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# Cavity modes in broadly tunable superconducting coherent terahertz sources

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**Abstract.** We discuss the cavity modes and radiation pattern in solid state terahertz (THz) sources based on layered high-temperature superconducting  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  (Bi-2212). We experimentally measure the emission spectra using the Fourier transform infrared spectrometer in order to elucidate the radiation mechanism of the mesa samples. Moreover, we experimentally study the angular dependence of the emission intensity obtained in one mesa's plane at the frequency  $f=0.61$  THz, at various detection angles  $\theta$  by rotating the sample holder relative to the detector, to identify the excited EM cavity modes within the mesa that participate in the device output power enhancement. We modelled the mesa cavity and find a relatively good agreement between the experiment and theory. Our results show that compact, coherent and continuous-wave Bi-2212 THz devices are one of the most promising THz sources, capable of bridging the microwaves to photonics gap.

## 1. Introduction

The frequencies of terahertz (THz) electromagnetic (EM) waves, which lie between microwaves and infrared, cover the vibrational frequencies of various kinds of molecules and materials. As such, the application of THz technology has become an important subject for various researches such as in ultra-high-speed communications, quantum information, pharmaceutical industries, medicine and medical diagnoses, bio-sciences and biotechnologies, non-destructive sensing testing and imaging purposes, *etc* [1-26].

Therefore, a solid-state THz source that is compact, intense, coherent and broadly tunable is highly desirable. The *ac*-Josephson effect intrinsic to atomic-scale layered superconductors can afford promising to provide such sources. Applications of a *dc* voltage  $V$  across a single Josephson junction



(JJ) leads to an *ac*-Josephson current and EM radiation at the frequency  $f$  that satisfies the *ac*-Josephson relation,  $f = f_J = (2e/h)V$ , where  $e$  is the electronic charge and  $h$  is Planck's constant.

The layered high- $T_c$  superconducting  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  (Bi-2212) is naturally formed as a stack of intrinsic Josephson junctions (IJJs). As a quantum material, it hosts naturally identical JJs which are evenly spaced with two junctions per unit cell along the  $c$ -axis edge length of 1.533 nm [2,8]. Bi-2212 is extremely anisotropic, behaving for  $\mathbf{E} \parallel \hat{\mathbf{c}}$  as an insulator. The mesa structure patterned and formed on top of Bi-2212 behaves as an internal EM cavity that couples to the non-linear *ac*-Josephson currents emitted in each JJ. Recent experiments have demonstrated an integrated THz emitter and detector on a chip scale tunable between 1 and 11 THz [23]. Such properties make Bi-2212 an excellent THz source with capability of closing the THz gap.

To enhance the emission power, one way is to synchronize arrays of radiating mesas patterned on the face of the same crystal [24]. Triangular cavities are the best candidates for synchronization purposes because of their circular polarization features important in array design. Especially, the resonant frequencies of an acute isosceles triangular mesa are inversely proportional to the height of the mesa but almost independent of its basal width, therefore a broad tunability can be observed just by varying the mesa dimensions. In this paper, the emission spectra of an acute isosceles triangular mesa are studied experimentally by using the Fourier transform infrared (FT-IR) spectrometer in order to elucidate the radiation mechanism of the mesa samples. The angular dependence of the emission intensity at various detection angles  $\theta$  is also measured by rotating the sample holder relative to the detector, to identify the excited EM cavity modes within the mesa that participate in the device output power enhancement. We modelled the mesa cavities as a pie-shaped wedge and find a relatively good agreement between the experiment and theory.

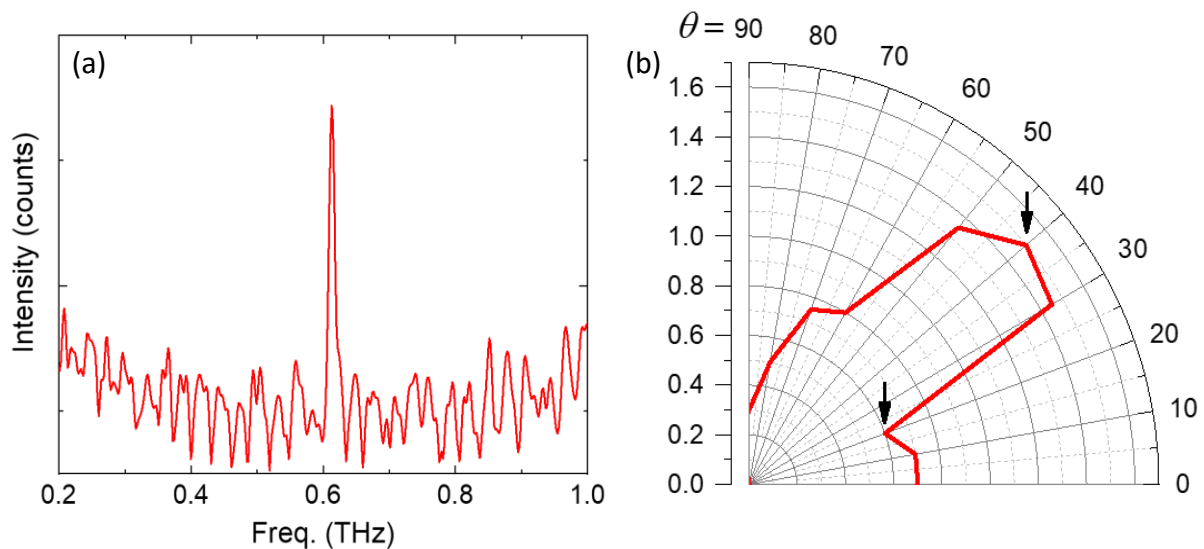


Figure 1. (a) The radiation spectra from an isosceles triangular mesa measured by the FT-IR spectrometer at the current  $I = 0.7$  mA and voltage  $V = 0.9$  V of the outermost IVC, at temperature  $T = 30$  K. (b) The angular  $\theta$  dependence of the radiation intensity (in one measured experimental run), obtained in the  $yz$  plane. The arrows indicate the first minimum and absolute maximum for  $\theta > 0$ .

## 2. Experimental results

In the case of an acute isosceles triangular mesa, we observed THz radiation over the wide frequency range of 0.495 to 0.934 THz, and the frequency dependence of the emission power exhibited an overall sharp peak. This observation is discussed in ref. [8]. In this paper, we concentrate on the experimental

and theoretical studies of the radiation pattern of the emitted THz wave in an acute isosceles triangular cavity. Figure 1(a) shows the radiation spectra from an isosceles triangular mesa measured by the FT-IR spectrometer at the  $I = 0.7$  mA and  $V = 0.9$  V of the outermost IVC at  $T = 30$  K. The angular dependence of the emission intensity obtained in the  $yz$  plane (in one measured run) for this sample at the frequency  $f = 0.61$  THz is shown in Fig. 1b. The radiation intensity (left axis) at various detection angles  $\theta$  was studied by rotating the sample holder relative to the detector in order to provide information that could help to elucidate which, if any, of the EM cavity modes within the mesa might have been excited and hence contribute significantly to the radiation. In the case of present device, the emission intensity is very anisotropic, similar to those earlier studies [2-20].

The emission exhibits maxima at about  $\theta_{\max} = +40^\circ$  in the  $yz$  plane (see Fig. 1(b)), where  $\theta = 0^\circ$  is directly above the top of the mesa. As it can be inferred from the figure, there is a local maximum at  $\theta = 0^\circ$ , where  $I(0^\circ)/I(\theta_{\max})$  varies substantially, depending upon the sample and the plane of the measurement. Furthermore, as  $\theta \rightarrow 90^\circ$ , parallel to the substrate plane, the emission intensity diminishes strongly, as for the radiation observed for an equilateral triangular mesa [9]. This near vanishing of the intensity as  $\theta \rightarrow 90^\circ$  in triangular mesas is very similar to that observed from disk and rectangular mesas which were also atop superconducting Bi-2212 substrates [2-20,26] but is distinctly different from that observed from a free-standing mesa with Au layers both on top and beneath the mesa [27]. The measured emission pattern does not agree well with those estimated from the usual patch antenna theory. This is similar to that of equilateral triangular mesas and previous studies on rectangular and disk mesas. The existence of two kinds of radiation sources, as well as substrate effects depending both upon the nature of the substrate and upon diffraction effects from finite substrate sizes may cause this discrepancy [28].

### 3. Numerical results

Although the exact solution for the cavity modes and wavefunctions of a general isosceles triangle cavity is not known, for the case of a very acute isosceles triangle, we can use an accurate approximation of the general, highly acute isosceles triangle cavity [8]. The closely related exactly solvable problem is that of a pie-shaped wedge cavity. We choose two such wedges to define the acute isosceles triangle [8]. In Fig. 2a, we show the pie-shaped wedge approximation to the shape of a thin acute isosceles triangular patch antenna. The acute angle is taken to be  $2\phi = 2\sin^{-1}(b/2a)$ , where  $a$  and  $b$  are the long and short sides of the isosceles triangle, respectively [8].

We studied two very simple but exactly soluble models, which both become exact in the limit of an infinitely acute isosceles triangle. The models are solved by separation of variables in polar coordinates  $(\rho, \phi)$ , the detailed calculation is not discussed here. We observe a range of the expected wedge cavity frequencies from the analytical calculations and they are summarized in table 1 of Ref. [8]. From this table it can be inferred that the odd cavity resonances appear to play a significant role in understanding of the observed emission intensity spectrum shown in Fig. 1(a). In particular, the observed cavity mode peak in the spectrum at 0.61 THz appear to be close to the wedge  $\text{TM}_{20}^o$  [8]. We note that the largest resonance is for a wavefunction of odd symmetry about the line  $\phi_0 = 0$ .

The observed odd symmetry appears to correlate well with results for rectangular and cylindrical mesas [28-32]. However, in general, most of the observed spectrum does not correlate well with the predicted wedge cavity resonances, providing support to the notion that the primary mechanism for the radiation is the *ac*-Josephson current source itself. In order to calculate the radiation pattern from the mode shown in Fig. 1 and from the uniform *ac*-Josephson current source, one needs to use the Love equivalence principles to obtain the effective surface electric and magnetic currents, the detailed calculation method is discussed elsewhere [33,34]. In the numerical evaluation of the uniform *ac*-Josephson junction contribution, the edge and volume average integration approximation were used [33,34]. The plot of the total calculated radiation power emitted from the acute isosceles triangular mesa is shown in Fig.2b, for the case of volume average integration approximation. From Figs. 1b and 2b, it

can be concluded that the pie-shaped wedge model provides a good approximation to experimental data for the angular dependence of the emission intensity.

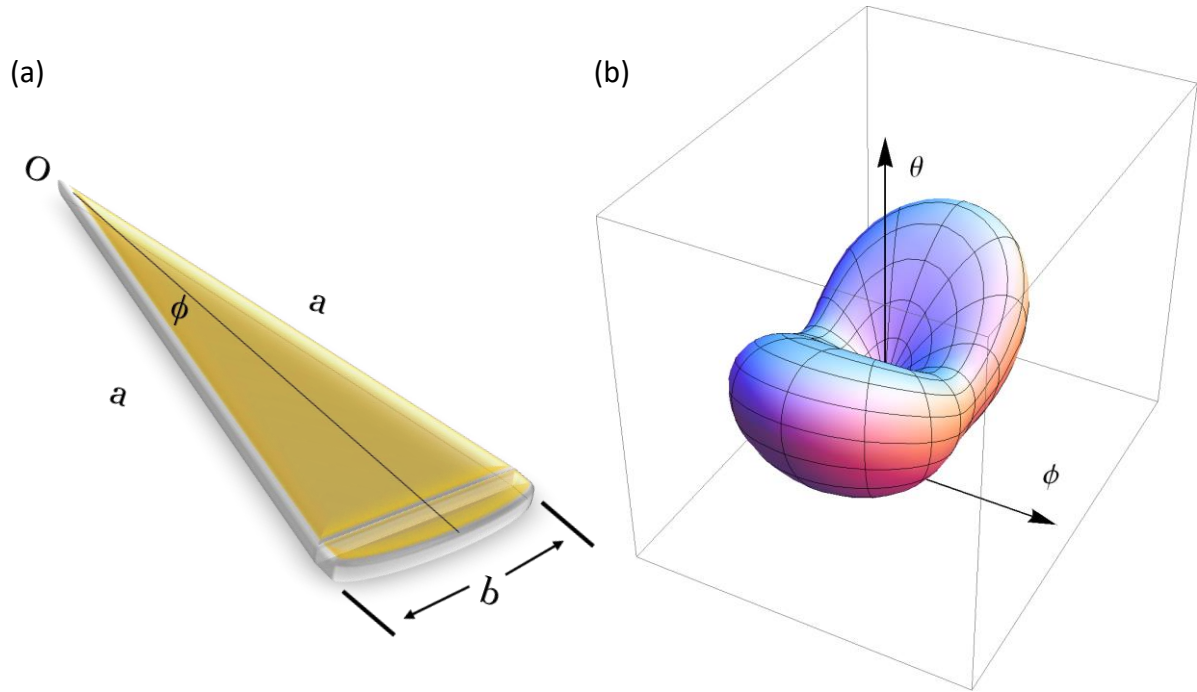


Figure 2: (a) Pie-shaped wedge approximation to the shape of a thin acute isosceles triangular patch antenna. (b) Plot of the total emission power radiated from the acute isosceles triangular mesa using a least-squares fit by the dual source radiation model. To numerically evaluate the uniform  $ac$ -Josephson junction contribution, the volume average approximation was used.

#### 4. Conclusion

A coherent THz source with triangular cavity based on intrinsic Josephson junctions in layered high- $T_c$  superconducting  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  was studied both experimentally and theoretically. We experimentally measured the emission spectra using the Fourier transform infrared spectrometer in order to elucidate the radiation mechanism of the triangular mesa samples. Moreover, the angular dependence of the emission intensity at the frequency  $f = 0.61$  THz was measured, at various detection angles  $\theta$ , by rotating the sample holder relative to the detector in order to understand the cavity modes excited in the mesa. We modelled the acute isosceles triangular mesa as a pie-shaped wedge and found a relatively good agreement between the experiment and theory. Our results show that such compact, coherent and continuous wave THz devices are one of the most promising sources that are capable of closing the THz gap.

#### References

- [1] Tonouchi M 2007 Cutting-edge terahertz technology *Nat. Photonics* **1** (2) 97–105
- [2] Welp U, Kadowaki K and Kleiner R 2013 Superconducting emitters of THz radiation *Nat. Photonics* **7** (9) 702–710
- [3] Kakeya I and Wang H 2016 Terahertz-wave emission from Bi2212 intrinsic Josephson junctions:

- a review on recent progress *Supercond. Sci. Technol.* **29** 073001
- [4] Klemm R, Davis A, Wang Q, Yamamoto T, Cerconey D, Reid C, Koopman M, Minami H, Kashiwagi T, Rain J, Doty C, Sedlack M, Morales M, Watanabe C, Tsujimoto M, Delfanazari K, Kadowaki K 2017 Terahertz emission from the intrinsic Josephson junctions of high-symmetry thermally-managed  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  microstrip antennas, *IOP Conf. Series: Materials Science and Engineering* **279** 012017
  - [5] Cerconey D, Reid C, Doty C, Gramajo A, Campbell T, Morales M, Delfanazari K, Tsujimoto M, Kashiwagi T, Yamamoto T, Watanabe C, Minami H, Kadowaki K, Klemm R 2017 Cavity mode enhancement of terahertz emission from equilateral triangular microstrip antennas of the high- $T_c$  superconductor  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  *J. Phys. Condens. Matter.* **29** 015601
  - [6] Delfanazari K, Asai H, Tsujimoto M, Kashiwagi T, Kitamura T, Sawamura M, Yamamoto T, Tachiki M, Klemm R, Hattori T, Kadowaki K 2015 Effect of electrode bias position on coherent and continuous terahertz wave radiation in superconducting  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  *IEEE Trans. Terahertz Sci. Technol.* **5** 505-511
  - [7] Delfanazari K, Asai H, Tsujimoto M, Kashiwagi T, Kitamura T, Sawamura M, Yamamoto T, Klemm R, Hattori T, Kadowaki K 2014 Terahertz oscillating devices based upon the intrinsic Josephson junctions in high temperature superconductor *J. Infrared Millim. Terahertz Waves* **35** 131-146
  - [8] Delfanazari K, Asai H, Tsujimoto M, Kashiwagi T, Kitamura T, Sawamura M, Yamamoto T, Klemm R, Hattori T, Kadowaki K 2013 Tunable terahertz emission from the intrinsic Josephson junctions in acute isosceles triangular  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  mesas *Opt. Express* **21** 2171-2184
  - [9] Delfanazari K, Asai H, Tsujimoto M, Kashiwagi T, Kitamura T, Sawamura M, Yamamoto T, Klemm R, Hattori T, Kadowaki K 2013 Study of the coherent and continuous terahertz wave emission in equilateral triangular mesas of superconducting  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  intrinsic Josephson junctions *Physica C* **491** 16-19
  - [10] Kashiwagi T, Yamamoto T, Minami H, Tsujimoto M, Yoshizaki R, Delfanazari K, Kitamura T, Watanabe C, Nakade K, Yasui T, Asanuma K, Saiwai Y, Shibano Y, Kubo H, Sakamoto K, Katsuragawa T, Markovic B, Mirkovic J, Klemm R and Kadowaki K 2015 Efficient fabrication of intrinsic Josephson junction terahertz oscillator with greatly reduced self-heating effects *Phy. Rev. Appl.* **4** 054018
  - [11] Kashiwagi T, Yamamoto T, Kitamura T, Asanuma K, Watanabe C, Nakade K, Yasui T, Saiwai Y, Shibano Y, Kubo H, Sakamoto K, Katsuragawa T, Tsujimoto M, Delfanazari K, Yoshizaki R, Minami H, Klemm R and Kadowaki K 2015 Generation of electromagnetic waves from 0.3 to 1.6 THz with a high- $T_c$  superconducting  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  intrinsic Josephson junction emitter *Appl. Phys. Lett.* **106** 092601
  - [12] Kitamura T, Kashiwagi T, Tsujimoto M, Delfanazari K, Sawamura M, Ishida K, Sekimoto S, Watanabe C, Yamamoto T, Minami H, Tachiki M, Kadowaki K 2013 Effects of magnetic field on the coherent THz emission from mesas of single crystal  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  *Physica C* **494** 117-120
  - [13] Kadowaki K, Tsujimoto M, Delfanazari K, Kitamura T, Sawamura M, Asai H, Yamamoto T, Ishida K, Watanabe C, Sekimoto S, Nakade K, Yasui T, Asanuma K, Kashiwagi T, Minami H, Tachiki M, Hattori T, Klemm R 2013 Quantum terahertz electronics using coherent radiation from high temperature superconductor  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  intrinsic Josephson junctions *Physica C* **491** 2-6
  - [14] Klemm R, Delfanazari K, Tsujimoto M, Kashiwagi T, Kitamura T, Sawamura M, Yamamoto T, Hattori T and Kadowaki K 2013 Modeling the electromagnetic cavity mode contributions to the THz emission from triangular  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  mesas *Physica C* **491** 30-34
  - [15] Tsujimoto M, Minami H, Delfanazari K, Sawamura M, Kitamura T, Nakayama R, Yamamoto T, Kashiwagi T, Kadowaki K 2012 THz imaging system using high- $T_c$  superconducting oscillation devices *J. Appl. Phys.* **111** 123111

- [16] Tsujimoto M, Yamamoto T, Delfanazari K, Nakayama R, Deguchi K, Orita N, Koike T, Kashiwagi T, Minami H, Tachiki M, Kadowaki K and Klemm R 2012 Broadly tunable sub-terahertz emission from internal branches of the current-voltage characteristics of superconducting  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  single crystal *Phys. Rev. Lett.* **108** 107006
- [17] Kashiwagi T, Tsujimoto M, Yamamoto T, Minami H, Yamaki K, Delfanazari K, Deguchi K, Orita N, Koike T, Nakayama R, Kitamura T, Hagino S, Sawamura M, Asai H, Ivanovic K, Tachiki M, Klemm R and Kadowaki K 2012 High temperature superconductor terahertz emitters: fundamental physics and its applications *Jpn. J. of Appl. Phys.* **51** 010113
- [18] Kadowaki K, Kashiwagi T, Asai H, Tsujimoto M, Tachiki M, Delfanazari K and Klemm R, 2012 Terahertz wave emission from intrinsic Josephson junctions in  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  *J. Phys.: Conf. Ser.* **400**, 022041
- [19] Delfanazari K, Tsujimoto M, Kashiwagi T, Nakayama R, Kitamura T, Hagino S, Sawamura M, Hattori T, Yamamoto T, Minami H and Kadowaki K 2012 THz emission from a triangular mesa structure of  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  IJJs *J. Phys.: Conf. Ser.* **400** 022014
- [20] Tsujimoto M, Yamamoto T, Delfanazari K, Nakayama R, Orita N, Koike T, Deguchi K, Kashiwagi T, Minami H and Kadowaki K 2012 THz wave emission from inner I-V branches of intrinsic Josephson junctions in  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  *J. Phys.: Conf. Ser.* **400** 022127
- [21] Kashiwagi T, Deguchi K, Tsujimoto M, Koike T, Orita N, Delfanazari K, Nakayama R, Kitamura T, Hagino S, Sawamura M, Yamamoto T, Minami H and Kadowaki K 2012 Excitation mode characteristics in Bi-2212 rectangular mesa structures *J. Phys.: Conf. Ser.* **400** 022050
- [22] Kalhor S, Ghanaatshoar M, Kashiwagi T, Kadowaki K, Kelly M and Delfanazari K 2017 Thermal tuning of high- $T_c$  superconducting  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  terahertz metamaterial *IEEE Photonics J.* **9** (5) 1400308
- [23] Borodianskyi E and Krasnov V 2017 Josephson emission with frequency span 1–11 THz from small  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  mesa structures *Nat. Communications* **8** 1742
- [24] Orita N, Minami H, Koike T, Yamamoto T and Kadowaki K 2010 Synchronized operation of two serially connected Bi2212 THz emitters *Physica C* **470** S786
- [25] Elarabi A, Yoshioka Y, Tsujimoto M and Kakeya I 2017 Monolithic superconducting emitter of tunable circularly polarized terahertz radiation *Phys. Rev. Applied* **8** 064034
- [26] Kadowaki K, Tsujimoto M, Yamaki K, Yamamoto T, Kashiwagi T, Minami H, Tachiki M and Klemm R 2010 Evidence for a dual-source mechanism of THz radiation from rectangular mesas 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
- [27] Asai H, Tachiki M and Kadowaki K 2012 Numerical simulation of THz emission from two mesa structured intrinsic Josephson junctions *J. Phys.: Conf. Ser.* **400** 022002
- [28] Klemm R and Kadowaki K 2010 Output from a Josephson stimulated terahertz amplified radiation emitter *J. Phys.: Condens. Matter* **22** 375701
- [29] Klemm R and Kadowaki K 2010 Angular dependence of the radiation power of a Josephson STAR-emitter *J. Supercond. Novel Magn.* **23** 613
- [30] Klemm R, LaBerge E, Morley D, Kashiwagi T, Tsujimoto M, Kadowaki K 2011 Cavity mode waves during terahertz radiation from rectangular  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  mesas *J. Phys.: Condens. Matter* **23** 025701
- [31] Asai H, Tachiki M and Kadowaki K 2012 Three-dimensional numerical analysis of terahertz radiation emitted from intrinsic Josephson junctions with hot spots *Phys. Rev. B* **85** 064521
- [32] Asai H, Tachiki M and Kadowaki K 2012 Proposal of terahertz patch antenna fed by intrinsic Josephson junctions *Appl. Phys. Lett.* **101** 112602
- [33] Klemm R, Delfanazari K, et al, Kadowaki K 2018 *in preparation*
- [34] Delfanazari K, Klemm R, et al, Kadowaki K 2018 *in preparation*