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Terahertz Wave Emission from Intrinsic Josephson Junctions in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$

K Kadowaki$^{1,2,3}$, T Kashiwagi$^{1,2,3}$, H Asai$^1$, M Tsujimoto$^{1,2,3}$, M Tachiki$^{1,3}$, K Delfanazar$^{1,2,3}$ and R A Klemm$^4$

$^1$Institute of Materials Science and Graduate School of Pure & Applied Sciences, University of Tsukuba, 1-1-1, Tennodai, Tsukuba, Ibaraki 305-8573, Japan
$^2$WPI-MANA satellite, National Institute for Materials Science(NIMS), 1-1, Namiki, Tsukuba, Ibaraki 305-0044, JAPAN
$^3$Core Research for Evolutional Science and Technology (CREST), Japan Science and Technology Agency (JST), Sanban-cho Bldg., 4F, 5 Sanban-cho, Chiyoda-ku, Tokyo 102-0075, Japan
$^4$Department of Physics, Bldg. 121, PS 402, University of Central Florida, 4000 Central Florida Blvd., Orlando, FL 32816-2385, USA

E-mail: kadowaki@ims.tsukuba.ac.jp

Abstract. We have studied the conditions for the THz radiation in many systems with different shapes and dimensions such as rectangles, squares, cylinders and (equilateral and isosceles including right-angled isosceles) triangles and rectangles with non-uniform width (asymmetric rectangles) fabricated from single crystals of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$, which are known as a typical intrinsic Josephson junction system. As a result two conditions have been deduced to be fulfilled: one is the ac-Josephson effect always working at each intrinsic Josephson junction. Another one is the standing wave formation of the THz waves excited inside the mesa due to the cavity resonance for the radiation. The former condition is always necessary for the radiation but the latter may have only the secondary role for the radiation because the $Q$-value of the resonance cavity in some cases seems to be quite low and of order of unity. Therefore, the radiation frequency can be controlled by the voltage effectively and widely varied by the ac-Josephson effect only. In addition, we show a new phenomenon observed at high current region and a comprehensive physical picture for the extraordinary THz radiation phenomenon is given.

1. Introduction

The discovery of the intense, monochromatic and continuous THz radiation from a large mesa of high-$T_c$ superconductor Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ has triggered intensive research for the physical mechanisms and development of THz applications[1,2]. This remarkable success was led by the deep understanding of the Josephson plasma resonance phenomena in the same compound both in and zero magnetic field. Since the Josephson plasma resonance phenomena is nothing but the resonant absorption due to the collective motion of the Cooper pairs through the intrinsic Josephson junctions of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$, it has been believed that the reverse process should be possible. This was, for the first time realized by Ozyuzer et al.[1], in large rectangular mesas with the dimensions of the width of $w$=40, 60, 80 and 100 $\mu$m, the length $L=300$ $\mu$m and the thickness of 1.1 $\mu$m. In the analyses of the experimental data it is easily evidenced two important relations: firstly the radiation frequency, $f$, is inversely proportional to the narrower width, $w$,
following the relation \( f_c = c_0/2nw \), where \( c_0 \) is the light velocity in vacuum, \( n \) the refractive index of the superconducting material. Secondly, the frequency obey strictly the ac-Josephson relation: \( f_J = 2ev/h = 2eV/hN \), where \( e \) is the elementary charge of electron, \( h \) Planck constant, \( v \) the voltage per intrinsic Josephson junction and \( N \) the total number of intrinsic Josephson junctions in a mesa. It seems that these two relations have to be fulfilled in order to have intense THz radiation.

![Figure 1](image.png)

**Figure 1.** Various types of mesas: (a) rectangular, (b) square, (c) cylindrical, (d) equilateral triangular, (e) isosceles triangular and (f) non-uniform rectangular (asymmetric) mesas. (g) represents the cross-sectional view of the rectangular mesa at the AA line. In (b), (c), (d) and (e), the width of the groove is \( \sim 15 \mu m \).

Since then, these relations have repeatedly been confirmed using a variety of mesa structures with shapes of rectangles, squares, cylinders, triangles (equilateral and isosceles including right-angle isosceles) and even rectangles with non-uniform width (asymmetric rectangles) and with many different sizes as shown in Figure 1[3-5]. In all cases we found that the ac-Josephson relation is always working. However, it turns out that for the cavity resonance the condition can be more specific in accordance with the geometrical shape of the mesa. This may be rather natural since the cavity resonance occurs by forming the standing of wave inside cavity, which is determined by the geometrical shape of the mesa. Furthermore, we noticed in some cases that the resonance \( Q \)-value seems to be very low, as low as nearly unity, so that the radiation frequency can be quite widely ranged. This property is somewhat surprising since in most of cases of high frequency generating devices it is common knowledge that the spectral width of radiation is determined by the \( Q \)-value of the cavity resonator. In or present case, the frequency width of the radiation is about 0.5 GHz, which is much narrower than the corresponding line width \( \Delta f \sim f/Q \) due to small \( Q \)-value of the cavity resonance. On the other hand, such a wide range of tunability may be beneficial for the wide-band oscillators but the spectral intensity may be reduced, being disadvantageous for high power applications.

In the following, we show how the cavity resonance condition varies with shapes as well as the dimension of the mesas and argue the role of the cavity resonance for the THz radiation in the intrinsic Josephson junction system Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$.

2. Mesa preparation: various types and shapes of mesa

The various mesas with different sizes and shapes are fabricated by the ion milling with metallic masks and/or photo-resist masks or by the FIB cutting. Each technique has merits and demerits but the footing phenomena of the mesa for the vertical direction is a common problem, which certainly degrades the effective \( Q \)-value of the cavity resonance due to ill-defined dimensions of
the cavity[6]. This footing amounts to the difference in dimensions of several to ~10 μm larger at the bottom than that at the top (see, Figure 1(g)). This certainly affect the formation of the standing wave and therefore the frequency of the radiation.

In Table 1, geometrical information of the various kinds of mesa so far measured in our experiments are summarized.

Table 1. Various kinds of mesas with different sizes and shapes so far studied. In the column of the resonance mode expected from the parallel plate capacitor patch antenna model is listed. m, n and p are integers, and a and b represent the radius of the cylindrical mesa and the side (base) length of the triangular mesa, respectively. Refer to Figure 1.

| Mesa              | Size (μm) | Height (μm) | Resonance mode |
|-------------------|-----------|-------------|----------------|
| rectangle         | 45 ≤ w ≤ 100, 120 ≤ L ≤ 400 | 0.8 ≤ t ≤ 2.0 | \( \frac{c_0}{2\pi n} \sqrt{\left(\frac{m}{L}\right)^2 + \left(\frac{p}{w}\right)^2} \) |
| square            | 66.7 ≤ L ≤ 146 | 1.0 ≤ t ≤ 1.5 | \( \frac{c_0}{2\pi n} \sqrt{\left(\frac{m}{L}\right)^2} \) |
| cylinder          | 33.9 ≤ a ≤ 61.5 | 1.0 ≤ t ≤ 1.2 | \( \frac{c_0}{2\pi n} \sqrt{\lambda_{mp}} \) |
| equilateral triangle | 100 ≤ b ≤ 260 | 1.0 ≤ t ≤ 1.5 | \( \frac{c_0}{2\pi n} \sqrt{m^2 + mn + n^2} \) |
| isosceles triangle | 75 ≤ b ≤ 120 | 1.0 ≤ t ≤ 1.5 | \( \frac{c_0\pi}{\sqrt{2bn}} m \) |

3. Experimental results and discussion
As shown in Table 1, we have made measurements of mesas with rectangular, square, cylinder and (equilateral and isosceles including right-angled isosceles) triangles with different sizes. The model applied here is the same one used for the parallel plate patch antenna, and the results can explain the radiation frequency and the angular dependence very well, where the lowest energy mode is excited in most of the cases according to the mode equations as shown in Table 1. However, there are a few exceptions observed especially in the case of the mesa with very weak radiation. The first exception is that the radiation frequency does not obey the cavity resonance mode frequency at all, and varies quite widely as the applied voltage is varied, according to the ac-Josephson relation. The similar phenomenon is also observed in the radiation from inner I-V branches. This means that the resonance originating from the geometrical shape does not work properly, i.e., the Q-value of the cavity resonance is so low that the frequency of 30-40% of the central frequency can easily be varied. The reason for such a small Q-value is not understood well but it must certainly be related with the fabrication processes of the mesa including the spurious coupling between mesa and the rest of the world. It is essential to improve the Q-value of the mesa itself in order to generate high power THz radiation.

On the other hand, the THz generation characteristic in such a wide frequencies are certainly a unique feature of this system and must be beneficial for various applications. As reported earlier the bias modulation technique can be used for the frequency modulation in the reversible radiation region. This enables us to make high resolution as well as an order of magnitude higher sensitivity measurements. Further detailed arguments including such as higher modes, radiation efficiency, angular dependence, power, etc. will be described elsewhere.

4. Anomalous oscillation phenomena
Now, we turn to the new phenomenon recently discovered. The typical example is shown in Figure 2, in which the I-V curve and the detected radiation power are plotted together. As seen
in the circled areas in Figure 2, the radiation power start to oscillate at a higher current region as a function of the current. This oscillatory behavior is reproducible as the current goes back and forth. When the power is plotted as a function of the voltage, this oscillation is hard to find because of the voltage being independent of the current. It is noticed that in some cases the amplitude of the oscillation become more than half of the peak intensity. Moreover, this phenomenon seems to occur in a mesa with stronger radiation. In such a mesa the temperature is increased up to just below $T_c$ due to the Joule heating of the order of 150 W/cm$^3$. Although this heavy overheating condition in the mesa would cause the hot-spot phenomenon as pointed out by Wang et. al., suggesting even phase separation in a mesa[7], we dare to take a physical picture that such anomalous oscillatory behavior occurs more coherently than the catastrophic hot-spot formation in inequilibrium thermal state with nonlinear dynamics of intrinsic Josephson junction systems. Further detailed study is certainly needed to elucidate this interesting phenomenon.

Figure 2. The radiation power from the rectangular mesa with $w=60 \, \mu$m mesa together with the $I$-$V$ curve. The new oscillatory behavior of the radiation power as a function of the current observed at 15 K is highlighted by circles.

5. Conclusion
We have throughly studied the conditions necessary for the THz radiation from mesas of intrinsic Josephson junctions fabricated from single crystalline Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ by changing the dimensions and sizes (rectangles, squares, cylinders, equilateral and isosceles triangles including right-angle isosceles one). It turns out that the geometrical cavity resonance plays a role of controlling the efficiency of the radiation as in the usual electromagnetic radiation sources.

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