Power enhancement of the high-$T_c$ superconducting terahertz emitter with a modified device structure

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Abstract. Continuous and monochromatic terahertz electromagnetic waves can be generated with sizable power ($\sim$30 µW) by the mesa-shaped device made of the high-$T_c$ superconductor $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$, by synchronizing the phase of the Josephson currents between multi-stacked intrinsic Josephson junctions. From the previous experimental results on the line width, spatial distribution of the emission, etc., we think that the relatively weaker power may originate from the partial failure of the phase synchronization of the Josephson currents in the mesa device. This may be improved by modifying the device structure to enhance the Josephson current density inside the mesa. In the present study, an array of four rectangle-shaped mesas with the dimensions of 80 µm×350 µm×3.2 µm was fabricated on a thin $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ single crystal, where several slots were made around the mesa by photolithography and chemical etching techniques in order to weaken electrical connection between mesa and superconductor base. The best result of the emission power for the array so far obtained is $\sim$80 µW at 0.42 THz, which is about 2.7 times bigger than the previous champion data in our group.

1. Introduction

Terahertz (THz) electromagnetic waves have attracted much attention as a new “light”, because they have huge potential applications to various fields such as spectroscopic analyses and identification of materials, non-destructive sensing and imaging for security, inspection of products and medicine, and high-speed communications, quantum computation, etc. [1]. The time domain spectroscopy technique (THz-TDS) becomes popular and used widely in spectroscopic research fields. However, applications of monochromatic THz waves are very limited so far because of lack of high-performance emitters and detectors. Monochromatic source is indispensable in spectroscopic research fields, and particularly in high-speed communications. Development of compact high-performance solid-state emitters, as well as highly sensitive detectors, at the THz frequency region are highly challenging topic of research.

High-$T_c$ superconductor $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ (Bi2212) is well-known to consist of a multi-stack of equivalent atomic-scale Josephson junctions (670 layers per 1 µm thick) commonly referred to as the...
intrinsic Josephson junctions (IJJs) [2]. The continuous and monochromatic THz electromagnetic waves whose frequencies obey the ac-Josephson effect can be generated with sizable power (∼30 µW), by passing dc current to IJJs to synchronize the phase of the Josephson currents between IJJs in the mesa-shaped device made of Bi2212 [3-5]. At present, the THz emission with frequencies beyond 2 THz can be generated, and the power of ∼1 µW at 1 THz can be obtained at 40 K [6]. It is also possible to generate a sizable power (∼2 µW) at 0.43 THz from the device cooled in liquid nitrogen [7,8]. As the power consumption of this device is enough low to work using a small battery, a compact cryocooler will be sufficient to cool this device. One of the main subjects is to increase the emission power of the devices to the level of 1 mW.

From the previous experimental results on the line width [9], spatial distribution [10,11] of the emission, etc., we think that one of the reasons of the relatively weak emission power may be due to the partial failure of the coherent phase synchronization of the Josephson current building up in the mesa device. According to the theory applied to the Josephson junction array oscillators for low-\(T_c\) superconductors [12,13], the line width is estimated to be ∼10 kHz at 50 K for the present device. However, the observed line width is about 23 MHz even at the best value [9]. In this device, it is known that an extremely inhomogeneous temperature distribution referred to as the hot-spot emerges at high bias currents [14-16]. This concentration of the superconducting quasi-particles originates from the instability on their flow due to the steep negative slope of the c-axis resistivity. Dynamic fluctuation due to this instability may be a cause of the broad line width. Actually, the emission line width has been observed to be strikingly improved after the hot-spot formation [9]. In addition, the Josephson current density inside the mesa may not be enough high to develop the phase synchronization between IJJs completely, because of good electric connection between mesa and superconductor base. Actually, Josephson current has been observed to leak out from mesas, from the fact that the THz emission is affected by external structures [17].

The Josephson current density may be improved by adjusting the impedance matching by simply modifying the device structure. In the present study, we have tried to control the electrical connection between mesa and superconductor base, by making several slots in the superconductor base around the mesa. In addition, we have tried to synchronize simultaneously four mesas which are made on a piece of Bi2212 crystal. Best result so far obtained is the emission power of ∼80 µW for the array of four mesas at 0.42 THz, which amounts to about 2.7 times more intense than the previous champion data in our group [5].

2. Experiment

2.1. Fabrication of Bi2212 mesa devices

Figure 1 (a) shows a photograph of the mesa device used for the present study. After a piece of a thin Bi2212 single crystal was glued on a sapphire substrate by thin polyimide, it was cleaved to ∼6 µm thick and was immediately deposited by Ag and Au films of 10 nm, respectively. Then, four mesas with an identical rectangular shape were etched by an argon ion milling technique using metal masks twice to determine the width first, then the length, second, of the mesa [18]. One of the mesas is highlighted by a yellow rectangle in figure 1 (a). They were arrayed with an interval of 80 µm, and the dimensions of each mesa measured by an atomic force microscope were 80±5 µm in width, 350 µm in length, 3.2 µm in height, and the thickness of the underlying superconductor was ∼3 µm. Finally, several slots as seen in figure 1 (a) were made in the superconductor base around each mesa by photolithography and chemical etching techniques [19].

In order to bias the mesa device, it was turned over and attached on plate electrodes of Au film with 0.5 µm thick, separated into two with 100 µm gap, on an alumina substrate, as shown in figure 1 (b). Two sets of mesas in which two mesas were connected in parallel were connected in series, as shown in the inset of figure 1 (c). Figure 1 (c) shows the temperature dependence of the mesa resistance measured by two terminal method at 100 µA. It is seen that the contact resistance between mesa and electrodes is negligibly small. The device structure is similar to the one which demonstrated the THz
emission in liquid nitrogen previously [7], where the Joule heat was removed not only from the thin superconductor base but also from the top of mesa. Because of the high heat removal efficiency and small heat generation due to the low contact resistance, the THz emission can be observed up to bath temperature $T_b=80$ K in this present array structure.

### 2.2. Measurements of THz-wave emitting characteristics

The mesa array was mounted on a copper finger cooled by a He-flow cryostat (Oxford Instruments, CF1104), and the temperature dependence of the resistance and the current-voltage characteristics ($IVCs$) were measured by a conventional two-terminal method. For the detection of THz emission, the same setup as the previous experiments was used for the direct comparison of emission intensity [5]. A lock-in technique was used with an InSb hot electron bolometer (HEB) detector (OMI Instruments, QF1/2B1) with a pre-amplifier gain of 1000 and an optical chopper with a frequency of 90 Hz. The InSb HEB detector has been calibrated using black body radiation, and the optical responsivity is 3.3 mV/nW. The emission spectra between 0.1 and 2 THz were measured by a Fourier transform infrared (FTIR) spectrometer (JASCO, FARIS-1) with the resolution of 8.0 GHz, using a TGS pyroelectric detector at room temperature. The THz wave from the mesa device was collected and guided to the FTIR spectrometer by a concave mirror.

### 3. Results and discussion

The $IVCs$ of the mesa device were measured by ramping up and down the bias current at $T_b$ from 30 K to 80 K, and the output voltages from the lock-in amplifier proportional to that of the HEB detector were simultaneously recorded. The THz waves emitted through the sapphire substrate were measured in the direction right above the sample. Figure 2 (a) shows the $IVC$ and the THz emission intensity as functions of the applied voltage and current, at $T_b=72.5$ K at which the emission intensity reaches at its maximum as seen in figure 2 (b). The emission intensity at its maximum is 2.7 times bigger than the previous champion data in our group [5], and the detected power is estimated to be 0.78 $\mu$W. Taking a value of 0.02 sr for the solid angle of detection and the attenuation factor of the cryostat window made of quartz glass of 0.75, the total power integrated, assuming a spatial distribution of the radiation power as seen in figure 4 in the reference [5], is estimated to be $\sim$80 $\mu$W.

Figure 2 (c) shows the emission spectrum from the mesa device (red curve) measured at $T_b=72.5$ K by an FTIR spectrometer with a TGS pyroelectric detector at room temperature. Note that the ordinate is plotted by the logarithmic scale. The peak intensity at 0.42 THz exceeds more than $10^3$ times in comparison with the detector noise. A broad and flat spectrum obtained from a mercury lamp (blue curve) is added for the comparison. Both measurements were performed with the same experimental set-up except for the data accumulation number as indicated in the graph. The emission frequency $f$ of 0.42 THz agrees with the cavity resonance frequency for the long rectangular mesa, $f_c=c_0/2nw$, where
Our previous investigation has shown that the harmonic peaks originate from the harmonic components of emission as well as the harmonic noise coming from the measurement apparatus. The number of active IJJs biased by voltage, \( N \), can be estimated from the ac-Josephson relation, \( f = \frac{2e}{h} \left( \frac{V}{N} \right) \), where \( e \) is the elementary charge, \( h \) the Planck’s constant, \( V \) the applied voltage where the THz emission occurs. The estimated \( N = 2500 \sim 2700 \) is slightly larger than 2100 estimated from the total number of IJJs in a mesa. This would mean that two mesas may be electrically connected in series and partially form one set of mesas with the Josephson voltage state. Actually, as seen later in figure 3 (a), the emission peaks are simultaneously observed up to two in one spectrum.

In figure 2 (b), it is interesting to point out that a sudden increase of the emission intensity starts above 65 K. The peak emission intensity at 72.5 K reaches 40 times larger than that at 65 K. Similar increase has been observed in previous results [5], although it was not so remarkable as present observation. Since the previous device also had a slot at each corner of the rectangular mesa, this sudden enhancement of the THz emission might be the effect of slots surrounding the mesas. It is known from the previous studies that the hot-spot does not appear above about 55-60 K [15], which means that the instability on the quasi-particle flow declines at high temperature. In addition to that, because the rf-current density may be enhanced by the effect of slots, the stronger phase synchronization of the Josephson currents may be induced in the direction of mesa length. The exact mechanism is still not clear yet, but this phenomenon may provide us a hint to enhance further the THz emission from the IJJ device. This mesa array emits the THz wave up to \( T_b = 80 \) K, just below superconducting transition temperature \( T_c = 90 \) K. This is due to the high heat removal efficiency of this device and the low contact resistance between the mesa and the electrodes. There may be further improvement on these points in the future.

Figure 3 (a) presents the emission spectra at \( T_b = 72.5 \) K measured at several bias currents. The FTIR spectrometer has an instrumental frequency resolution limit of 8 GHz. At higher current more than

\[ c_0 \] is the speed of light in vacuum, \( n \) the refractive index of Bi2212, and \( w \) the width of the mesa [3].
76.5 mA, emission peaks appear around 0.42 THz, but the peak jumps to 0.432 THz at 76.0 mA. Decreasing the bias current further, the emission line splits into two at 75.0 mA, and then only one peak with lower frequency survives at 74.0 mA. It is probably because the Josephson frequency may shift away from the cavity resonance frequency \( f_c \) of one of two mesas. The emission frequency, \( i.e. \), the Josephson frequency, must shift together with applied voltage in accordance with the \( ac \)-Josephson relation. Figure 3 (b) presents the peak intensities and the line widths by the full width at half maximum (FWHM) collected from the emission spectra data. The FWHM takes the minimum, when the spectrum splits into two peaks at 75.0 mA and the emission intensity takes its maximum at 78.0 mA. The values of FWHM are very close to the resolution limit of the FTIR spectrometer. That means that actual emission line widths must be much sharper than the resolution limit of 8 GHz. The results of figure 3 (a) and (b) suggest that the frequency pulling mechanism is working here between two mesas having slightly different \( f_c \)’s and as a result two mesas are synchronously coupled at 78.0 mA.

In summary, the new experimental results of THz wave emission are reported from a mesa device made of high-\( T_c \) superconductor Bi2212. The array structure of mesas with surrounding several slots were fabricated and tested. First of all, the emission power of \( \sim 80 \mu W \) at 0.42 THz is obtained. This power is about 2.7 times bigger than the previous champion data in our group. Secondly, in the temperature dependence of the emission intensity, a striking sudden enhancement of about 40 times is observed around 72.5 K. Proper understanding of this phenomenon may provide us a clue to generate higher power emission from the IJJ device.

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