Polarization analysis of the terahertz emission from Bi-2212 cross-whisker intrinsic Josephson junction and its refractive index

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Polarization analyses of the THz emission from Bi1−xSr2CaCu2Oδ+δ (Bi-2212) whisker crystals as a new material for superconducting THz emitters were conducted. The THz emission mode was estimated by a simple polarization measurement, and a simulation study was conducted to examine the validity of the polarization analysis. The refractive index of whisker crystals revealed through the polarization analysis is greater than that of bulk single crystals, and agrees well with our previous THz emission report. The simulation study suggests the complexed plasma excitation mode of the THz emission, then an interpretation of the refractive index obtained in this study is given.

A superconducting THz emitter consisting of a cuprate high-temperature superconductor Bi2−xSr2CaCu2Oδ+δ (Bi-2212) has attracted interest because of its capability of continuous THz wave generation at a frequency of approximately 1 THz in the mW range. See Refs. [8] for recent reviews. At present, the main concern of the development is an increase in the emission power up to a practical level (∼mW). One of the most promising strategies is to increase the number of intrinsic Josephson junctions (IJJs) that contribute to THz emissions.

To date, the maximum reported output power of ∼0.6 mW was achieved by the mutual synchronization of stacks of IJJs (so-called mesas). However, this mutual synchronization to achieve strong radiation is difficult to reproduce because the interactions among mesas on a Bi-2212 single crystal have not been thoroughly investigated. Recently, Tsujimoto et al. revealed that synchronized emission from a mesa array can be described by a linear combination of polarization states for individual radiations. This finding indicates that polarization properties are important measures of the THz emission from Bi-2212 IJJ mesas. However, few studies focusing on polarization states have been reported. Polarization analysis is expected to be useful for the identification of the emission modes, which have as yet only been estimated from emission frequencies.

Previously, we reported a THz emission from a device made of Bi-2212 whisker crystals instead of bulk single crystals. Whisker crystals are small and needle-like single crystals suitable for micro-electronics applications. In our previous report, the THz emission mode was not identified from the emission frequency alone. That was because the refractive index of whisker crystals is possibly different from that of bulk single crystals, where they are known to have a non-stoichiometric composition (∼ Bi2−xSr2CaCu2Oδ). The THz emission is governed by the cavity resonance formula \[ f_{np} = \left( \frac{c_0}{2\sqrt{\varepsilon_r}} \right) \sqrt{\left( \frac{m}{W} \right)^2 + \left( \frac{p}{L} \right)^2}, \] where \(c_0\) is the speed of light in a vacuum; \(W\) and \(L\) are the shorter and longer sides of a rectangular sample, respectively; and \(m\) and \(p\) are the numbers of nodes of a standing wave along the \(W\) and \(L\) directions, respectively. The conventional value of \(\sqrt{\varepsilon_r} = 4.2\) for Bi-2212 bulk single crystals was deduced from the linear scaling relation of the emission frequency and \(1/W\), implying that the THz emission takes place in the transverse mode with zero wavenumbers along the \(L\) direction. Because the THz emission is calculated using \(f_{np}\), the emission mode at the corresponding frequency can be estimated from the polarization direction of the emitted electromagnetic waves. Recent studies have indicated the coexistence of longitudinal components in the THz emission from modulation in low-temperature scanning laser microscopy (LTSLM) patterns and frequency analysis. Thus, polarization measurement is one of the most straightforward and effective methods to identify the THz emission mode and estimate the refractive index of whisker crystals.

In this study, we conducted a polarization measurement for several THz emitting samples made of Bi-2212 whisker crystals with varied dimensions. The refractive index of whisker crystals is obtained by the THz emission mode estimated through the polarization analysis and found to be greater than that of Bi-2212 bulk single crystals. In addition, the validity of the polarization analysis is investigated by a simulation study. The simulation results suggest that the polarization features are not able to be explained by a single-mode plasma excitation at the resonance point, which is consistent with the recent experimental and theoretical studies.

Figure 1(a) shows a scanning electron microscope image of Bi-2212 whisker crystals grown using the Te-doping method. The typical composition of the whiskers was Bi2−xSr1−xCa1−yCu2Ox, as analyzed by energy-dispersive X-ray spectroscopy. The stack of IJJs were fabricated in a lower whisker of “cross-whisker junction” samples (see Fig. 1(b)), hereinafter referred to as CW-IJJ. A detailed fabrication procedure can be found in the literature. Table I summarizes the characteristics of the samples.

The temperature dependence of the resistance (R-T) for sample 1 is shown in Fig. 1(c). It exhibits a slight upturn with nearly unity ratio of \(R(T_c)/R(300\,\text{K})\) and decrease of the
FIG. 1. (a) A SEM image of typical Bi-2212 whiskers grown by Te-doping method. (b) A schematic of a CW-IJJs sample with an associated electrical diagram. (c) The temperature dependence of the resistance for sample 1.

TABLE I. The dimensions of the CW-IJJs samples, \( T_\text{Zero} \), the bath temperature \( T_b \) and frequency \( f \) where the polarization was measured, and the estimated cavity resonance mode are summarized.

| Parameters | Sample 1 | Sample 2 | Sample 3 |
|------------|----------|----------|----------|
| Width (\( \mu \text{m} \)) | 40       | 48       | 50       |
| Length (\( \mu \text{m} \))  | 80       | 61       | 117      |
| Height (\( \mu \text{m} \))  | 0.9      | 0.8      | 0.8      |
| \( T_\text{Zero} \) (K)     | 73       | 72       | 61       |
| \( T_b \) (K)               | 40       | 40       | 55       |
| \( f \) (GHz)               | 737      | 488      | 264      |
| Mode                     | TM\(_{10}\) | TM\(_{01}\) | TM\(_{01}\) |

resistance down to \( \sim 150 \) K, suggesting that the whisker is in slightly over-doped state.

Figure 2 shows the experimental setup for the optical measurements. The THz emission was collimated by a high-density polyethylene lens and then transported into a liquid He-cooled InSb hot electron bolometer through an optical chopper and mirror. The spectrum of the THz wave was obtained using a Fourier transform infrared (FT-IR) spectrometer (JASCO Inc., FARIS-1) with a resolution limit of 0.25 cm\(^{-1}\). Polarization measurements were conducted as follows. First, the sample was current-biased at a certain emission point. The wire-grid polarizer (WGP) placed in the optical path was rotated from 0° to 360° in steps of 10° or 15°. The extinction ratio of the WGP reached 25 dB at 1.0 THz. The bolometer signal was recorded to accumulate data at each WGP angle. After the polarization measurement was completed, FT-IR spectroscopy was performed. The bolometer signal in the non-emission state was also recorded to determine the background signal level, which is essential for determining the polarization.

Figure 3(a) shows the current-voltage characteristics (IVCs) of sample 1 at \( T_b = 40 \) K. Dashed red arrows indicate the current-bias sweep. (b) Bolometer signal corresponding to the IVCs. The inset shows the FT-IR spectrum for high-bias regime (red) and low-bias regime (blue).

The IVCs showed hysteresis, typically observed in the under-damped IJJ array. The IJJ system started to become resistive at a current bias of \( I \approx 10 \) mA, and the critical current gradually increased to \( I \approx 25 \) mA before the entire IJJ system became resistive. The back-bending feature in the IVCs was less distinguishable than that of the previous studies; it has been reported that the back-bending feature originates from the self-heating effect of an IJJ mesa. For our samples, a good cooling efficiency was expected by the following reasons: 1) the sample volume was smaller than that of typical IJJ mesas (\( \sim 400 \mu \text{m} \times 80 \mu \text{m} \times 1 \mu \text{m} \)) and 2) whereas typical IJJ mesas are cooled down through the Bi-2212 base crystal with the thickness of \( > 10 \mu \text{m} \), our CW-IJJ samples were thermally connected to an MgO substrate directly. The thermal conductivity of Bi-2212 is one thousandth that of MgO. In addition, the superconducting top electrode of CW-IJJs might be generating less Joule heating compared to metallic electrodes, contributing to the efficient cooling performance.

Figure 3(b) displays the lock-in signal of the bolometer sig-
nal corresponding to Fig. 3(a), indicating that the THz emission occurs in both high-bias ($I = 24-35$ mA) and low-bias regimes ($I < 10$ mA). The inset of Fig. 3(b) shows the normalized FT-IR spectra obtained at the maximum intensity of each emission regime. Radiation in the range of 700–740 GHz for the high-bias regime and 790–890 GHz for low-bias regime were confirmed by FT-IR spectroscopy.

In this section, the polarization properties of the THz emission are analyzed to identify the oscillation mode. The refractive index of the Bi-2212 whiskers is then discussed. Based on previous studies, THz emission originates from the high-frequency current on the sample surface driven by the standing wave of synchronized transverse Josephson plasma, which is governed by cavity resonance excitation. To discuss the cavity resonance mode, we obtained the emission frequency and polarization profile using a WGP. The rotation angle $\theta$ was defined as the angle between the metal wire of the WGP and the reference direction. Here, the reference direction ($\theta = 0$) was parallel to the longer side (length) of the sample, which was defined as the $y$-axis. The $x$-axis was defined in the same manner as the shorter side (width) of the sample. Because a polarization ellipse represents the angular dependence of the detected power ($I(\theta) \propto |E|^2$), it can be decomposed into diagonal components of electric fields: $E_x = E_{0x} \exp[i(kz - \omega t + \delta_x)]$ and $E_y = E_{0y} \exp[i(kz - \omega t + \delta_y)]$, where $E_{0x}$ and $E_{0y}$ are the amplitudes of the electric fields, and $\delta_x$ and $\delta_y$ are the arbitrary phases.

The cavity resonance mode can be roughly estimated from the electric field amplitude ratio $|E_x|/|E_y| = E_{0x}/E_{0y}$. For example, the predominance of $|E_x|$ over $|E_y|$ suggests the internal cavity mode excitation along the sample width, namely TM$_{10}$ mode as the lowest excitation mode. Electric fields are not directly measurable but can be inferred by analyzing the polarization ellipse using the Jones formulation. The angle-dependent power $I(\theta)$ for fully polarized light passing through a linear polarizer is expressed as

$$I(\theta) = E_{0x}^2 \cos^2 \theta + E_{0y}^2 \sin^2 \theta + 2E_{0x}E_{0y} \cos \theta \sin \theta \cos \delta.$$  

Thus, the value of $|E_x|/|E_y| = E_{0x}/E_{0y}$ can be obtained from the fitting parameters of $E_{0x}$, $E_{0y}$, and $\delta = \delta_x - \delta_y$. It should be noted that the degree of polarization of the raw emission remains uncertain, because the Jones formulation can only be applied to fully polarized light. However, the magnitude relation between $E_{0x}$ and $E_{0y}$ was not affected by the incoherent components.

Figure 4 shows polar plots of the WGP transmission intensity and corresponding FT-IR spectra for samples 1 - 3. The THz transmission intensity and FT-IR spectra were simultaneously obtained at a specific fixed bias point. It is noteworthy that this experiment was enabled by the stable emission in the high-bias regime. In the polar plots, the black dots represent the normalized bolometer signal amplitude, and the polarization ellipses are shown as black lines. The error bar for sample 3 corresponds to 2$\sigma$ error. The solid blue lines represent the least-squares fitting of Eq. (1), where the pale blue rectangles represent the aspect ratio of the sample. The emission modes were estimated from the fitting results $E_{0x}$/$E_{0y}$ and by assuming that these were the fundamental modes of TM$_{01}$ or TM$_{10}$ modes. We obtained $E_{0x}/E_{0y} = 2.7$ (TM$_{10}$ mode) for sample 1, $E_{0x}/E_{0y} = 0.54$ (TM$_{01}$ mode) for 2, and $E_{0x}/E_{0y} = 0.44$ (TM$_{10}$ mode) for 3. In this case, the lowest excitation (TM$_{01}$) was not observed for sample 1. We attributed this to a mismatch in the AC-Josephson relation.

Figure 5 shows a frequency plot of the inverse of the cavity resonant length $L_{res}$ identified from the mode identification. In the half-wavelength (TM$_{01}$ or TM$_{10}$) mode, the cavity resonance formula is reduced to $f = c_0/2\sqrt{\varepsilon_r L_{res}}$. Thus, the emission frequency is inversely proportional to the resonant length.
length $L_{\text{res}}$, and the proportionality factor reflects the refraction index $\sqrt{\varepsilon}$. This plot is equivalent to the asymptotic line of the dispersion relation for transverse Josephson plasma, $\omega(k)/\omega_p = \sqrt{1 + \lambda_c^2 k^2}$, where $\omega_p$ is the Josephson plasma frequency and $\lambda_c$ is the penetration length along the c-axis. When wavenumber $k$ is sufficiently large, the dispersion relation is approximated by the linear relation $\omega(k) = \omega_p \lambda_c k$. By considering the expression $\omega_p = c_0/\sqrt{\varepsilon} \lambda_c$, the linear relationship $\omega(k) = (c_0/\sqrt{\varepsilon}) \lambda_c k$ can be obtained, which coincides with the cavity resonance formula. The dielectric constant $\varepsilon$, discussed here is the high-frequency dielectric constant of the insulating layers.

The experimental data for samples 1 - 3 are plotted in Fig. 5 as black dots, and the red dotted line represents linear fitting. From the fitting results, the refractive index of Bi-2212 whisker crystals was found to be $\sqrt{\varepsilon} = 5.1$. This value gives good agreement with our previous THz emission report by assuming that it was in TM$_{02}$ mode, where the sample dimensions were $85 \times 30 \mu\text{m}^2$ in-plane and the maximum emission was obtained at $f = 680\text{ GHz}$. The found refractive index of whisker crystals ($\sqrt{\varepsilon} = 5.1$) was greater than that of bulk single crystals ($\sqrt{\varepsilon} = 4.2$). Blue dotted line in Fig. 5. This change in the refractive index would be attributed to the difference in the material composition, where Bi$_2$Sr$_{1.6}$Ca$_{1.4}$Cu$_2$O$_{8}$ for our whisker crystals and typically Bi$_2$Sr$_{1.7}$Ca$_{1.0}$Cu$_2$O$_{8}$ for bulk single crystals. On the other hand, optical response studies reported the refractive index of $\sqrt{\varepsilon} \approx 3.5$ for Bi-2212 single crystals. This value was obtained from both of c-axis far-infrared reflectivity and microwave resonance measurement. The difference of the refractive index derived from THz emission study and optical response is possibly attributed to the difference of the nature of spontaneous excitation and passive response of Josephson plasma in Bi-2212 system.

In this section, we discuss the simulation study conducted to examine the validity of the mode identification, which was roughly estimated from $E_{0x}/E_{0y}$. Since we have assumed the two lowest orthogonal modes of TM$_{01}$ and TM$_{10}$, linear polarization in the parallel or vertical direction should be expected. However, the experimental results (Fig. 4) show the polarization ellipses with an offset of the main-axis (sample 1) and a small axial ratio (samples 2-3). Here, we show that these features can be reproduced by setting an appropriate configuration in 3D electromagnetic simulation software (CST STUDIO SUITE). The inset of Fig. 6 shows the simulation model of sample 1 modeled as a perfect electric conductor (PEC) antenna patch atop the dielectric layer ($\varepsilon_r = 26$) with a thickness of 0.9 $\mu\text{m}$. The in-plane size of the patch was $40 \times 80 \mu\text{m}$. The feeding line was also modeled as a PEC patch with an area of $10 \times 5 \mu\text{m}^2$, placed at the corner of the antenna patch. The position of the feeding line was chosen to have good resonance quality (-9 dB at 730 GHz, FWHM < 2 GHz) at the proximity of the emission frequency ($f = 737\text{ GHz}$). Figure 6 shows simulated traces of the normalized electric fields at nearby frequencies. The linear polarization along x-axis at $f = 732\text{ GHz}$ corresponds to the antenna resonance of this model, and the experimental polarization ellipse of Sample 1 (shown in Fig. 4) is reproduced at in-between $f = 735$ and 739 GHz. Subsequently, the polarization direction deviates from the x-axis, and a small axis-ratio begins to appear as the frequency increases. This is consistent with that the polarization measurement point is off at the intensity maximum of sample 1. Recently, Kobayashi et al. proposed an RLC resonant circuit model for a stack of IJJs to describe the experimental results, with pointing out a mismatch in its resonant frequency with the frequency of their THz emission intensity maximum.

One interpretation of this elliptical polarization is that the feed position is diagonally placed on a rectangular patch. According to antenna theory, a phase difference between orthogonal excitation modes, which creates a circular polarization, is generated by placing a feed point diagonally on a rectangular patch. This can be interpreted as the transverse Josephson plasma being excited dominantly in TM$_{01}$ or TM$_{10}$ mode in our IJ system, along with another orthogonal mode with a phase difference. Previously, Elarabi et al. demonstrated circular polarization from truncated square mesas and notched circular mesas by taking advantage of the perturbation effect between two orthogonal modes with a phase difference of $\pi/2$ radians. Their work proved that the Josephson plasma was excited in two orthogonal cavity modes simultaneously with phase differences under appropriate conditions. Although the perturbation effect is hardly expected from rectangular IJ mesas with large aspect ratios ($L/W > 4$), Benseman et al. explained that LTSLM patterns can be approximated as the sum of two cavity modes with a phase difference, forming a composite mode excitation. In addition, Stokes parameter analysis showed small axial ratios and a non-negligible phase difference $\delta_\nu$ from rectangular IJ mesas. In conjunction with previous studies, our polarization measurement results agree with the composite-mode excitation model for Josephson plasma in a cavity. Since whisker crystals have an extremely elongated shape, typically $> 1 \text{ mm} \times 30 \mu\text{m}$ in ab-plane, this composite-mode excitation might be excluded by choosing the width of CW-IJJs is too short to be a resonant length.

The discussed nature of the THz emission might originate...
from the spontaneous excitation of Josephson plasma, unlike a conventional patch antenna driven by an external alternating current source. This is consistent to the earlier discussion that explains the difference of two kinds of refractive index by the different nature of spontaneous and passive Josephson plasma excitation. Thus, the refractive index and the polarization features discussed in this report are the results of the unique nature of the spontaneous Josephson plasma excitation in the Bi-2212 IJJ system. However, further polarization studies are necessary for a more detailed discussion.

In conclusion, we studied the polarization characteristics of the THz wave emitted from Bi-2212 whisker crystals, and the refractive index was deduced using emission mode estimation. The refractive index of the whisker crystals was found to be greater than that of bulk single crystal, agreeing with the experimental results including our previous report. We conducted a 3D electromagnetic simulation to examine the validity of the polarization analysis. The simulation study found that the tilted polarization ellipse appears when the emission point is offset from the cavity resonance point, and suggested that the THz emission originates from complexed plasma excitation. Therefore, the refractive index derived in this study should be treated as more of an effective material parameter to describe the THz emission. We believe that this work provides a new perspective on the materials and the principles for superconducting THz emitters and will contribute to more powerful emission in the future.

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FIG. 6. The simulated polarization ellipses in the vicinity of the antenna resonance frequency.
using tellurium-doped precursors,” Applied Physics Letters 61, 2612–2614 (2001).

K. Kadowaki, H. Yamaguchi, K. Kawamata, T. Yamamoto, H. Minami, I. Kakeya, U. Welp, L. Ozyuzer, A. Koshelev, and C. Kurter, “Direct observation of tetrahertz electromagnetic waves emitted from intrinsic Josephson junctions in single crystalline Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$,” Physica C: Superconductivity 362, 195–199 (2001).

T. Benseman, A. Koshelev, V. Vlasko-Vlasov, Y. Hao, U. Welp, W.-K. Kwok, B. Gross, M. Lange, D. Koelle, R. Kleiner, et al., “Observation of a two-mode resonant state in a Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ mesa device for terahertz emission,” Physical Review B 100, 144503 (2019).

H. Zhang, R. Wieland, W. Chen, O. Kizilaslan, S. Ishida, C. Han, W. Tian, Z. Xu, Z. Qi, T. Qing, et al., “Resonant cavity modes in Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ intrinsic josephson junction stacks,” Physical Review Applied 11, 044004 (2019).

K. Delfanazari, K. Deguchi, N. Orita, T. Koike, R. Nakayama, A. Yurgens, “Temperature distribution in a large Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ mesa,” Physical Review B 61, R9269 (2000).

T. Mochiku and K. Kadowaki, “Growth and properties of Bi$_2$Sr$_2$Ca$_{(2-n)}$(Y,Ca)$_n$Cu$_2$O$_{8+δ}$ single crystals,” Physica C: Superconductivity 235, 523–524 (1994).

T. Kashiwagi, M. Tsujimoto, T. Yamamoto, H. Minami, K. Yamaki, K. Delfanazari, K. Deguchi, N. Orita, T. Koike, R. Nakayama, et al., “High temperature superconductor terahertz emitters: Fundamental physics and its applications,” Japanese Journal of Applied Physics 51, 010113 (2011).

T. Mochiku and K. Kadowaki, “Growth and properties of Bi$_2$Sr$_2$Ca$_{(2-n)}$(Y,Ca)$_n$Cu$_2$O$_{8+δ}$ single crystals,” Physica C: Superconductivity 235, 523–524 (1994).

T. Motohashi, J. Shiomaya, K. Kitazawa, K. Kishio, K. Kojima, S. Uchida, and S. Tajima, “Observation of the Josephson plasma reflectivity edge in the infrared region in Bi-based superconducting cuprates,” Physical Review B 61, R9269 (2000).

S. Tajima, G. Gu, S. Miyamoto, A. Odagawa, and N. Koshizuka, “Optical evidence for strong anisotropy in the normal and superconducting states in Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$,” Physical Review B 48, 16164 (1993).

M. Gaifullin, Y. Matsuda, N. Chikumoto, J. Shiomaya, and K. Kishio, “Abrupt change of Josephson plasma frequency at the phase boundary of the Bragg glass in Bi$_2$Sr$_2$CaCu$_2$O$_{8+δ}$,” Physical Review Letters 84, 2945 (2000).

A. Elarabi, Y. Yoshioka, M. Tsujimoto, and I. Kakeya, “Monolithic superconducting emitter of tunable circularly polarized terahertz radiation,” Physical Review Applied 8, 064034 (2017).

A. Elarabi, Y. Yoshioka, M. Tsujimoto, and I. Kakeya, “Circularly polarized terahertz radiation monolithically generated by cylindrical mesas of intrinsic Josephson junctions,” Applied Physics Letters 113, 052601 (2018).