Developing High-sensitivity Spectroscopic Technology for the Terahertz Band

Terahertz wave spectrum detection using a superconducting hot electron bolometer mixer

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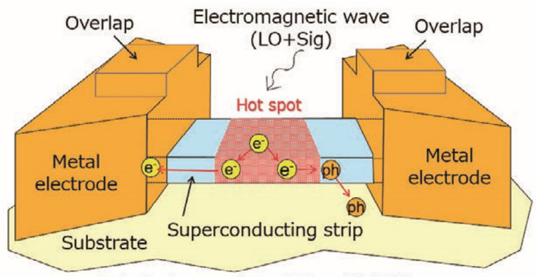
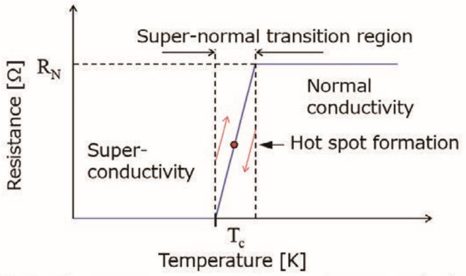
"Terahertz waves" refers to electromagnetic waves in a frequency range of 100 GHz to 10 THz, which includes some millimeter waves and infrared rays. It is a relatively unexplored frequency band which has not yet been fully developed and used. High-speed radiocommunication, non-destructive inspections, frequency standards, security, medicine, and earth atmosphere/astronomical observation are some of the areas that hold promise for terahertz applications. To make such applications a reality, it is essential to develop the platform technologies of oscillation and detection. There is still insufficient technological progress, particularly for terahertz frequencies exceeding 1 THz. This section will introduce a 2 THz band high-sensitivity spectrum detector (hot electron bolometer mixer) created and developed from devices through laboratory collaborations with the Terahertz Technology Research Center.



(a) Schematic of the HEBM



(b) Resistance–temperature characteristics of a superconducting strip.

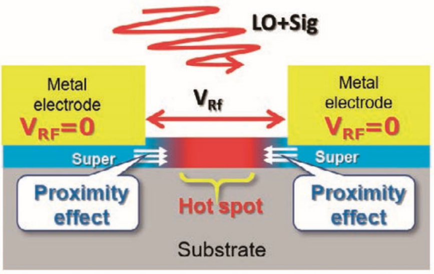
Figure 1 HEBM structure and operation overview

Terahertz band spectrum detection using a superconducting hot electron bolometer mixer

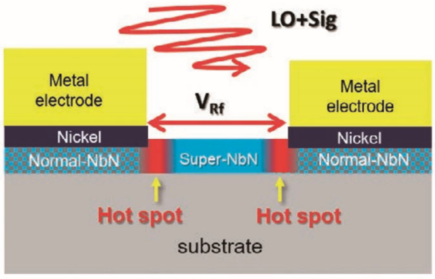
A superconducting hot electron bolometer mixer (HEBM), has a structure in which a microscopic piece of superconductive film (a superconductive strip) several hundreds of nm in length and width and less than 5 nm thick is placed between electrodes at a position corresponding to an antenna's power feed point (see Figure 1(a)). The mixer device uses strong nonlinear impedance produced when the superconductive strip transitions between superconductive and normal conductive states. Irradiating the HEBM with electromagnetic waves causes the electron temperature in the superconductive strip to rise, and a normal-conductive region (called a "hot spot") is formed in part of the superconductive strip in a temperature range exceeding the superconducting transition temperature (Tc) (see Figure 1(b)). When a local oscillation source (LO) along with a signal source (Sig) is used for the irradiated electromagnetic waves, the size of the hot spot is modulated according to the difference frequency (IF) signal component, and IF output can thus be obtained. The maximum operating frequency of the HEBM is limited only by its structure and dimensions, which makes mixer operations possible up to several tens of THz.

Novel hot electron bolometer mixer structure using magnetic material

Making bolometers smaller is normally useful in increasing detector sensitivity and achieving broader IF bands. However, there have been issues to be addressed when it comes to miniaturizing HEBMs. In the HEBM device structure, the metal electrodes overlap the superconductive strip in order to ensure reliable electrical contact between the strip and the electrodes (the "overlapping region" in Figure 1(a)). However, at this overlapping region, the superconductive strip is in a superconductive state even at normal mixer operating temperature, and furthermore is not directly suppressed by electromagnetic radiation due to being located under metal. The superconducting proximity effect from this region is thus expected to inhibit hot spot formation and reduce the sensitivity of the mixer. Attempting to make the device smaller will instigate superconductive bonding between the electrodes, which will instead negatively affect the mixer's performance (Figure 2(a)). We therefore proposed a new HEBM structure unique to NICT, in which a thin film of nickel (Ni)—a magnetic material—is inserted between the superconductor and metal electrode films. This Ni-HEBM, as it is called, suppresses superconductivity under the electrodes to ensure that only the superconductive strip between the electrodes remains superconductive (Figure 2(b)). We have already confirmed that superconductivity in a 5 nm-thick niobium nitride (NbN) superconductive thin film can be suppressed using a 0.6 nm ultra-thin Ni film. This structure makes it possible to further reduce the size of the HEBM, and is expected to be useful in improving the mixer performance by, for example, reducing LO power, increasing sensitivity, and broadening the IF bands.



(a) Conventional HEBM structure



(b) New HEBM structure using a magnetic thin film

Figure 2 Schematics of a conventional and a new HEBM structure

In the 2 THz-band Ni-HEBM we constructed, the length and width of the NbN strip were set to 0.1 and 0.5 μm, respectively. At 2 THz, and with input optical system loss corrected, the Ni-HEBM achieves a mixer noise temperature of Trx = 570 K (DSB), as well as an IF bandwidth of about 6.9 GHz which was improved around 3 GHz more than the bandwidth of HEBMs having a traditional structure, demonstrating the improved performance the Ni-HEBM structure provides (Figure 3). Unlike measurements taken thus far, these results (and especially the IF bandwidth result) were obtained at the actual operating temperature of 4 K, which is easy to recreate using a typical cryogenic refrigerator. As a terahertz band HEBM, the performance is considered among the highest in the world.

Examples of applications for terahertz-band high-sensitivity mixers

Terahertz-band mixers using this device provide high sensitivity, high-frequency resolution, and real-time operability, and can therefore be used in as general terahertz-band spectrum analyzers for a variety of applications. Using this receiver, we succeeded in the detection of an approximately several hundred nW-terahertz spectrum created from an optical comb and a uni-traveling-carrier photodiode (UTC-PD), the high-sensitivity detection of the radio wave spectrum emitted from methanol molecular gas, and so on. We also detected THz waves from a THz Quantum Cascade Laser, or THz-QCL, and verified phase locking of the THz-QCL using that signal. Furthermore, we have also started developing communication experiments using high frequencies exceeding 2 THz (see pp. 4-5), terahertz wave frequency standards (see pp. 6-7), and the like by applying these techniques.

Future prospects

Thus far, we have worked to develop an HEBM using a planar antenna, known as a "quasi-optical" type. We are currently working jointly with the Academia Sinica, Institute of Astronomy and Astrophysics (ASIAA), to develop a 2 THz-band waveguide-type HEBM as an even more advanced mixer with a cleaner beam pattern. The mixer is built on a 55 μm-wide, 800 μm-long, and 1 μm-thick silicon nitride thin-film bridge, which is supported by a 200 μm-thick silicon frame. The size (cross-section) of the waveguide is an extremely small 130 μm × 65 μm (WR - 0.51). As such, highly-precise microstructure creation, mechanical processing, advanced assembly techniques, and more are necessary.

Terahertz wave technology will continue to mature through the development—or actual application—of such receivers in areas such as remote sensing of the Earth's atmosphere, radio astronomy measurement, and so on from flying objects such as balloons or aircraft, or from space (e.g., high-sensitivity spectral measurement of trace amounts of molecules). We expect the technology to spread extensively to other fields in the future.

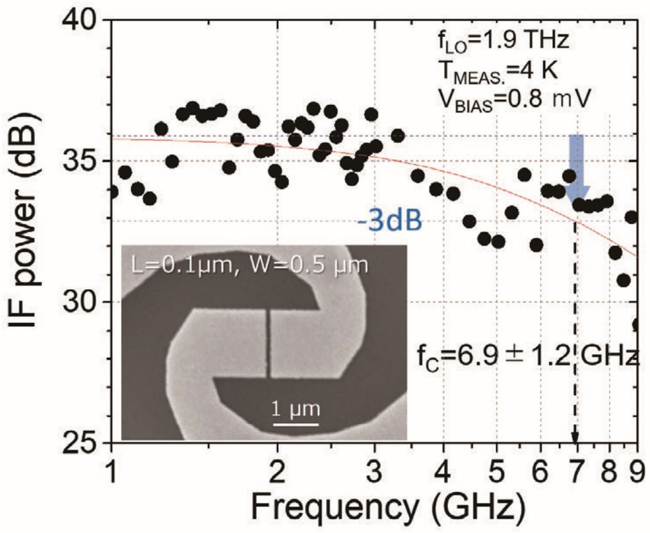


Figure 3 Measured IF bandwidth of a Ni-HEBM