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Powerful terahertz emission from $Bi_2Sr_2CaCu_2O_{8+\delta}$ mesa arrays

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Stacks of intrinsic Josephson junctions in high-temperature superconductors enable the fabrication of compact sources of coherent terahertz radiation. Here, we demonstrate that multiple stacks patterned on the same $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystal can—under optimized conditions—be synchronized to emit high-power THz-radiation. For three synchronized stacks, we achieved 610 μW of continuous-wave coherent radiation power at 0.51 THz. We suggest that synchronization is promoted by THz-waves in the base crystal. We note that synchronization cannot be achieved in all samples. However even in these cases, powers on the 100-μW scale can be generated. © *2013 AIP Publishing LLC*.
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There is rapidly growing interest in the generation of electromagnetic (EM) waves at terahertz frequencies ($1\,\text{THz} = 10^{12}$ c/s), because of their potential applications in nondestructive imaging and spectroscopy in a wide range of settings. These include not only the physical, chemical, and biological sciences, but also pharmaceuticals, manufacturing, environmental monitoring, medical diagnostics, high-bandwidth communication technologies, security applications, and defense purposes.[1] For these applications, it is highly desirable to have sources of THz radiation that are compact and stable, with power levels in the milliwatt range. A variety of technologies have been developed;[1,2] nevertheless, the frequency range from 0.5 to 1.3 THz—the so-called THz-gap—has been difficult to fill with solid-state sources.

Recently, we have demonstrated that stacks of intrinsic Josephson junctions (IJJs) in the highly anisotropic high-T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) can be induced to emit coherent continuous-wave radiation in this frequency range.[3] These samples were designed in such a way that an electromagnetic cavity resonance promotes synchronization of a large number of IJJs[4] into a macroscopic coherent state. Power levels of up to 80 μW (Ref. 5) from a stand-alone mesa and frequencies up to 1 THz (Ref. 6) have been reported, while Orita *et al.* have demonstrated synchronized emission from two mesas on the same crystal.[8] Nonetheless, power levels reported to date have been significantly below what is required for practical applications and what has been theoretically predicted to be possible.[9] Here, we describe the generation of power levels as high as 0.6 mW of continuous-wave radiation from compact solid state sources in the THz gap frequency range.

When a DC voltage V_J is applied across a Josephson junction, high-frequency electromagnetic oscillations will be generated at the Josephson frequency $f_J = V_J/\Phi_0$, that is, 1 mV per junction corresponds to 0.482 THz. Here, Φ_0 is the flux quantum. For a long rectangular mesa-shaped sample, emission occurs when the Josephson frequency is close to the cavity resonance, whose frequency is given by $f = c(T)/2w$. Here, $c(T)$ is the temperature-dependent far-infrared light speed in the Bi-2212 mesa,[10,11] while w is the mesa's width.

Achieving significant emission power depends on phase synchronization of the junctions in the stack, and it was found in Ref. 3 that the radiated power was proportional to the square of the number of junctions switched to the resistive state, implying that at the correct bias voltage, junctions emit coherently. At the resonance condition, resistive power dissipation in the mesa is of the order of tens of mW. Consequently, one limit on the feasible number of junctions in a stack—and thus the THz power it can generate—is removal of heat through the base of the mesa.[12] Lithographic process constraints also limit the mesa height to a few microns at most. For both of these reasons, it is highly advantageous if many mesas can be made to radiate coherently. The THz power would then scale as the square of the number of mesas as long as all mesas fall within one free-space wavelength at the cavity resonance frequency (i.e., up to three or four mesas) and would then scale linearly as the number of mesas thereafter. Phase synchronization between adjacent mesas may be achieved via electromagnetic coupling through the bulk of the crystal, as shown in the top inset of Fig. 1. Part of the THz power generated in individual mesas escapes as leakage radiation into the base crystal.[13,14] Since the leakage radiation contains mostly the same in-plane wavevector as the mesas, i.e., π/w, efficient synchronized coupling is expected for mesas spaced at a distance of w.

Here, we describe the results on two mesa arrays, both fabricated on optimally doped Bi-2212 crystals. The first consists of 8 parallel $350 \times 60 \times 0.75\,\mu\text{m}^3$ mesas fabricated using optical lithography and argon ion milling on a crystal that has been mounted on a sapphire substrate using silver conductive epoxy. The second contains 6 parallel $400 \times 60 \times 1.1\,\mu\text{m}^3$ mesas on a crystal that has been soldered to a Cu substrate. A device of this type is shown in the bottom inset of Figure 1. The devices were mounted in a liquid helium flow cryostat with optical windows and wired such that the bias current through each mesa could be controlled independently. The detection optics are configured to allow the overall intensity

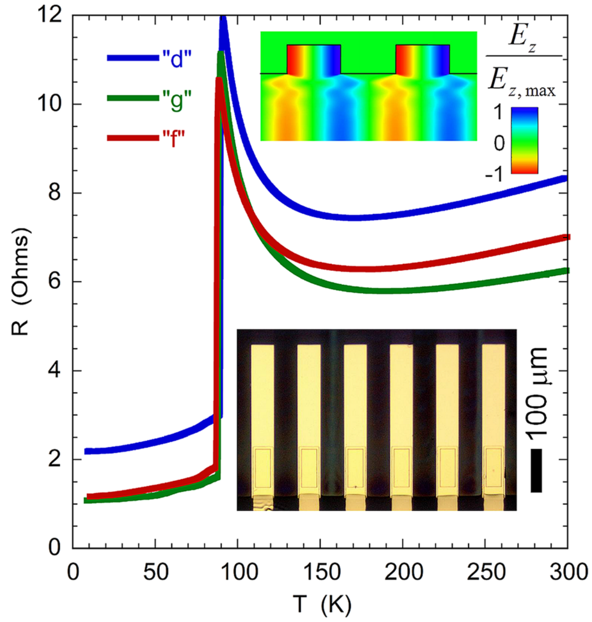

FIG. 1. Temperature dependence of the resistance of three mesas in array 1. Lower inset: Optical micrograph of array of $400 \times 60\,\mu$m mesas. Top inset: Numerical simulation of the *c*-axis component of THz-frequency electric field for an array of mesas with width and spacing 60 μm, showing the electromagnetic coupling of the mesas through leakage of radiation into the Bi-2212 base crystal (see Ref. 14 for details of simulation methodology).

and power spectrum of the radiation to be measured simultaneously using silicon bolometers and a Bruker Vertex 80v FTIR spectrometer (see supplementary material[19]).

Fig. 1 shows the temperature dependence of the resistance of three mesas in the first array. There is some spread of the value of T_c and variations in the contact resistance across the array, which may affect the mutual synchronization of the mesas (see below). Initially, the bias current through an individual mesa was swept up until all junctions were driven into the resistive state, whereupon the IV-characteristics and THz-emission power are recorded on decreasing the bias current (Fig. 2). As can be seen in the plot, the I–V characteristics are strongly influenced by self-heating, to the extent that it is S-shaped, which is typical for mesas of this size.[12,15] For the mesas on this chip, THz emission occurs where dI/dV is very large, or even negative, and it has been suggested[16] that this may be essential for some modes of THz emission in these devices. The jumps in the I–V curves around 40 mA may be a signature of the formation of hot-spots in the mesas.[16] The over-all features of the I–V curves of different mesas are very similar; however, details vary which will affect their synchronization. Maximum THz power as a function of bias voltage typically peaked around 120 μW, at a bath temperature of 40–55 K (Fig. 2). When two or three mesas on the chip are biased, the maximum achievable THz power scales almost as the square of the number of energized mesas (see inset in Fig. 3(a)), up to a maximum of 610 μW for three mesas. In this case, we find that maximal emission occurs at a slightly higher mesa temperature than for one or two mesas and at correspondingly lower bias voltage (as seen in Fig. 3(a)) and emission frequency (Fig. 3(b)). For four or more mesas on this chip, the total power dissipation becomes excessive, and it is no longer possible to cool the mesas to their optimal operating temperature.

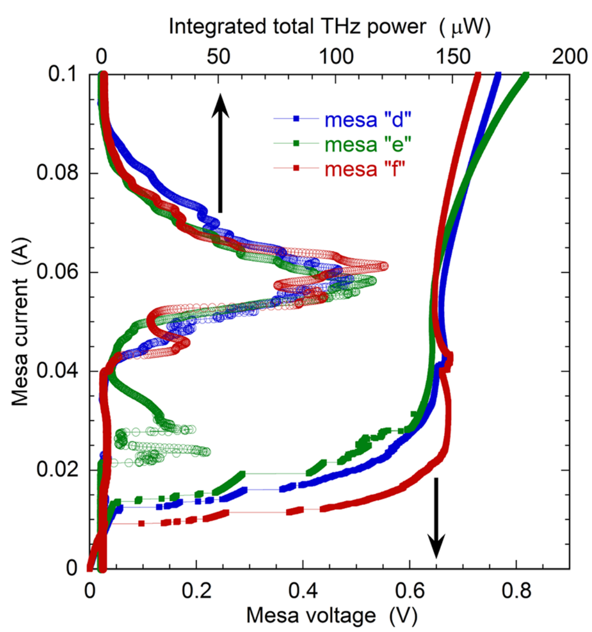

FIG. 2. Current-voltage characteristic and THz-emission power of three mesas in array 1 at 55 K.

We also find that the combined THz emission spectrum is monochromatic at 0.51 THz, to within the 2.25 GHz resolution of the spectrometer (see Fig. 3(b)), agreeing closely with the Josephson relation $f_J = V_{mesa}/N\Phi_0$. All of these results imply that at the correct temperature and bias settings, strongly enhanced coherent THz emission from multiple mesas is being generated. Achieving monochromatic emission may in some cases require individual adjustment of the bias currents, depending on the bath temperature and the combination of mesas used, since the heat sinking properties, contact resistances, and details of the I–V characteristics of the mesas may not be identical. Consequently, the maximum radiated power from an array of mesas represents the best compromise across the properties of the varying individual stacks, with the result that the power scales as slightly less than the square of the number of stacks (Fig. 3(a), inset).

The line intensity measured by our spectrometer in Fig. 3(b) does not scale exactly as the radiation power plotted in Fig. 3(a), since the angular distribution of emitted radiation changes when multiple mesas are radiating in phase as shown in Fig. 3(c). Regions "a" and "b," respectively, mark the acceptance angles for the spectrometer and intensity bolometer. Although the emission pattern of a single mesa is similar to previous observations,[7,17] the emission for three synchronized mesas is enhanced and becomes asymmetric. The cause of this behavior is not established yet but may result from THz voltage phase shifts between the mesas. Sufficiently large arrays of mesas form a grating on the BSCCO crystal and ideally should enhance the out-coupling of the in-plane THz-waves into the perpendicular direction. Enhanced radiation power due to grating coupling has been demonstrated in quantum cascade lasers.[18] Since the height of the individual mesas ($\sim$0.75 μm) is much smaller the THz free-space wavelength, a single mesa emits approximately spherical or cylindrical waves (see Fig. 3(c)). In contrast, a sufficiently large coherent array will generate a parallel beam, which is desirable for many applications.

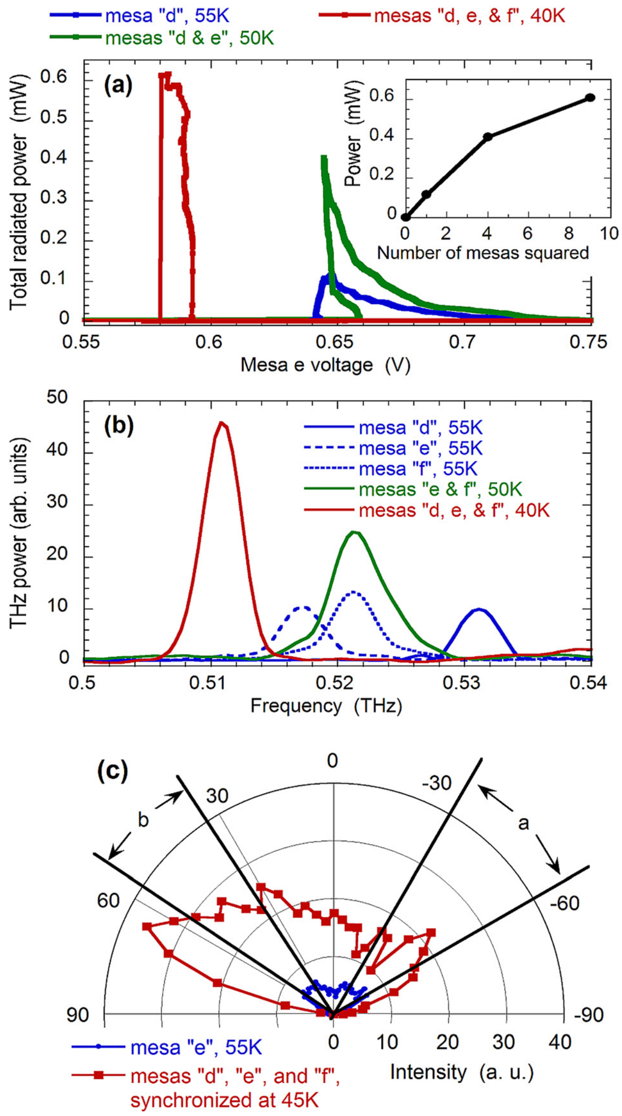

FIG. 3. (a) Radiation power versus bias voltage across mesa at optimized bath temperature for one, two, and three mesas. Curve for one mesa is same as in Figure 2, albeit with intensity plotted against voltage instead of current. When multiple mesas are biased, the bath temperature must be reduced to offset the increased power dissipation and maintain the mesas at their optimal temperature. Inset shows scaling of maximum THz signal as approximate square of number of mesas. (b) Spectra at maximum THz power (for optimized bath temperature) for one, two, and three mesas. Spectrometer resolution is $0.075\,\text{cm}^{-1}$ or 2.25 GHz. (c) Angular dependence of the emission from a single mesa and from three synchronized mesas. Regions "a" and "b" mark the acceptance angles for the spectrometer and bolometer, respectively. The data were taken with a slit 3 mm wide, corresponding to 14°.

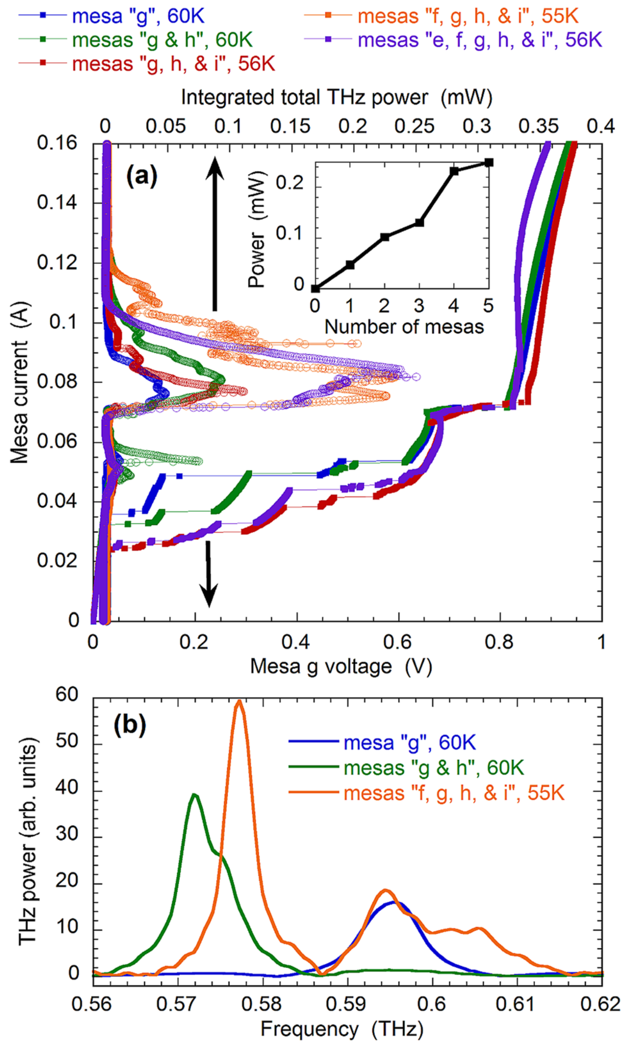

FIG. 4. (a) Bias dependence of the THz emission power of the second array for various activated mesas and I–V curves of mesa "g" and (b) emission spectrum of the second array for various activated mesas. A monochromatic emission line could not be achieved.

Figure 4(a) shows the bias dependence of the THz emission intensities from the second array. With increasing number of activated mesas, the emission power increases reaching 250 μW for biasing five mesas simultaneously. For each combination of mesas, the array temperature has been adjusted to achieve highest power as reflected in the figure legend. Nevertheless, the total power scales approximately linearly with the number of mesas energized, rather than quadratically (see inset in Fig. 4(a)), indicating incoherent superposition of the emission of individual mesas. We were not able to synchronize the emission from the mesas in this array as is evidenced by the spectra shown in Fig. 4(b). In all conditions, the emission line is broad and/or multi-peaked. At this time, the exact mechanism for synchronization of multiple stacks via the base crystal—and the physical conditions necessary for it to occur—is not yet fully understood. However, as shown for mesa "g" in Fig. 4(a), the I–V curve for the individual mesas changes as other mesas are activated. From the foregoing, it appears that details of the temperature distribution and self-heating at the resonance point play an important role.

In making an accurate determination of the THz power radiated by the devices, it is essential to have a reliable optical responsivity calibration for the detectors used. Few directly calibrated radiation sources exist in this frequency range. We have calibrated the two silicon bolometers employed in this experiment at a number of wavelengths between 0.5 and 12 THz, using a reference source comprised of a blackbody cavity standard and gold mesh bandpass filters. See supplementary material for details of the responsivity calibration. We find a strongly wavelength and device dependent optical responsivity of 6.9×10^6 V/W and 4.4×10^6 V/W at 588 μm (i.e. 0.51 THz), respectively, even though the manufacturer's quoted electrical responsivities are almost the same for both devices. This variability between sensors may also account for varying results obtained in different labs.

In summary, we have generated continuous-wave coherent THz radiation with power up to 0.6 mW at 0.51 THz by simultaneously energizing multiple Bi-2212 mesas fabricated on the same single crystal. The emitted radiation appears to be monochromatic, and the total power level scales approximately as the square of the number of mesas energized, suggesting that the mesas are emitting coherently with respect to each other. We find that in practice, self-heating of the mesas limits the power output and in fact may prevent synchronization of multiple mesas. On a second array, the incoherent superposition of the emission from five mesas yields an emission power of 250 μW. A better understanding is, therefore, needed of the relationship between device geometry, self-heating, and coupling of THz radiation between mesas.

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