research is another domain in which terahertz may play an important role. When terahertz detectors carried by the space science satellite are faced to the Earth, atmosphere physics research can be taken in a wider area. Odin and Aura are satellites launched for such purpose.

V. CONCLUSIONS

The authors have attempted to survey the terahertz SIS detector and some of their space applications. As the technology improves it is likely that even more terahertz space SIS detection system will be proposed and employed. Many exciting proposals have already made their way into space agencies in the U.S.A., Europe and Japan. China also has now entered the space race with full passion and finds her way in space science. With those achievements of Herschel and Planck, ODIN, ALMA, APEX, scientists and engineers are filled with confidence.

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