THz-wave emission from inner $I$-$V$ branches of intrinsic Josephson junctions in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$

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Abstract. We have observed emissions of intense, continuous and monochromatic EM waves at THz frequencies from intrinsic Josephson junctions in the single crystalline Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ mesa structure, which take place deep inside the multiple branch structures of the current-voltage characteristics. We measured a rectangular groove-type mesa sample with a nearly square shape fabricated by focused ion beam milling. The detection of emitted THz-waves and the spectroscopic measurement by the FT-IR spectrometer for obtaining the radiation frequency were performed simultaneously during the current-voltage measurement. By sweeping the voltage on a particular branch, we have observed that the radiation frequency varied in a relatively wider range than expected from the conventional cavity resonance condition, and that the frequency obeys the ac Josephson relation, in which the Josephson frequency is universally proportional to the voltage. These experimental facts may provide us significant information to understand the mechanism of the THz-wave emission from intrinsic Josephson junctions in order to make use of them as useful THz sources for many practical applications.

1. Introduction
The discovery of intense, continuous and monochromatic sub-terahertz (THz, 1 THz=10$^{12}$ Hz) electromagnetic (EM) wave emission from single crystalline high $T_c$ superconductor Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi-2212) [1] has opened the door to the possibility of filling the “terahertz gap” in the EM spectrum [2]. In 1992, it was established that Bi-2212 behaves as a stack of intrinsic Josephson junctions (IJJ’s) showing the multiple branches in the $c$-axis current-voltage ($I$-$V$) characteristics [3]. In a single Josephson junction, application of dc voltage $V$ across IJJ’s led to an ac Josephson current and EM radiation with the same frequency, $f_J$, satisfying the ac Josephson relation, $f_J = 2eV/h$, where $e$ is the electric charge and $h$ is Planck’s constant [4]. The THz-wave radiation is induced by applying dc $V$ to the stack of IJJ’s in the small mesa structure [1, 5, 6, 7, 8, 9, 10, 11, 12]. In this system, each of junctions is naturally evenly spaced in the unit cell of Bi-2212 in the $c$-axis direction at intervals of 1.533 nm. In any geometrical mesa, it was confirmed that the three-dimensional mesa structure acts as an internal EM cavity [11]. Besides satisfying the ac Josephson relation, it was therefore consistently reported that the radiation frequency locked onto an internal cavity mode frequency.

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In this study, we found that the THz-wave emission can also take place in inner branch regions of multiple $I$-$V$ structures of the IJJ system. We investigated these emissions in detail in order to confirm the ac Josephson effect as a fundamental mechanism for generating THz-waves. By examining inner $I$-$V$ regions, we observed the radiation frequency $f_J$ can widely vary depending on the voltage $V$. The number of active IJJ’s during THz-wave emissions can be accurately estimated from the $V$-dependence of the radiation frequency, which may provide us valuable information on the synchronization of the stack of IJJ’s.

2. Sample preparation and experimental setup

Single crystalline Bi-2212 was grown by the travelling solvent floating zone method [13]. Strip-shaped crystals ($2 \times 10 \times 0.05$ mm$^3$) were annealed at 650 °C for 24 h in Ar mixed with 0.1% O$_2$ in order to obtain slightly underdoped crystals. A piece of a cleaved crystal ($1 \times 1 \times 0.01$ mm$^3$) was glued onto a sapphire substrate and silver and gold thin layers were evaporated onto it. Then, a groove of 10 μm in width was patterned around the terraced mesa by focused ion beam milling. Finally, a thin gold wire as an electrode was fixed onto the top surface of the mesa by silver paste. The actual dimensions of the mesa structures such as the width $w = 145$ μm, the length $\ell = 152$ μm, and the groove depth $d = 1.6$ μm were precisely measured by using an atomic force microscope. The number of IJJ’s in the mesa, $N_{\text{max}} = 1040$, can be estimated from $d$. The scanning ion microscope image and the schematic view of the mesa sample are presented in Fig. 1(a) and 1(b), respectively. The mesa sample was mounted on the cooled copper finger plate in the He-flow type cryostat. The bath temperature $T$ was monitored by the RhFe thermometer attached close to the finger plate. The EM wave emission was detected by a Si-bolometer. The radiation frequencies were measured by a Fourier transform infrared (FT-IR) spectrometer with a spectral resolution of 0.25 cm$^{-1}$, or ~7 GHz.

3. Experimental results and discussions

Figure 2(a) shows the $I$-$V$ characteristic of the mesa sample at $T = 35.0$ K. The contact resistance is subtracted in all $I$-$V$ characteristics presented in this paper. The outermost $I$-$V$ curve indicates that the stack of $N_{\text{max}}$ IJJ’s are in the resistive state simultaneously, i.e., $N = N_{\text{max}}$, where $N$ should be the number of the active IJJ’s. In Fig. 2(b), the current $I$ in the vertical axis common to Fig. 2(a) is plotted as a function of the radiation intensity detected by the bolometer. A dashed curve in Fig. 2(b) indicates the expected drift due to thermal radiation from the sample and the finger plate. By decreasing $I$ after the largest jump from $V = 0.14$ to 0.81 V, the intense emission of EM waves were clearly observed in the range between $I = 19$ mA and 8 mA.

Figure 3(a) shows the multiple $I$-$V$ branch structures at $T = 35.0$ K. Note that some parts of $I$-$V$ branches are not all shown here due to experimental difficulties. Figure 3(b) shows the
radiation spectrum measured by the FT-IR spectrometer at \( V = 0.821 \) V and \( I = 12.67 \) mA. In the spectrum a sharp peak at \( f_J = 0.52 \) THz is clearly observed, where \( f_J \) is defined as a central frequency of the spectral peak. The inset of Fig. 3(b) represents three inner \( I-V \) branches selected from Fig. 3(a).

In this study, we found that THz-wave emissions with various radiation frequencies \( f_J \) also occur at many \( I-V \) points even in inner regions of the multiple \( I-V \) branch structures, where \( N = 1, 2, \ldots, N_{\text{max}} \) is fixed but different for each branch. We therefore investigated the \( V \)-dependence of \( f_J \) by sweeping \( V \) on each branch, and the obtained result is presented in Fig. 4. In Fig. 4, three symbol colors common to that used in the inset of Fig. 3(b) indicate the respective branches. Three dashed lines indicate the ac Josephson relation, \( f_J = (2e/h) V/N \). The estimated values of \( N = 483, 624, \) and 760 are put beside the corresponding dashed lines in Fig. 4. From these analyses, we confirmed that the radiation frequency \( f_J \) always satisfies the ac Josephson relation. In this particular sample, 73% IJJ’s seem to contribute to the THz-wave emission, since the maximum value of \( N = 760 \) is 73% of \( N_{\text{max}} = 1040 \). This may be caused by the dip structure of the \( I-V \) curve around \( I \sim 20 \) mA shown in Fig. 2(a), which may give rise to the reduction of \( N \) on the outermost \( I-V \) curve.

![Figure 2](image1.png)

**Figure 2.** (a) \( I-V \) characteristics of the mesa sample at \( T = 35.0 \) K. (b) Current \( I \) versus the output intensity of emitted EM waves from the Si-bolometer.

![Figure 3](image2.png)

**Figure 3.** (a) Overall multiple \( I-V \) branch structures. (b) Radiation spectrum at \( V = 0.821 \) V and \( I = 12.67 \) mA. The inset shows representative \( I-V \) curves selected from \( I-V \) branches in Fig. 3(a).
4. Conclusions
In conclusion, we have investigated THz-wave emissions which occur in inner regions of the multiple I-V branch characteristics. By examining inner branches, the observed frequency can be tuned in a relatively broader range than expected from the cavity resonance condition. From the voltage dependence of radiation frequency, we have proved that the radiation frequency exactly obeys the ac Josephson relation. We then estimated the number of active IJJ’s during THz-wave emissions from fitting analyses, which may provide us the significant information on the synchronization mechanism of stack of IJJ’s for generating THz-waves.

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