A Millimeter Wave Detecting System Based on High Temperature Superconducting Device and Pulse Tube Cryocooler

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A millimeter (mm) wave broadband video detecting system based on high temperature superconducting (HTS) junction and compact pulse tube cryocooler (PTC) has been studied. The lowest attainable temperature of the PTC is 42 K and the operating temperature (T) can be adjusted by changing the pressure difference in the compressor. By measuring the linewidth of the Josephson oscillation as well as the dynamic range of the Josephson detector, it is found that the PTC has no excess noise compared with other kinds of cryostats such as liquid helium cryostats, and is very suitable for the applications in the mm wave detecting system. Furthermore, to improve the sensitivity of the system, the coupling efficiency of the system has been studied in detail. It is found that the coupling efficiency increases with the increase of $R_N$ linearly, and is better than 1% for $R_N$ of 1.7 Ω. A sensitivity of about 318 V/W has been obtained for the system based on the PTC and a junction with $R_N = 1.7$ Ω and $I_C R_N = 1$ mV.

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I. INTRODUCTION

Simple and compact detecting systems working at millimeter (mm) and sub-millimeter (sub-mm) wave bands are very desirable from the point of view of practical applications. Up to now, using high temperature superconducting (HTS) Josephson junctions (such as bicrystal junctions or other grain boundary Josephson junctions, GBJJs), broadband video detections of high frequency signals up to a few terahertz (THz) have been demonstrated, featuring high sensitivity and wide dynamic range [1–3]. However, most of the measurements are carried out in a liquid helium cryostat (LHC). Typically such a cryostat (for example, Infrared Lab., Inc., DHL-10) measures Φ290×H350 mm, and liquid helium should be refilled frequently to keep continuous operations. These hinder the wide applications of such detection systems. In recent years compact pulse tube cryocoolers (PTCs) with low noise and high cooling power have been developed quite rapidly [4]. Thus, replacing LHC with PTC seems a good solution, as the whole system will be made simpler and more compact. We have carried out thorough investigations on how a mm wave detecting system based on HTS device will behave once it is switched from LHC to PTC, and the main results will be reported in this paper.
FIG. 1: Photo of experimental set-up at mm wave band.

FIG. 2: Schematic diagram of experimental set-up as shown in Fig. 1.

II. EXPERIMENTAL DETAILS

The PTC (PDC08) with one-stage was made by Iwatani Industrial Gases Corp., Japan [4]. The cold head measures $\Phi 105 \times H 360$ mm and weighs 4 kg, providing a cooling power of about 15W at 77 K. Starting from room temperature, it takes about 30 minutes to reach the lowest possible temperature of 42 K. The operating temperature ($T$) can be adjusted by changing the pressure difference through a by-pass between the input and the output of the compressor (CA501). Also, to reduce the electrical interferences as much as possible,
the cold head of the PTC is carefully isolated from the compressor and the vacuum pump electrically. As there is no moving part in the cold head, the vibration is much less than that in other kinds of cryocoolers, without using any vibration absorbing system such as a plate of large mass. A Gunn oscillator at 98 GHz is the signal source, whose output level can be adjusted using a set of calibrated attenuators with a total attenuation of 90dB. Thin film YBCO on MgO bicrystal (24°) is ion-milled to form a junction plus a planar antenna; the normal-state resistance \(R_N\) of the junction is around 1 Ω and \(I_C R_N\) product is about 1 mV at \(T = 45\ K\), where \(I_C\) is the critical current of the junction. Fig. 1 shows the photo of the experimental set-up in detail. Via a waveguide, attenuators, and a horn antenna, the radiation from the source goes into free space. Then, using two parabolic mirrors and a Si hyperhemispherical lens with the diameter of 6 mm, the radiation is focused onto the HTS bicrystal junction via the planar antenna integrated with it. Analog electronics consisting of a dc-bias circuit and a low-noise preamplifier, which has the input noise voltage of about 2nV/Hz\(^{1/2}\), is used to measure the dc current-voltage \((I-V)\) characteristics of the junctions. The applied radiation is modulated by an optical chopper, and the voltage response across the junction is measured by a lock-in amplifier, whose measuring channel bandwidth \((B)\) is 1 Hz. The outputs of the preamplifier and the lock-in amplifier are connected to two separate digital multimeters, and then recorded by a personal computer through a GPIB interface. A detailed diagram for the measurement system is shown in Fig. 2. All measurements are carried out in a radio-frequency (RF) shielding room, but no \(\mu\)-metal or other dc magnetic shielding materials are used.

### III. RESULTS AND DISCUSSION

The basic principles of broadband video detection using Josephson effect were described elsewhere [2]. Briefly, when a weak RF signal at the frequency of \(f_S\) is applied to the junction, the \(I_C\) will be suppressed. If the radiation is modulated at a low frequency \(f_L\) and the junction is current-biased, the voltage across the junction changes also at \(f_L\). This is the so-called broadband response or non-selective response. On the other hand, due to the ac Josephson effect, Shapiro steps will appear, the first one at a voltage of \(V = \Phi_0 f_S\), where \(\Phi_0\) is the flux quantum. Obviously, it is frequency-selective response. The voltage response can be obtained near zero voltage as a peak and at \(V = \Phi_0 f_S\) as an odd-symmetric resonance.

The fabricated bicrystal junctions show typical resistively-shunted-junction (RSJ) behavior without excess current [1–2], thus enabling us to do some simulations and calculate the parameters from the measured data, such as the dynamic resistance \(R_D(V) = dV/dI = R_N[V^2 + (I_C R_N)^2]^{1/2}/V\), etc..

To check the noise properties of the detecting system mounted on PTC, the linewidth of the Josephson oscillation from the junction is measured and compared with that of the system when it is in a LHC. Fig. 3 shows the results measured by the video detecting method [5]. Obviously, there is no difference between the noise properties of these two systems, indicating that no excess noise is introduced by the PTC and thus confirming its
FIG. 3: Temperature ($T$) dependence of linewidth ($\delta f$) for same junction with the PTC and the LHC.

FIG. 4: Input mm wave power dependence of response for a junction with $I_C R_N = 150 \mu V$ at $T = 72$ K.

usefulness in constructing a simple and compact high-frequency detecting system.

The dynamic range of the detecting system has also been checked in detail. According to the RSJ model, the response should be proportional to the input power. At power level high enough, the response deviates from this linearity; and the high power limit of the dynamic range is defined as such a power level at which the deviation reaches 3 dB. On the other hand, the minimum detectable power level is the lower limit of the dynamic range. Fig. 4 shows the responses of the 1st Shapiro step, as a function of the input power in double logarithmic scale. The junction has $I_C R_N$ of $150 \mu V$ at 72 K and $R_N$ of 0.9 $\Omega$. The obtained dynamic range is about 38 dB.

If we use junctions of different parameters, or if we change the operating temperatures for the same junction, we can easily investigate how the dynamic range depends on the junction parameters. It turns out that the dynamic range is a constant of 38 dB, independent of the junction parameters. Instead, the dynamic range and the minimum
detectable power are determined by the input noise voltage of the preamplifier. Again, this means that the system with PTC has no excess noise for mm wave detectors. The minimum detectable signal (MDS) power level is $-88\text{dBm} (=1.6 \text{ pW})$ for a system with $I_C R_N = 150 \mu\text{V}$ working at $T = 72 \text{ K}$ (Fig. 4). As the bandwidth of the measuring channel is $B = 1 \text{ Hz}$, this minimum level is actually equal to the noise equivalent power (NEP) of $1.6 \text{ pW}/\sqrt{\text{Hz}}$. The dynamic range and the minimum detectable power can be improved by using a preamplifier of lower noise and operating at lower temperature. In this case, the dynamic range is one order larger or the minimum detectable power is one order lower, if the amplifier’s input noise voltage can be $0.2 \text{ nV/Hz}^{1/2}$.

For fast measurements, e.g. resolving of pulse structure signals [6], $B$ should be increased to a high value of about $1 \text{ MHz}$. Because the MDS is proportional to the root of $B$, the dynamic range will decrease with the same rule. So, the dynamic range will be still large enough (8 dB) for the system with $B = 1 \text{ MHz}$. That means our system can be expected to apply to fast measurements.

Furthermore, as the sensitivity ($S_S$) of the system is the product of intrinsic sensitivity ($S$) of the junction and coupling efficiency ($\kappa$) of the system, it is very important to know the parameter dependence of $\kappa$ and to make it as large as possible. Same as the dynamic range, using different junctions with different $R_N$, the $R_N$ dependence of $\kappa$ has been measured and shown in Fig. 5. We have found that there is a linear relation between $\kappa$ and $R_N$ for the system with planar log-periodic antenna. The higher $R_N$, the larger $\kappa$. Also, similar measurements have been carried out for the junctions integrated with Bow-tie antenna (angle of $45^\circ$). The data are plotted in Fig. 5 for comparison. As a result, system with the planar log-periodic antenna has the largest $\kappa$ for same value of $R_N$. According to the calculations, the impedance of log-periodic antenna has a lowest value of about $82 \Omega$ on MgO substrates. So the impedance mismatching between the antenna and the junction is
a main problem for $\kappa$. As $R_N$ is around 1 $\Omega$ typically and much smaller than that of the used antennas, it is necessary to find a suitable antenna with lower impedance and wider operating band for larger $\kappa$ as well as $S_S$. For a junction with $R_N$ of 1.7 $\Omega$, $\kappa = 1.06\%$ is obtained. So, $S_S$ will be about 318 V/W, as the $S$ is about 30,000 V/W for $I_C R_N = 1.0$ mV [1].

IV. CONCLUSIONS

Mm wave detecting system using HTS bicrystal junction has been successfully demonstrated using a compact PTC. Switching from a LHC to a PTC does not change the linewidth of the Josephson oscillation in the junction, nor the minimum detectable power and the dynamic range of the detector, indicating that no excess noise is introduced. The NEP of 1.6 pW/$\sqrt{\text{Hz}}$ has been obtained for the system with $I_C R_N = 150$ $\mu$V at $T = 72$K. The system sensitivity is dominantly affected by the impedance mismatching between the planar antenna and the junction. It is about 318 V/W for the system with a log-periodic antenna and a junction of $I_C R_N = 1$ mV and $R_N = 1.7$ $\Omega$.

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