Coupling to External Structures: Boundary Conditions for the Bi2212-based Superconducting THz Emitter

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Abstract. It is known that a mesa fabricated from intrinsic Josephson junctions of
Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ emits intense terahertz radiation at a certain frequency in accordance with the
ac-Josephson relation and the general resonance conditions determined by the geometrical
shape and dimensions. When more than two mesas are placed on the crystal surface,
synchronization phenomenon of two mesas and the cavity resonance due to the coupling to the
external structures outside the biased mesa are observed. These phenomena are interpreted by
the current propagation effect through the superconducting substrate over the range of a few
hundreds of μm even with the phase coherency. This opens up the possibilities of improving
the individual device by external antenna and cavity, and of constructing the large-scale planer
array of mesas for the purpose of power enhancement.

1. Introduction
Compact, convenient and inexpensive solid-state emitters, as well as highly sensitive detectors, in a
frequency range between 100 GHz and several THz are highly demanded, because of a variety of
useful applications such as spectroscopic analyses, various non-destructive sensing and imaging, and
high speed communications, etc. It is well known that Josephson junctions are excellent voltage-
frequency transducers; the dc voltage, $V$, is converted to the ac Josephson current in the Josephson
junction according to the relation, $f=(2e/h)V$, where $f$ denotes the frequency of the induced ac
Josephson current, $h$ Planck constant, $e$ the elementary charge of an electron, and
$2e/h=483.597891(12)$ GHz/mV. Thus, the Josephson junction can be regarded as an excellent source
of continuous and monochromatic high-frequency electromagnetic radiation, but the output power of
$10^{-12}$ W to $10^{-10}$ W from single Josephson junction is too small to make use of it for fundamental
researches as well as applications. In conventional low-$T_c$ superconductors, this problem can be
overcome by integrating Josephson junctions to large-scale arrays, so that the output power can be
raised up to sub-mW level (on-chip detection) [1,2] or 2 μW (off-chip detection) [3]. In the case of
high-$T_c$ superconductors, however, there are hurdles to fabricate large-scale arrays, because of
the extremely short coherence lengths (the order of Å~10Å) and the difficulty to fabricate identical
junctions from multi-element compounds [4].

Recently, Ozyuzer et al. gave a clue to overcome the difficulty by using a natural stack of the
intrinsic Josephson junctions (IJJ’s) built in a high-$T_c$ compound Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (BSCCO) [5], and
demonstrated a continuous and monochromatic THz radiation with power of ~0.5 μW by exciting the
2. Fabrication of mesa emitters and experimental methods

High quality single crystals of BSCCO used in the present studies were prepared by a traveling solvent floating zone technique [10], and annealed in reduced oxygen condition prior to the device fabrication. Rectangular superconducting THz emitters with several different dimensions were fabricated on a surface of mm-size thin BSCCO single crystal by an Ar-ion milling method with metal masks [9,11], as shown in Figures 1~3. A focused ion beam (FIB) technique was used to cut out a part from the mesa and divide it in two mesas as in Figure 2 (a) [12]. The shape of the mesas has been measured precisely by an atomic force microscope (AFM) (Keyence, Japan, VN8000/8010) or a laser microscope (LM) (Keyence, Japan, VK-9700). It turned out that all mesas prepared have trapezoidal shape with a considerable foot at their edges.

As the mesa emitter fabricated basically works as a two-terminal device like a light-emitting diode (LED) and the I-V characteristic is highly non-linear and hysteretic, it was biased with a load resistor of 10~300 Ω connected in series. The terahertz radiation was measured by a conventional modulation technique using an optical chopper with a Si-composite bolometer filtered internally above 3 THz (IR laboratories, $f_c$=100 Hz), while the I-V characteristic was simultaneously measured [13]. The radiation spectra were analyzed by a Fourier transformation infrared (FT-IR) spectrometer (JASCO Co., Japan, FARIS-1) incorporated with the Martin-Puplett interferometer with the resolution of 7.5 GHz.

3. Results and discussion

In order to take out the electromagnetic waves generated inside the mesa, another necessary condition is required. For simple mesa devices, it is the cavity resonance that is necessary for the THz radiation, which is determined by the geometrical shape and dimensions of the biased mesa. In almost all cases of a long rectangular mesa, although an exception has been reported [14], the excitation of radiation has been empirically observed in such a condition that the fundamental mode corresponding to one-half wavelength is equal to the shorter width of the mesa, $w$. It is expressed as $f = c_0/n\lambda = c_0/2nw$, where $c_0$ is the speed of light in vacuum, $n$ the refractive index of BSCCO, and $\lambda$ the wavelength of the emission in vacuum. The intense and monochromatic emission occurs, when the ac Josephson relation and this condition are simultaneously satisfied and the synchronization of all junctions in the mesa is realized.

In this paper, we present radiation characteristics observed when more than two rectangular-shaped mesas are arranged in a row on a surface of mm-size thin single crystal of BSCCO. The sample shown in Figure 1 (a) has eight mesas of 60 μm in width placed side by side at a distance of 60 μm (only three mesas are displayed). The mesas have asymmetric trapezoidal shape with widths of 60 μm at the top and 75 μm at the bottom, height of 3.8 μm and length of 350 μm. As seen in Figure 1 (b), the edge of a long side of mesas is considerably slanted and the width of the edge results in nearly 10 μm. The mesa at the bottom in Figure 1 (a) was only wired by an Au wire of 10 μm in diameter, and was biased. Although the radiation around 0.60 THz is expected from the empirical relation, $f = c_0/2nw$, for a long rectangular mesa of 60 μm, the fundamental radiation is observed at 0.32 THz, a half of the expected...
frequency, as shown in Figure 1 (c). This strongly suggests that the considerably slanted edge does not
work as an end of the cavity, but the sharp edge of the next mesa works as an end of the cavity.

Another sample investigated is shown in Figure 2 (a) [12]. First, a mesa with dimensions of
120 × 350 × 1.6 μm$^3$ was fabricated by an Ar ion milling technique using metal masks, and then an Au
wire of 10 μm was glued on top of the mesa by silver paste for a current lead. Finally, the mesa was
cut into two long rectangular mesas and trimmed a short side by an FIB milling technique with the
groove width of 10 μm. Two mesas with dimensions of 80 × 320 × 1.6 μm$^3$ and 30 × 320 × 1.6 μm$^3$
were finally arranged side by side with a distance of 10 μm. The cross-sectional view along the A-A’
line measured by an LM is displayed in Figure 2 (b). Only the 80 μm mesa was wired and biased.

As shown in Figure 2 (c), the radiation is observed at 0.92 THz, two times of 0.46 THz inferred
from $f = \frac{c_0}{2nw}$ for a long rectangular 80 μm mesas. It is interesting to note that there is no peak at
0.46 THz. Since all single and long rectangular mesas have been so far observed to emit the radiation
in accordance with $f = \frac{c_0}{2nw}$, it is reasonable to attribute this phenomenon to the additional structure.
A mesa edge which is located at the position dividing the whole width of 120 μm with 2:1 may work
as a weak boundary which provides a node to the excited cavity resonance mode. When a considerable
amount of oscillating current flows into the narrower part of the cavity, the regular resonance at one-
half wavelength for the 80 μm mesa can not be excited, but the resonance at one wavelength results in
as the fundamental, analogous to a playing technique of string instruments known as “flagioletto” or
“harmonics”.

Synchronization of two mesas connected in series has been demonstrated by using rectangular
mesas separately located side by side at a distance of 200 μm on a BSCCO single crystal [11]. Figure
3 (a) is a photograph of the sample. By the AFM measurement, the widths of mesas were 47, 53 and
52 μm at the top and 55, 61 and 60 μm at the bottom for O3-1, O3-2 and O3-3, respectively. The O3-1
mesa is narrower than other two. The lengths were 400 μm and the heights were 1.3 μm for three
mesas. A gold wire of 10 μm in diameter was attached to each mesa by silver paste.

Synchronization has been observed when the O3-2 and O3-3 mesas are biased in series. The $I$-$V$
curve exhibits a characteristic hysteresis of the IJJ system and a negative differential resistance due to
Joule heating in high current region (not shown here). The both mesas have been observed to emit
simultaneously in the high current region of the outermost reversible branch at the frequencies around
0.7 THz [11]. Figure 3 (b) shows the radiation frequency and radiation power integrated for two
separated lines at 30 K as a function of current when the O3-2 and O3-3 mesas are biased in series.
The power signal includes a large offset due to the ambient thermal radiation and the thermal radiation
from the sample which appears at high currents, in addition to the THz radiation. The THz radiation

![Figure 1](image1.png)

![Figure 2](image2.png)

**Figure 1.** (a) A scanning ion microscope image of the fabricated mesas. (b) The cross-
sectional profile of the mesas measured by an AFM. (c) A spectrum measured by an FT-IR
spectrometer.

**Figure 2.** (a) A scanning ion microscope image of the fabricated mesas. (b) The cross-
sectional view of the mesas observed by a LM along the A-A’ line. (c) A spectrum measured by an FT-IR spectrometer. [12]
occurs in the wide range of bias currents of 15~33 mA. The spectra have two peaks in the bias current below 25 mA, while they merge into one line in the range of bias current above 26 mA and stay together until the emission stops by Joule heating. The radiation intensity increases with increasing current and takes a constant intensity between 22 and 26 mA. It increases again at the start of the merging and takes a maximum value of 1.5 times of that before the merging. This result, similar to the previous observation for an array of low-$T_c$ discrete Josephson junctions [15], means that two separated mesas coherently work as a strongly coupled THz emitter.

The efficiency of this emitter is at present about 0.1 % and most of supplied power is consumed as Joule heat generated in the mesa, probably because the mesa is highly dissipative and the radiation efficiency as an antenna is quite low. The BSCCO-base mesa emitter itself can be viewed as a large scale array of strongly coupled Josephson junctions, but they are stacked in the direction of the height. There would be a limitation in the height, because this device is highly dissipative with poor thermal conductivity of BSCCO so that the mesa gets heated easily above $T_c$. The present results are naturally understood by the current propagation from biased Josephson junctions to external structures through the superconducting substrate, over the range of a few hundreds of $\mu$m even with the phase coherency. In order to enhance the efficiency and radiation power, it may be desirable for us to design a new device model which couples to external low-loss cavity and high-efficient antenna, and/or to construct 1D or 2D planer array of mesas like the arrays of Nb-base discrete Josephson junctions [1-3]. The demonstration of synchronization between two mesas shown here provides a hope of the larger-scale array. The present results also urge us to reconsider the boundary condition that assumes a mesa to be a box with a bigger dielectric constant than vacuum.

In conclusion, experimental results on the cavity resonances associated with the external structure outside a biased mesa and on the synchronization of two mesas placed on a BSCCO crystal surface indicate the current propagation through the superconducting substrate over the range of a few hundreds of $\mu$m keeping the phase coherency.

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