Imaging of local temperature distributions in mesas of high-$T_c$ superconducting terahertz sources

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Abstract. Stacks of intrinsic Josephson junctions in high-$T_c$ superconductors are a promising source of intense, continuous, and monochromatic terahertz waves. In this paper, we establish a fluorescence-based temperature imaging system to directly image the surface temperature on a Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ mesa sample. Intense terahertz emissions are observed in both high- and low-bias regimes, where the mesa voltage satisfies the cavity resonance condition. In the high-bias regime, the temperature distributions are shown to be inhomogeneous with a considerable temperature rise. In contrast, in the low-bias regime, the distributions are rather uniform and the local temperature is close to the bath temperature over the entire sample.

1. Introduction

The terahertz wave with a frequency range of 0.3–10 THz is thought to be the most unique electromagnetic wave, since it provides numerous opportunities for a host of applications [1]. In recent years, much effort has been put into the development of compact and solid-state terahertz sources using semiconductors [2, 3] and laser technologies [4]. Since the first demonstration of terahertz emissions from intrinsic Josephson junctions (IJJs) [5] in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi-2212) [6], terahertz generation using IJJ stacks has become a major focus of research, both experimental [6–26] and theoretical [27–41]. In Bi-2212, application of dc voltage $V$ leads to an ac current and electromagnetic emission at the Josephson frequency in the form: $f_J = (2e/h)V/N$, where $e$ is the electric charge, $h$ is the Plank’s constant, and $N$ is the number of active junctions [42]. To generate the intense terahertz wave, the mesa structures were milled from the Bi-2212 single crystal in order to excite the cavity resonance: in the case of a long rectangular mesa, the cavity condition is expressed as $f_c = c_0/(2nw)$, where $n$ is the refractive index of Bi-2212 and $w$ is the width of the mesa [6].

The most interesting physics of the terahertz emissions is the synchronization of thousands of stacked IJJs with distributed widths, due to the trapezoidal cross-section of the mesa. This system is considered an instructive demonstration of the Kuramoto model, in which a large number of nonlinear oscillators synchronize due to weak couplings [35]: a Josephson junction array shunted by an LCR load can spontaneously synchronize to a common frequency, despite differences in bare frequencies [43]. Essentially the same phenomena can be perceived in many physical and biological systems, including relaxation-oscillator circuits, networks of neurons, and fireflies that flash in unison [44]. Meanwhile, mutual synchronization based on hot-spot formation was recently identified in a mixing experiment [40]. A complete study of increases...
in local temperature in the emitting IJJ stack will further our understanding of the nonlinear phase dynamics of the IJJ system. Moreover, effective prevention of overheating is required to increase the emission power, and may be essential for designing powerful sources [23].

In this study, we establish a temperature imaging system based on a fluorescent technique in order to visualize local temperature rises in the emitting stack. We observe intense emissions both in high- and low-bias regimes, and image the temperature distributions during emission.

2. Sample preparation and experimental setup

Single crystals of Bi-2212 grown by a traveling-solvent floating-zone technique were annealed at 650°C for 12 h. The temperature dependence of the c-axis resistance exhibited a behavior typical of underdoped crystals with $T_c = 78$ K. A small piece of a cleaved crystal was glued onto a sapphire substrate using epoxy resin. The mesa structure was then milled from the crystal surface by photolithography and argon-ion milling techniques. The top width of the mesa ($w$) was 73 $\mu$m and length ($L$) 400 $\mu$m. The thickness of 1.1 $\mu$m corresponds to $N \sim 720$.

To image the local temperature distribution on the sample, we use a fluorescent technique based on the strong temperature dependence of fluorescence intensity on the coordination complex [45]. Figure 1 shows a schematic view of the temperature imaging system. For the temperature marker, a film consisting of europium thenoyltrifluoroacetone (Eu-TFC) in a polymer matrix of polybutylmethacrylate (PBMA) had been deposited on the surface of the sample using a spin-coating technique and baked in a drying oven at 175°C for 30 min. The sample was then installed into the microscopy cryostat and irradiated by 365-nm light emitted by an UV LED. A room-temperature CMOS camera, with a UV filter, was used to acquire the fluorescent image. The spatial resolution, estimated to be less than 5 $\mu$m, was determined by the diffraction limit of the lens system. The acquired data can then be directly converted to a surface local temperature ($T_{\text{local}}$) by calibrating the temperature dependence of the fluorescence intensity (cf. Fig. 2). Since the sensitivity of the film depends on the surface materials, i.e., Bi-2212 (mesa and base crystal) or silver (electrode), a calibration curve must be determined for each surface. Nevertheless, as the inevitable edge effect at the narrow electrode stripes may degrade image quality and obscure details [21], in the present experiment we imaged $T_{\text{local}}$.

![Figure 1. Schematic view of the temperature imaging system.](image1.png)

![Figure 2. Temperature dependence of the fluorescence intensity for the Eu-TFC polymer film deposited on the Bi-2212 surface.](image2.png)
distributions only for the Bi-2212 surface, in order to facilitate the analysis.

3. Results and discussion

Figure 3(a) shows the four-terminal current-voltage ($I$-$V$) characteristics (IVCs) at bath temperatures of $T_b = 10$ K (left scale) and the emission intensity (right scale) measured using a Si-composite bolometer with a 1-THz low-pass filter. Dashed lines at $V = \pm 0.884$ V in Fig. 3(a) represent calculated emission voltages that satisfy $f_J = f^c$, namely, $V = N \cdot (c_0/2n) \cdot (h/2e)$, where we assumed that whole $N$ junctions in the stack were in the resistive state. In Fig. 3(b), the emission intensity was plotted versus $I$ corresponding to Fig. 3(a). Intense emissions were indeed observed when $f_J$ matched $f^c$ in two characteristic bias regimes: a high-bias regime ($I = 11$–23 mA) and a low-bias regime ($I = 4$–5 mA). As discussed earlier, we suggest that the extreme temperature inhomogeneity in the mesa is key for the synchronization of the IJJ stack in the high-bias regime.

Five panels in Fig. 4(b) display the $T_{\text{local}}$ distributions at various $I$-$V$ points, indicated by A–E in Fig. 4(a). In the $T_{\text{local}}$ image, the bounded rectangular region indicates the mesa. The images were taken while decreasing $I$, from 33 mA to 9 mA at a 6-mA interval. The orange parts in the mesa are no longer superconducting with $T_{\text{local}} > T_c$. The exposing condition of the CMOS camera had been optimized for measuring the surface temperature of Bi-2212. The data for the silver electrodes, however, cannot be presented (cf. blacked-out stripes).

In the high-bias regime, the mesa was inevitably heated at a rate of about 30 mW, corresponding to the enormous heating power density. As $I$ had been decreased from 33 mA to 21 mA, the hot spot that initially localized on the left side moved to the center of the mesa. The hot spot disappeared at 12 mA, resulting in a uniform distribution. Such hot-spot behavior in the high-bias regime correlates closely with previous observations [7, 11, 12, 26], which indicates that the huge heating power density cannot be removed quickly enough from the mesa to maintain equilibrium, which results in a considerable rise of the mesa temperature. Although the local heating may induce a chaotic nonequilibrium state and may adversely affect the terahertz emission, mutual synchronization based on hot-spot formation has been identified in a mixing experiment [40]. Since heat conduction became progressively worse as $T_{\text{local}}$ lowered.

![Figure 3](image-url)

Figure 3. (a) Outermost IVC (left scale) and emission intensity detected by a Si-composite bolometer (right scale) at $T_b = 10$ K. Dashed lines at $\pm 0.884$ V represent the calculated emission voltages that satisfy $f_J = f^c$. (b) Emission intensity versus $I$ corresponding to (a).
and the gap vanishes as $T_{\text{local}} \to T_c$, these features may account for the peculiar temperature dependence of the emission intensity [26].

The hot-spot formation mechanism, based on the strongly negative temperature coefficient of the $c$-axis resistivity of Bi-2212, allows for hot spots near the center of the mesa with a maximum temperature above $T_c$ [39]. As a contact resistance of a few ohms, separately measured using the two-terminal method, is much less than the $c$-axis resistivity, power dissipation at the contact is small and does not affect the temperature distribution.

From the local temperature imaging results, we can presume that emission intensity also has a strong correlation with the volume of the superconducting parts in the emitting mesa. The steady-state temperature distribution in the Bi-2212 mesa had been determined by a delicate balance between current distribution and local Joule heating. Thus, we can control the temperature distributions and the emission intensity by altering the dc current distributions. Further studies on the external control of temperature distribution could provide more information for understanding the mechanism of terahertz emission from IJJ.

4. Conclusion
In conclusion, we established a fluorescent temperature imaging system based on the strong temperature dependence of sfluorescence intensity of the coordination complex. We observed intense and continuous terahertz emissions from the IJJ stack in Bi-2212. The intense emissions take place in both high- and low-bias regimes when $f_J$ matches $f^c$. The local temperature on the sample surface was directly imaged and shown to be inhomogeneously distributed, with a considerable temperature rise in the high-bias regime. In contrast, in the low-bias regime, the temperature distributions have been rather uniform and the local temperature had been close to $T_b$ over the whole mesa. Since no regard has been given to eliminating of excess heat from mesas, or to controlling the position of the hot spot in the emitting sample, further improvements in terms of the sample structure and bias conditions may enable the development of powerful terahertz sources using IJJ stacks.

Figure 4. (a) Outermost IVC at $T_b = 10$ K. (b) $T_{\text{local}}$ images for the temperature distribution on the Bi-2212 surface at $I$-$V$ points indicated by A–E in (a).
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