Characteristics of terahertz radiation emitted from the intrinsic Josephson junctions in high-T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$

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Characteristic features of terahertz radiation emitted from a rectangular mesa comprised stacked intrinsic Josephson junctions in the layered high-T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ are reported. The emission with the total power of ~5 μW at 0.63 THz shows a characteristic spatial distribution reflecting the rectangular shape. The stability of the emission was measured for at least 20 min. and the power fluctuation was found to be less than 4%. Furthermore, the radiation is highly polarized linearly with a ratio of 50:1. All features, including the spectral purity narrower than 4 GHz at full width at half maximum, promise a stable, coherent, and continuous terahertz source for various applications. © *2009 American Institute of Physics*. [doi:10.1063/1.3269996]

Compact solid-state light sources in the terahertz frequency region have long been desired for a variety of sensing, imaging, spectroscopic applications, etc.[1,2] Semiconductor devices such as quantum-cascade lasers,[3] unitraveling-carrier photodiodes, and conventional Schottky barrier diode multiplexers are so far potential candidates for the extension of the frequency range into the terahertz region. Among them, the quantum-cascade laser is most promising as a powerful terahertz light source down to 1.6 THz with a continuous emission power of 0.36 mW in zero magnetic field as reported,[4] and down to 1.39 THz in high magnetic field.[5] Recently, unitraveling-carrier photodiodes have also reached the frequency range up to 1.5 THz with an emission power of 10 μW at 1 THz.[6]

Just recently, we demonstrated a continuous and monochromatic terahertz-light emitting device with sizable power using the intrinsic Josephson junctions in layered high-T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) single crystal.[7,8] This device is fabricated into a rectangular mesa on top of the large single crystal and works as a *dc*-voltage to high-frequency current converter, with 1 mV corresponding to 0.483 THz, according to the *ac*-Josephson effect. Although this sort of Josephson device is ideal for high frequency electromagnetic wave generation, the radiation power from a single junction is known to be very weak in the range of ~pW, unfortunately. In the case of BSCCO, however, the intrinsic Josephson junctions, which are composed of stacking of superconducting CuO_2-layers separated by 12 Å of insulating Bi–Sr–O layers, are so densely packed in an atomic scale that the synchronized Josephson current, if any, is expected to generate high power coherent terahertz-radiation.[9–11] In our previous paper,[7] it was shown that more than $N=650$ junctions can be synchronized to oscillate in phase, generating continuous and coherent radiation with power up to ~0.5 μW at emission frequencies ranging from 0.36 to 0.85 THz which is inversely proportional to the mesa width from 100 to 40 μm. The radiation was detected outside the cryostat after traveling through ambient space unlike the previous measurements.[12–14] This is only possible since the power emitted from this device is several orders of magnitude stronger than the previous ones. Another striking contrast to the previous results[13–18] is that no magnetic field is required to excite the terahertz oscillation in this case.

Here, we report on the enhancement of the radiation power by more than ten times in comparison with the previous report.[7] Furthermore, the radiation is characterized by the spectroscopic measurement in addition to the various physical measurements, such as the angular dependence of the radiation power, polarization, stability, etc.

A rectangular mesa with designed dimensions of the width of 60 μm, length of 400 μm, and height of 1.9 μm was fabricated on the surface of an under-doped BSCCO crystal of $T_c=85$ K by a conventional technique using photolithography and Ar-ion milling step by step. By an atomic force microscopy (Keyence, VN8000/8010) observation, it turned out that the actual mesa has a trapezoidal shape with dimensions of 54.6 μm at the top and 70.7 μm at the bottom. Two pads for electrodes were made on the base of the BSCCO crystal and the third one was constructed by evaporating gold on top of the mesa after depositing insulating CaF_2 layer. This electrode arrangement is utilized for the three terminal methods in measurements. The mesa arrangement with respect to the experimental coordinate is schematically illustrated in Fig. 1(a), while an actual picture of the sample is shown in Fig. 1(b). As illustrated in Fig. 1(a), a Silicon hemispherical lens was often used to efficiently focus and collect the emitted radiation.

The mesa was biased by a function generator (Agilent Technologies, 33120A) or a dc voltage source (Advantest, TR6142) with a load resistor of 10–100 Ω connected in series in the current supply circuit. The polarization and frequency of the radiation were analyzed by a Fourier transform infrared (FT-IR) spectrometer employing Martin–Puplett interferometer (JASCO Co., Japan, FARIS-1), a modified type of the Michelson interferometer using wire grids at the entrance, the exit, and for the beam splitter. The spatial distribution and the long time stability were measured by a modulation technique employing an optical chopper, a Si-

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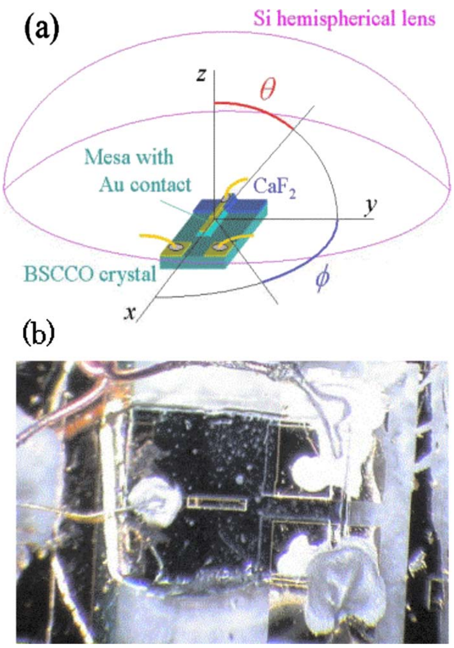

FIG. 1. (Color online) Sample arrangement. The (x,y,z) coordinates and the angles θ and φ are defined on the mesa as shown in (a). (b) A photograph of the BSCCO mesa used for the present experiment.

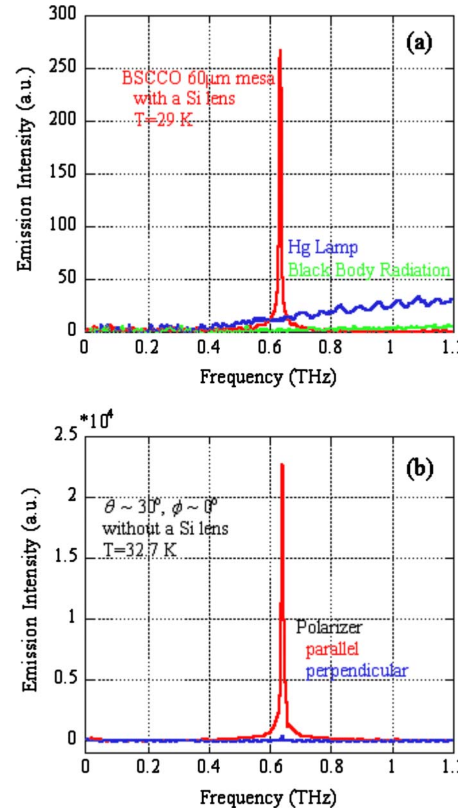

FIG. 2. (Color online) Spectral characteristics of the radiation from the present BSCCO mesa. (a) The radiation from the BSCCO mesa with 60 μm width is compared with those from the mercury lamp [gray (blue) curve] and the black body at 1200 K [light gray (green) curve]. All are measured by a TGS pyroelectric sensor. (b) The radiation spectra are measured at perpendicular and at parallel settings of the wire grids at the entrance and at the exit of the Martin–Puplett interferometer to the layers of BSCCO crystal. The observed polarization ratio of the radiation is about 50.

composite bolometer and a lock-in amplifier at 70 Hz as previously described.[8]

Figures 2(a) and 2(b) show typical spectral characteristics of the radiation. The emission frequency is in good agreement with the fundamental cavity resonance mode, $f = c_0/2nw$, where w is the width of the mesa, $n \approx 4.1-4.2$ is the c-axis far-infrared refractive index[19] of BSCCO, and c_0 is the speed of light in vacuum. The frequency, f, simultaneously satisfies the ac-Josephson relation, $f = V_{\mathrm{jct}}/\Phi_0$, in a multijunction system, where Φ_0 is the flux quantum and V_{jct} the voltage per junction.[7] In Fig. 2(a), the radiation from the mesa through a Si hemispherical lens, which increases the signal intensity by five times, is compared to the radiations from a mercury lamp and black body at 1200 K, which are all detected by a trigycine sulfate (TGS) pyroelectric sensor. These radiation sources are standards for the FARIS-1 spectrometer. The intensity of the radiation peak at 0.63 THz is about 23 times stronger than the radiation from the mercury lamp commonly used for the far-infrared spectroscopy. Since the observed linewidth of ~11 GHz (full width at half maximum) is considered to be limited by the resolution of the FT-IR spectrometer of 7.5 GHz, the actual intensity ratio may be much larger and the spectral purity better than 4 GHz.

Figure 2(b) shows the experimentally observed spectra measured at perpendicular and parallel settings of the wire grids at the entrance and exit of the Martin–Puplett interferometer with respect to the ab-plane of the BSCCO crystal. The terahertz radiation emitted at angles $22.5° < \theta < 37.5°$ and $-7.5° < \phi < 7.5°$ [see Fig. 1(a)] is collected by a concave mirror without a Si hemispherical lens and is fed into the Si-composite bolometer. The intensity of the spectral peaks for perpendicular and parallel configurations are compared and the ratio between the two is about 50, whereas the thermal radiation gives a ratio of about 1.0–1.2, indicating unpolarized radiation, as expected. This experimental result clarifies that the terahertz radiation emitted from the mesa is linearly polarized with the polarization direction of the electric field being perpendicular to the ab-plane of the BSCCO crystal.

Figures 3(a) and 3(b) display the θ-dependence of the emission intensity at $\varphi = 0°$ and the φ-dependence at $\theta = 90°$, respectively, measured in the angular resolution of 4.3° without a Si hemispherical lens. From the θ-dependence measurement, it is revealed that the emission has a strong directional anisotropy as follows: a broad maximum at around $\theta = 30°$ and a local minimum at $\theta = 0°$. It is noted that a small side lobelike structure is also found around $\theta = 60-70°$. These essential features of the emission can be understood by considering the geometrical diffraction effect due to the much longer wavelength of $\lambda = 470$ μm compared with the height of the mesa of 1.9 μm. On the other hand, the angular dependence for the φ direction at $\theta = 90°$ shows a maximum for the perpendicular direction to the long edge of the mesa and a minimum for the parallel direction to the long edge of the mesa as is shown in Fig. 3(b), since the length of the mesa is 400 μm and is comparable to the wavelength λ.[20] Here, the asymmetrical radiation intensity seen in Fig. 3(b) solely originates from the slight misalignment of the angle of the sample to the detector.

Taking into account these anisotropic spatial distribution of the emission and some losses at the windows, filters and so on, the total integrated radiation power is estimated to be about 5 μW, which is approximately ten times larger than

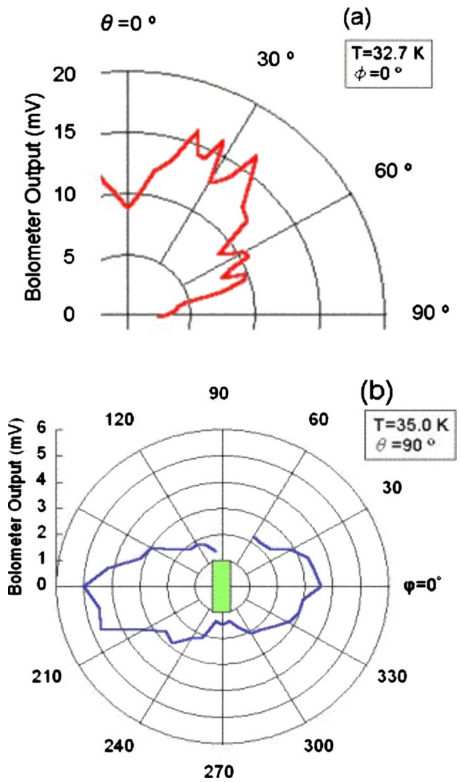

FIG. 3. (Color online) Spatial distribution of the emission from a mesa of BSCCO. The data were taken with an intensity accuracy of about 0.5 mV without a Si hemispherical lens. (a) The θ dependence of the emission intensity at $\varphi=0°$ and (b) the φ dependence at $\theta=90°$, with the angle resolution of 4.3°.

previously reported.[7] This enhancement in radiation power enables us to make the spectral measurements easily by a TGS pyroelectric sensor with sufficient signal-to-noise ratio of ~50. The reason for this is still unclear, however, the radiation efficiency to the total power supplied is still only ~0.03%, which leaves a plenty of room for further improvement by both optimizing material parameters such as doping level and adjusting engineering parameters such as mesa structure, magnetic field,[21] etc.

In Fig. 4, an example of the time dependent stability measurement of the radiation from this device is shown. The radiation is switched on at a time indicated as "ON" by adjusting the bias voltage and current, and switched off at a time indicated as "OFF" by shifting the bias voltage. From this result, it is worth mentioning that the emission is very stable with the power fluctuation being less than 4% only over 20 min with the integration time of 0.3 s of the detector, although more than 80% of the detected signal is due to the thermal origin from the surroundings.

In summary, the radiation characteristics of continuous and monochromatic terahertz emitter constructed by the intrinsic Josephson junctions in high-T_C BSCCO superconductor are presented. The performance of the terahertz source presented here is confirmed to exhibit enough frequency purity, intensity, and controllability suitable for device applications. These findings described above move us one-step closer to filling the so-called terahertz gap by making use of this compact, all solid-state superconducting terahertz source.

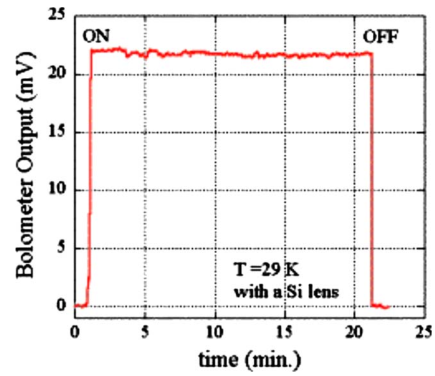

FIG. 4. (Color online) The long time stability of the emission. The bolometer output suddenly increases when the radiation condition is set at "ON," and it suddenly decreases when the radiation condition is out of tune.

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