

# High-power terahertz electromagnetic wave emission from high- $T_c$ superconducting $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ mesa structures

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**Abstract:** In this paper, we report intense electromagnetic wave emissions generated by the rectangular mesa structure of intrinsic Josephson junctions with high- $T_c$  superconducting  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ . The radiated power is an order of magnitude stronger than that of the previously observed power of a few  $\mu\text{W}$ . Two emission regions, reversible (R-type) and irreversible (IR-type), with comparable intensities can be observed at different  $I$ - $V$  curve locations in the same mesa. We find peculiar temperature dependences of the emission power in both the R- and IR-type radiations, suggesting that a non-equilibrium thermodynamic state may be realized through the  $dc$  input current. The R-type emission is quite stable, whereas the IR-type emission is rather unstable. Although the emitted frequency for both cases obey the cavity resonance conditions, this sharp contrast in emission stability is indicative of two different states in a multi-stacked intrinsic Josephson junction system.

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**OCIS codes:** (190.4720) Optical nonlinearities of condensed matter; (270.1670) Coherent optical effects.

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## References and links

1. R. Kleiner, F. Steinmeyer, G. Kunkel, and P. Müller, "Intrinsic Josephson effects in  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$  single crystals," *Phys. Rev. Lett.* **68**(15), 2394–2397 (1992).
2. G. Oya, N. Aoyama, A. Irie, S. Kishida, and H. Tokutaka, "Observation of Josephson junctionlike behavior in single-crystal  $(\text{Bi,Pb})_2\text{Sr}_2\text{CaCu}_2\text{O}_y$ ," *Jpn. J. Appl. Phys.* **31**(Part 2, No. 7A), L829–L831 (1992).
3. R. Kleiner, and P. Müller, "Intrinsic Josephson effects in high- $T_c$  superconductors," *Phys. Rev. B Condens. Matter* **49**(2), 1327–1341 (1994).
4. M. Tachiki, T. Koyama, and S. Takahashi, "Electromagnetic phenomena related to a low-frequency plasma in cuprate superconductors," *Phys. Rev. B Condens. Matter* **50**(10), 7065–7084 (1994).
5. T. Koyama, and M. Tachiki, "Plasma excitation by vortex flow," *Solid State Commun.* **96**(6), 367–371 (1995).
6. M. Tachiki, M. Iizuka, K. Minami, S. Tejima, and H. Nakamura, "Emission of continuous coherent terahertz wave with tunable frequency by intrinsic Josephson junctions," *Phys. Rev. B* **71**(13), 134515 (2005).
7. S. Savel'ev, V. Yampol'skii, A. Rakhmanov, and F. Nori, "Generation of tunable terahertz out-of-plane radiation using Josephson vortices in modulated layered superconductors," *Phys. Rev. B* **72**(14), 144515 (2005).
8. L. N. Bulaevskii, and A. E. Koshelev, "Radiation from a single Josephson junction into free space due to Josephson oscillations," *Phys. Rev. Lett.* **97**(26), 267001 (2006).
9. S. Lin, and X. Hu, "Possible dynamic state in inductively coupled intrinsic Josephson junctions of layered high- $T_c$  superconductors," *Phys. Rev. Lett.* **100**(24), 247006 (2008).
10. A. E. Koshelev, and L. N. Bulaevskii, "Resonant electromagnetic emission from intrinsic Josephson-junction states with laterally modulated Josephson critical current," *Phys. Rev. B* **77**(1), 014530 (2008).
11. A. L. Rakhmanov, S. E. Savel'ev, and F. Nori, "Resonant electromagnetic emission from intrinsic Josephson-junction stacks in a magnetic field," *Phys. Rev. B* **79**(18), 184504 (2009).
12. S. Savel'ev, V. A. Yampol'skii, A. L. Rakhmanov, and F. Nori, "Terahertz Josephson plasma waves in layered superconductors: spectrum, generation, nonlinear and quantum phenomena," *Rep. Prog. Phys.* **73**(2), 026501 (2010).

13. M.-H. Bae, H.-J. Lee, and J.-H. Choi, "Josephson-vortex-flow terahertz emission in layered high- $T_c$  superconducting single crystals," *Phys. Rev. Lett.* **98**(2), 027002 (2007).
14. E. Kume, I. Iguchi, and H. Takahashi, "On-chip spectroscopic detection of terahertz radiation emitted from a quasiparticle-injected nonequilibrium superconductor using a high- $T_c$  Josephson junction," *Appl. Phys. Lett.* **75**(18), 2809 (1999).
15. K. Lee, W. Wang, I. Iguchi, M. Tachiki, K. Hirata, and T. Mochiku, "Josephson plasma emission from  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_y$  intrinsic junctions due to quasiparticle injection," *Phys. Rev. B* **61**(5), 3616–3619 (2000).
16. I. E. Batov, X. Y. Jin, S. V. Shitov, Y. Koval, P. Müller, and A. V. Ustinov, "Detection of 0.5 THz radiation from intrinsic  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$  Josephson junctions," *Appl. Phys. Lett.* **88**(26), 262504 (2006).
17. V. M. Krasnov, A. Yurgens, D. Winkler, and P. Delsing, "Self-heating in small mesa structures," *J. Appl. Phys.* **89**(10), 5578 (2001).
18. L. Ozyuzer, A. E. Koshelev, C. Kurter, N. Gopalsami, Q. Li, M. Tachiki, K. Kadowaki, T. Yamamoto, H. Minami, H. Yamaguchi, T. Tachiki, K. E. Gray, W.-K. Kwok, and U. Welp, "Emission of coherent THz radiation from superconductors," *Science* **318**(5854), 1291–1293 (2007).
19. K. Kadowaki, H. Yamaguchi, K. Kawamata, T. Yamamoto, H. Minami, I. Takeya, U. Welp, L. Ozyuzer, A. Koshelev, C. Kurter, K. E. Gray, and W.-K. Kwok, "Direct observation of terahertz electromagnetic waves emitted from intrinsic Josephson junctions in single crystalline  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ ," *Physica C* **468**(7-10), 634–639 (2008).
20. H. Minami, N. Orita, T. Koike, T. Yamamoto, and K. Kadowaki, "Continuous and reversible operation of  $\text{Bi}2212$  based THz emitters just below  $T_c$ ," *Physica C* **470**, S822–S823 (2010).
21. H. B. Wang, S. Guénon, J. Yuan, A. Iishi, S. Arisawa, T. Hatano, T. Yamashita, D. Koelle, and R. Kleiner, "Hot spots and waves in  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$  intrinsic Josephson junction stacks: a study by low temperature scanning laser microscopy," *Phys. Rev. Lett.* **102**(1), 017006 (2009).
22. H. B. Wang, S. Guénon, B. Gross, J. Yuan, Z. G. Jiang, Y. Y. Zhong, M. Grünzweig, A. Iishi, P. H. Wu, T. Hatano, D. Koelle, and R. Kleiner, "Coherent terahertz emission of intrinsic Josephson junction stacks in the hot spot regime," *Phys. Rev. Lett.* **105**(5), 057002 (2010).
23. S. Guénon, M. Grünzweig, B. Gross, J. Yuan, Z. G. Jiang, Y. Y. Zhong, A. Iishi, P. H. Wu, T. Hatano, D. Koelle, H. B. Wang, and R. Kleiner, "Interaction of hot spots and THz waves in  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$  intrinsic Josephson junction stacks of various geometry," arXiv:1005.2341v1.
24. K. Kadowaki, M. Tsujimoto, K. Yamaki, T. Yamamoto, T. Kashiwagi, H. Minami, M. Tachiki, and R. A. Klemm, "Evidence for dual-source mechanism of THz radiation from rectangular mesa of single crystalline  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  intrinsic Josephson junctions," *J. Phys. Soc. Jpn.* **79**(2), 023703 (2010).
25. C. Kurter, K. E. Gray, J. F. Zasadzinski, L. Ozyuzer, A. E. Koshelev, Q. Li, T. Yamamoto, K. Kadowaki, W.-K. Kwok, M. Tachiki, and U. Welp, "Thermal Management in Large  $\text{Bi}2212$  Mesas used for Terahertz Sources," *IEEE Trans. Appl. Supercond.* **19**(3), 428–431 (2009).
26. K. E. Gray, A. E. Koshelev, C. Kurter, K. Kadowaki, T. Yamamoto, H. Minami, H. Yamaguchi, M. Tachiki, W.-K. Kwok, and U. Welp, "Emission of Terahertz Waves from Stacks of Intrinsic Josephson Junctions," *IEEE Trans. Appl. Supercond.* **19**(3), 886–890 (2009).
27. H. Minami, I. Takeya, H. Yamaguchi, T. Yamamoto, and K. Kadowaki, "Characteristics of terahertz radiation emitted from the intrinsic Josephson junctions in high- $T_c$  superconductor  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ ," *Appl. Phys. Lett.* **95**(23), 232511 (2009).
28. M. Tsujimoto, K. Yamaki, K. Deguchi, T. Yamamoto, T. Kashiwagi, H. Minami, M. Tachiki, K. Kadowaki, and R. A. Klemm, "Geometrical resonance conditions for THz radiation from the intrinsic Josephson junctions in  $\text{Bi}(\frac{2}{3}\text{Sr}_{2/3}\text{CaCu}_{2/3}\text{O}_{(8+\delta)})$ ," *Phys. Rev. Lett.* **105**(3), 037005 (2010).
29. M. Tsujimoto, K. Yamaki, T. Yamamoto, H. Minami, and K. Kadowaki, "Terahertz radiation generated from cylindrical mesas of  $\text{Bi}2212$ ," *Physica C* **470**, S779–S781 (2010).
30. K. Yamaki, M. Tsujimoto, T. Yamamoto, H. Minami, and K. Kadowaki, "Magnetic field effects on THz radiation from rectangular shape  $\text{Bi}2212$  IJJs," *Physica C* **470**, S804–S805 (2010).
31. N. Orita, H. Minami, T. Koike, T. Yamamoto, and K. Kadowaki, "Synchronized operation of two serially connected  $\text{Bi}2212$  THz emitters," *Physica C* **470**, S786–S787 (2010).
32. T. Kashiwagi at University of Tsukuba is preparing a manuscript to be called, "Geometrical full-wavelength resonance mode generating terahertz waves from a single crystalline  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  rectangular mesa."
33. T. Mochiku, and K. Kadowaki, "Growth and properties of  $\text{Bi}_2\text{Sr}_2(\text{Ca},\text{Y})\text{Cu}_2\text{O}_{8+\delta}$  single crystals," *Physica C* **235–240**, 523 (1994).
34. V. R. Misko, S. Savel'ev, A. L. Rakhmanov, and F. Nori, "Nonuniform self-organized dynamical states in superconductors with periodic pinning," *Phys. Rev. Lett.* **96**(12), 127004 (2006).
35. V. R. Misko, S. Savel'ev, A. L. Rakhmanov, and F. Nori, "Negative differential resistivity in superconductors with periodic arrays of pinning sites," *Phys. Rev. B* **75**(2), 024509 (2007).

## 1. Introduction

High-temperature superconductors are typically constructed from a stack of several intrinsic Josephson junctions (IJJs) because they have a peculiar crystal structure, in which the superconducting ( $\text{CuO}_2$ ) and insulating ( $\text{Bi}_2\text{O}_2$ ) layers are alternately stacked within a unit cell of the crystal [1–3]. A typical example is the well-known  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  ( $\text{Bi}2212$ ). Although, there have been theoretical suggestions proposing electromagnetic (EM) wave

emissions from this type of multilayered Josephson junction [4–12], the EM wave emission from high- $T_c$  superconductors has not been observed experimentally in more than ten years, perhaps because of the problems due to electrical contact, surface impedance mismatching, sample damage during the manufacturing process, the heating effect, and most likely, the quality of single crystals used for the experiments. There are few exceptions where low-intensity emissions have been detected [1,13–17].

Recently, strong, continuous, and monochromatic THz radiation [18] generated from rectangular mesas of  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$  intrinsic Josephson junctions (IJJs) 300  $\mu\text{m}$  long (for a long junction system), 40–100  $\mu\text{m}$  wide, and  $\sim 1$   $\mu\text{m}$  thick, and fabricated using an argon ion milling technique, has been successfully observed. Thus for, the emission mechanism can be understood as an *ac* Josephson effect along with a cavity resonance. Accordingly, the emitted frequency is inversely proportional to the width of the rectangular mesa,  $\nu = c_0/2nw$ , and proportional to the applied voltage,  $\nu = 2eV/hN$ . Here,  $\nu$  is the emitted frequency,  $c_0$  is the speed of light in a vacuum,  $n$  is the refractive index of  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ ,  $w$  is the width (shorter side of the rectangle) of the mesa,  $e$  is the free electron charge,  $V$  is the bias voltage along the *c*-axis of the mesa,  $h$  is Planck constant, and  $N$  is the number of resistive Josephson junctions. Moreover, the radiation power, as previously reported, is proportional to the square of the applied voltage, that is, the number of synchronized Josephson junctions. Therefore, increasing the number of synchronized emitting Josephson junctions is believed to be an effective way to achieve high-power emissions.

As shown in previous reports, the emission power itself was not very high, and the total emission power was estimated to be roughly 0.5–5  $\mu\text{W}$ , with an efficiency of 0.003–0.03% [18,19]. Powerful emissions of 1 mW are therefore desirable for realizing a compact solid-state THz generator application.

Emission stability is another key issue for practical applications. Minami *et al.* [20] discovered an additional emission type, which is much more stable than the previous one. The authors succeeded in characterizing this discovery using a direct detection of THz emissions through FT-IR spectroscopy. This new emission type occurs in a reversible region of an *I-V* curve, and is therefore very stable. It turns out that the frequency of emitted THz radiation obeys the cavity resonance mode similar to a previously observed emission [18,19]. This type of emission was named a reversible (R-type) emission, when compared with the previous irreversible (IR-type) emission found only in the return branch. Recently, Wang *et al.* also confirmed this type of emission, including a hot spot located inside the mesa [21–23]. In this paper, the output power of these two emission types are also compared. Recent experimental relevant works for emission from IJJs were reported elsewhere [24–32].

## 2. Preparation of mesas

Single crystals of  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$  were grown using the TS-FZ method [33]. The crystals were annealed under a reduced atmosphere in order to adjust the doping level to a slightly underdoped state, including a reduced  $T_c$  of 75–90 K and a sharp upturn behavior in the temperature dependence of the resistance above  $T_c$ . A piece of single crystal of a size (approximately  $1.0 \times 1.0 \text{ mm}^2$ ) sufficient for fabricating several mesas on an atomically flat surface was obtained through cleaving using Scotch tape. The crystal was glued onto a sapphire substrate using a PIX (HD Micro Systems, Ltd.) resin, and was then dried at a temperature of 353 K for 10 min. Rectangular-shaped mesas 400  $\mu\text{m}$  long, 40–100  $\mu\text{m}$  wide, and 0.7–2.1  $\mu\text{m}$  thick were fabricated using an argon ion milling technique as previously reported [18,19,24].

In this paper, the results of two samples, #A with dimensions of  $w = 80 \mu\text{m}$  and  $t = 1.1 \mu\text{m}$ , and #B with dimensions of  $w = 80 \mu\text{m}$  and  $t = 1.5 \mu\text{m}$ , are reported. Details of the technique and method used to make the electrical contacts have been described elsewhere [18,19,29]. The shape and dimensions of the mesa were checked using AFM measurements. As a result, it turns out that the fabricated mesas have a trapezoidal shape, with a considerable slope at their edges. The differences in width and length are about 13  $\mu\text{m}$  when measured at both the top and bottom of the mesas, corresponding to 15% and 3% of the total width and length.

Figure 1(a) shows a schematic view of the sample, where  $\theta_2$  is defined as the polar angle from the top of the mesa to the longer side of the rectangular surface (length), and  $\theta_1$  is the polar angle from the top of the mesa to the shorter side (width). An optical micrograph of the mesa (sample #A) is also shown in Fig. 1(b).

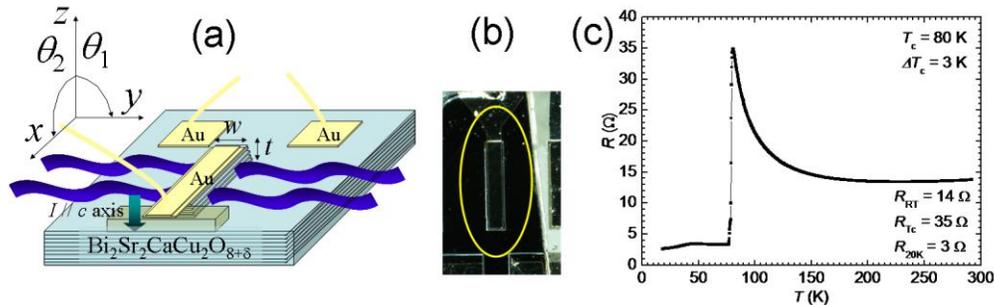


Fig. 1. (a) A schematic view of the mesa. Ag and Au are evaporated on top of the mesa, and the electrodes are fabricated on the mesa surface and single crystal substrate. The angles  $\theta_1$  and  $\theta_2$  are defined as shown in the figure. A current is applied along the  $c$ -axis. (b) An optical micrographic image of the mesa is shown inside the yellow oval. The length of the mesa is 400  $\mu\text{m}$ , and its width is 80  $\mu\text{m}$ . (c) The temperature dependence of the resistivity for sample (#A).

### 3. Results and discussions

#### 3.1 $R$ - $T$ measurement

The temperature dependence of the  $c$ -axis resistance ( $R$ - $T$ ) of the mesa (#A) is shown in Fig. 1(c). Sample #A showed a superconducting transition at 80 K with a width of  $\Delta T = 3$  K, which was broadened a few times from the original transition width after the mesa fabrication process. The resistance of the mesa at room temperature was 14  $\Omega$  and 35  $\Omega$  at just above  $T_c$ . The residual resistance was 3  $\Omega$  below  $T_c$  because of the contact resistance associated with the three-terminal measurement, and the ratio was  $R(\text{RT})/R(T_c) = 0.34$  (the residual resistance was subtracted). The corresponding values for sample #B were  $T_c = 89$  K,  $\Delta T = 2$  K, and  $R(\text{RT})/R(T_c) = 0.57$ .

#### 3.2 $I$ - $V$ characteristics and detection of emission

The  $I$ - $V$  characteristics of the mesas were measured simultaneously with the emissions. Typical examples for the R- and IR-types of sample #A are shown in Figs. 2(a) and 2(b), respectively, where the contact resistance is subtracted. It is interesting to note that both types of radiation (R and IR) can occur within different regions of the  $I$ - $V$  curve in the same #A sample, as seen in Fig. 2. The red points (line) indicate the signal of the Si bolometer used to detect the emissions. The bias voltage initially remains at zero with a linearly increasing current because of the superconductivity up to about 40 mA. The voltage then jumps suddenly to reach about 0.7 V. A further increase in current causes a reduction in the voltage, indicating a negative resistance behavior in this high current region, because of overheating of the mesa from the large  $dc$  current. A related type of negative resistance behavior in vortices in superconductors has been studied [34,35]. On the return, the  $I$ - $V$  curve does not trace the same route, and it shows a large hysteresis with a complicated jumping behavior, although the current is reduced at a constant rate. There may be two reasons for this hysteresis. One is due to the heating, and the other is due to the non-linear characteristic of the intrinsic Josephson junctions. The heating effect is rather obvious because the power fed into the mesa is on the order of  $10^6$  W/cm<sup>3</sup>, which cannot be removed in a time scale of measurements. This causes overheating, where the temperature becomes considerably higher than in the original superconducting state. This overheating behavior is clearly evidenced by the Si bolometer

detector, whose intensity gradually increases as the bias point moves to higher currents [18]. In this region, it is noted that the emission spectrum does not show any sharp peaks in the FT-IR spectroscopy, suggesting a black body radiation.

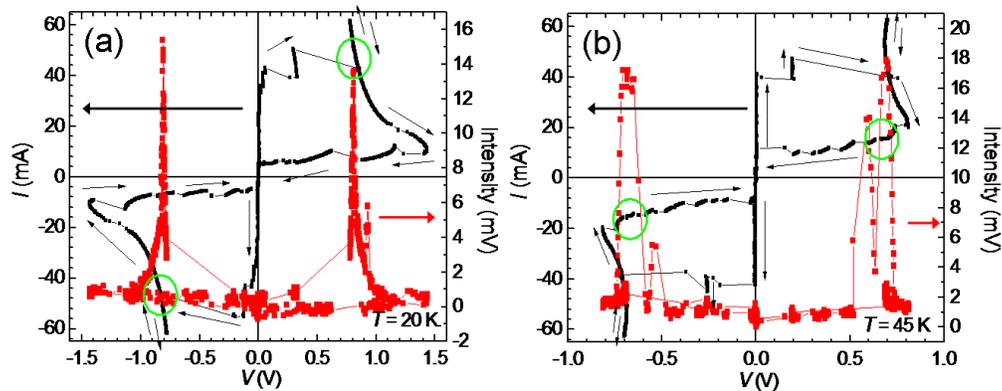


Fig. 2. Typical  $I$ - $V$  characteristics (black line) and detected radiation signals from a bolometer (red line) used to measure the (a) R- and (b) IR-type radiation. Temperature is measured at the sample holder. (a) An emission is observed near  $T_c$  in the resistive branch and is indicated by a green circle. The temperature at which the emission occurs is higher than that of the IR-type emission, and the emitted frequency obeys the cavity resonance of the width (shorter side of the rectangle). (b) An emission is observed in a re-trapping region in the return branch and is indicated by a green circle. The temperature at which the emission occurs is lower than that of the R-type emission, and the emitted frequency is governed by the cavity resonance and the  $ac$  Josephson relation. The contact resistance was subtracted for both cases.

In Fig. 2(b), an emission from the mesa was observed in the re-trapping region of the return branch at  $V = 0.7$  V, which is marked with a green circle on the  $I$ - $V$  curve. The corresponding  $I$ - $V$  curve has a very narrow stability range, where the emission power grows rapidly until it jumps to other modes. In some cases, the radiating branch splits into a few sub-branches, depending on the  $I$ - $V$  hysteresis curve; this is similar to previous reports [19,24].

In Fig. 3(a) we show the temperature dependence of the radiation power for sample #A. Note that the temperature is measured at the sample holder, and thus the actual temperature of the mesa may be considerably higher. This can indeed be estimated by extrapolating the normal state resistance down to the superconductivity region, and this rough estimation results in a reasonable value of the resistance obtained by the  $I$ - $V$  curve. The strong negative resistance behavior ( $dI / dV < 0$ ) in a higher current region actually originates from this heating effect, as seen Fig. 2(a). An R-type emission only occurs in a current region with a higher bias at below 35 K and shows a decreasing tendency as the temperature is reduced further to below 20 K. In contrast, an IR-type emission occurs in a current region with a lower bias at between 30 K and 60 K. Although the temperature regions are quite different, it is rather surprising that the maximum intensity is almost the same in both cases. Furthermore, according to the spectroscopic measurements, the emission frequencies are also almost identical in both cases. This can be accounted for by the cavity resonance with a  $\lambda/2$  standing wave mode in the width ( $w$ ) of the mesa. No resonance is observed in the length ( $l$ ) of the mesa. From a previous study on a slightly underdoped case, the Josephson plasma frequency of Bi2212 is known to be about 200 GHz. Since the excitation energy from the length of the mesa is less than 200 GHz, the cavity resonance condition for this longer side corresponding to the fundamental mode cannot be fulfilled.

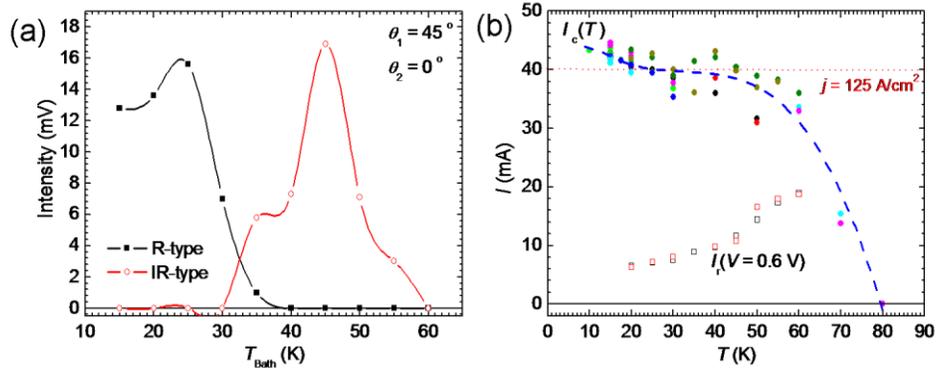


Fig. 3. (a) Bath temperature dependence of the emitted intensity detected by a Si-composite bolometer. The optimum bath temperature is about 25 K and 45 K for the R- and IR- types of emission, respectively. The maximum intensity of emission in both cases is almost the same. (b) Bath temperature dependences of  $I_c$  and  $I_r$ . Although  $I_c$  of our sample is almost constant at below 50 K,  $I_r$  gradually increases with an increase in bath temperature.

Figure 3(b) shows the temperature dependence of  $I_c$  and  $I_r$ , which is defined as the critical current of junction in the  $I$ - $V$  characteristics. In this paper, we define  $I_r$  as a re-trapping current at  $V = 0.6$  V. Although the value of  $I_c$  in our sample is almost constant below 50 K,  $I_r$  gradually increases with an increase in bath temperature. This may be related to the suppression phenomenon of the IR-type radiation below approximately 30 K in this particular intrinsic Josephson junction system.

### 3.3 Observation of highly intense emission

Recently, we succeeded in the fabrication of a much more powerful THz emitting mesa by improving the sample fabrication technique, including the methods of electrode connection and heat removal from the sample. An interesting and novel observation in both samples is that the emission power greatly increases by approximately several-to-ten times the previous level, as shown in Fig. 4. Although the reason for this power enhancement is unclear, we attribute it to a technical improvement in the mesa manufacturing process. The most significant fact is that the  $I$ - $V$  curve shows a very complicated shape. It seems that a strong radiation occurs within a very narrow and unstable window, which is quite different from the previous radiation. Sometimes, such a mode is skipped, and the  $I$ - $V$  curve does not enter into radiation mode.

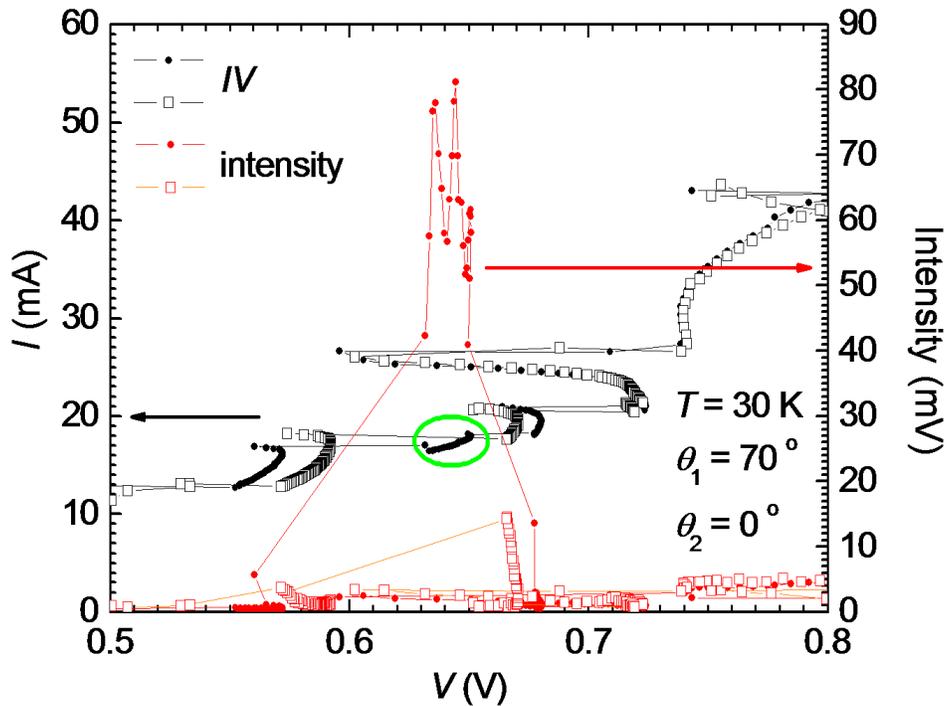


Fig. 4.  $I$ - $V$  characteristics and emission intensity detected by a Si-composite bolometer. An intense emission is observed at  $V = 0.644$  V, which is indicated in the green circle. This output power is increased considerably by a factor of 6–8 times that shown in previous reports.

### 3.4 FT-IR measurements

FT-IR spectroscopy measurements were also carried out for both intense and ordinary types of emission, and are shown in Fig. 5. The intensity was normalized by the maximum intensity of each type of emission, as shown in the figure inset. The frequencies are 0.49 and 0.43 THz for the ordinary and intense emissions, respectively.

The difference in the emitted frequency of the two modes may be explained as follows. The frequency of ordinary radiation resonates at the top side of the mesa width. On the other hand, the new intense emission resonates at the bottom side. The percentage of this difference in emitted frequency, 15%, corresponds to the difference in width between the top and bottom of the mesa. As a result, the cavity resonance condition is fulfilled in both cases.

An interesting point is that the full width at half maximum (FWHM) for an ordinary emission of sample #A is about 3 times broader than that of an intense emission; that is, despite both spectra being from the same mesa, their line shapes are different. It seems that the broad FWHM for an ordinary emission may be composed of second lines closely located along the main line. This appears more clearly at the 2nd harmonics line and is a much more broadened line than the one located at the 2nd harmonics line in the intense emission.

The intensity of emission,  $S$  (arbitrary unit), is estimated based on the integration of the spectrum area. The value of  $S$  ordinary, which is 14.5, is compared with the 81.2 of  $S$  intense. Although the peak height intensity is about 12 times greater (19 and 242 in arbitrary unit), the integrated intensity is only 7 times greater. This coincides with the value of the intensity estimated by the bolometer.

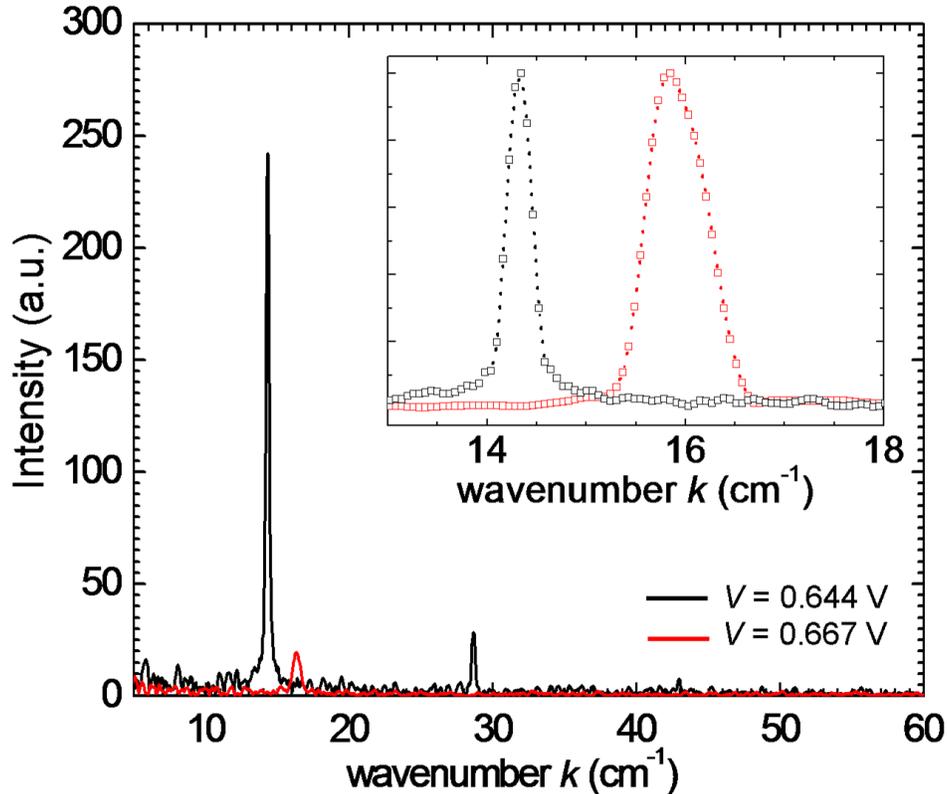


Fig. 5. Emission spectra observed at  $V = 0.644$  V (intense) and  $0.667$  V (ordinary). The frequencies are  $0.49$  and  $0.43$  THz for the ordinary and intense emissions, respectively. The inset shows a magnification of the fundamental frequency. The intensity was normalized against the maximum intensity of each emission type.

### 3.5 Estimation of radiated power

The total emission power was calculated based on a factor of  $0.8$  for the Winston cone loss, filter transparency, and window loss, and a calibration factor of  $2.19 \times 10^5$  [V/W] for the bolometer (Infrared Laboratories Inc. LN-6/C). The directivity of the emission was checked based on angular dependence measurements of the output power as previously reported [24]. As a result, the total output power of the emission is estimated to be about  $30 \mu\text{W}$  from an  $80$  mV output signal of the bolometer at  $30$  K, where  $\theta_1 = 70^\circ$  and  $\theta_2 = 0^\circ$ . Improvement of the output power above a factor of  $7$  was confirmed by both the bolometer output and peak intensity of the FT-IR spectroscopic measurements.

### 4. Conclusion

We have investigated the THz radiation from high- $T_c$  superconducting Bi2212 mesas fabricated using an argon ion milling technique. It was concluded that the maximum output power of both the R- and IR-type of emissions was almost the same at each optimum bath temperature. When the  $I$ - $V$  characteristics were accurately measured at the optimum bath temperature, a new intense excitation state, with about a  $6$ – $8$  times stronger power and complicated  $I$ - $V$  behavior characteristics, was observed for the first time. This emission was reproducible for several samples but is unstable. Moreover, it occurs at relatively lower frequency and voltage (about  $15\%$  lower than the frequency expected from the previous cavity resonance). The FWHM of the fundamental spectrum peak for this intense emission is sharper

than that of ordinary radiation. This implies that synchronizing the Josephson junctions is effective in improving the emission power, as previously expected. A radiated power of up to 30  $\mu$ W was obtained from this new type of excitation. Finally, we demonstrate experimentally the possibility of high-power THz radiation sources from superconductors. This rapid improvement of intensity encourages us to promote the development of THz technology based on high-temperature superconducting intrinsic Josephson junctions.

### **Acknowledgments**

This work has been performed in close collaboration with Dr. Wai -K. Kwok and his group (especially Dr. U. Welp) at the Argonne National Laboratory. It was supported by the Strategic Initiative (A), Univ. of Tsukuba, and by a Grant-in-Aid for JSPS Fellows. The authors thank Prof. M. Tachiki, Prof. T. Hattori at the University of Tsukuba, Prof. A. Irie at the Utsunomiya University, and Prof. L. Ozyuzer at the Izmir Institute of Technology for helpful discussions. We also thank Prof. Y. Ootuka at the University of Tsukuba for his advice and the use of his photolithography facility.