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Terahertz emission and detection both based on high-T_c superconductors: Towards an integrated receiver

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We have combined a stand-alone $Bi_2Sr_2CaCu_2O_8$ intrinsic Josephson junction stack, emitting terahertz radiation, with a $YBa_2Cu_3O_7$ grain boundary Josephson junction acting as detector. The detector is mounted on a lens, positioned 1.2 cm away from the emitter on a similar lens. With the emitter radiating at 0.5 THz, we observed up to 7 Shapiro steps on the current-voltage characteristic of the detector. The ac current induced in this junction was 0.9 mA, and the dissipated power was 1.8 μW. The setup, although far from being optimized, may be considered as a first step towards an integrated high-T_c receiver. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4794072]

In recent years the investigation of coherent terahertz (THz) emission from stacks of intrinsic Josephson junctions (IJJs) made of the high temperature superconductor $Bi_2Sr_2CaCu_2O_8$ (BSCCO) has become a major field of research, in terms of both experiment[1–17] and theory;[18–37] for reviews, see Refs. 38 and 39. An IJJ is formed naturally in the BSCCO unit cell, with the CuO_2 layers forming the superconducting electrodes and the BiO and SrO layers forming the barrier layer.[40] A crystal of 1 μm thickness consists of ~670 IJJs. In 2007 it was discovered that such stacks can emit coherent radiation at frequencies up to 0.85 THz.[1] In the work the (rectangular) stack was realized as a ~300 μm long, some 10 μm wide, and 1 μm thick mesa structure patterned on top of a BSCCO single crystal. For a given width of the stack the emission frequency was almost fixed but could be varied between 0.3 THz and 0.85 THz by changing the width. Although the *detected* emission power was only in the range of 10 nW, an extrapolation to 4π yielded an estimated total power around 0.5 μW. In subsequent years the (estimated) total emission power improved to values >30 μW, and the maximum emission frequency increased to >1 THz at the fundamental mode and to ~2.5 THz at the higher harmonics.[39] Besides mesa structures, THz emitting BSCCO stacks have been realized as Z-shaped structures using a double sided fabrication method[12] and by contacting stand-alone IJJ stacks with gold from bottom and from top.[39] Also, arrays of IJJ stacks are studied.[39] While the emission power detected from the Z-shaped stacks is comparable to the power detected from mesas,[12] the power emitted from Au contacted stacks was found to be higher, reaching values of several tens of μW.[39] Besides emission power, the stability and tunability of the source and the linewidth of radiation are important figure of merits. For mesa structures it has been found that THz emission occurs in two regimes. There is a low bias regime—the emission found in Ref. 1 was detected here—where Joule heating is of minor importance and a high bias regime, where a region heated to temperatures above the superconducting transition temperature T_c (hot spot) coexists with a "cold" region.[2,6,7,37] In both regimes the emission frequency often can be tuned, for various reasons, within ~10%.[5,7,10,16] In comparison, the high bias regime still has some advantages. At low bias the IJJs can easily switch from the resistive state to the zero voltage state, affecting the stability of the oscillator. At high bias, the oscillator is stable.[7,11] Further, while at low bias the linewidth of radiation is on the order of 0.5 GHz or higher,[13,39] at high bias the linewidth of radiation has turned out to be very small, reaching values well below 50 MHz.[13] Using low temperature scanning laser microscopy the formation of a hot spot at high bias has also been confirmed in the Z-type mesas.[12] Such hot spots are also likely to exist in the free standing mesas.

Thus, all in all, IJJ THz emitters have reached a level where some applications can be demonstrated. For example, a THz imaging system has been operated already.[14] One can consider combining IJJ stacks with other high frequency structures in order to obtain some integrated device. A particularly useful device is the Nb integrated superconducting receiver (SIR).[41,42] This niobium-based receiver, combining a superconducting oscillator, an SIS mixer, a harmonic mixer (HM) for the oscillator phase-locking, plus a variety of passive structures on a single chip, has, for example, been used to measure the linewidth of radiation emitted from the IJJ stacks.[13] Due to the use of Nb-based circuits the SIR is restricted by the Nb energy gap to frequencies below ~0.75 THz. At least on a long term time scale, one can envision a similar device using an IJJ stack as local oscillator, plus some suitable detection scheme based on high temperature superconductors, in order to increase the range of operation to

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frequencies well above 1 THz. Presently, there is no suitable high-T_c SIS mixer. Also, integrating all components on a single chip is presumably a major task. However, it is still possible to make use of a high-T_c Josephson junction reacting on the radiation emitted by the local oscillator. Josephson junctions can be used as mixers although with a less good noise performance than SIS mixers.[43] Another option might be a combination of an IJJ stack local oscillator with a hot-electron bolometer (HEB) mixer.[44,45] In this case a high-T_c Josephson mixer integrated with the local oscillator on one chip could be used for local oscillator frequency stabilization (similarly to SIR[41,42]).

In the experiment we report here we have combined a $YBa_2Cu_3O_7$ (YBCO) grain boundary Josephson junction with a BSCCO IJJ stack. By contrast to IJJ's the YBCO junction has low capacitance and a nonhysteretic current voltage characteristic (IVC), allowing for an effective coupling of radiation over a wide range of frequencies. When irradiated by the IJJ stack, steps of constant voltage (Shapiro steps) appear on the IVC of this junction. They can be used to evaluate the emission frequency and the induced ac current. The BSCCO stack was fabricated in the form of a stand-alone mesa contacted by Au and mounted face down to a hyper-hemispheric Si lens (9 mm in diameter), cf., Fig. 1(a). Since the MgO substrate is 0.5 mm thick, the mesa is not exactly in the focal point of the lens. The YBCO junction was integrated with a self-similar logarithmic-periodic antenna (cf., Fig. 1(b)) and mounted on a similar lens, which was positioned 1.2 cm away from the oscillator, cf., Fig. 1(c). With the IJJ stack in the "on state" at a frequency of 0.5 THz, we observed several Shapiro steps on the IVC of the YBCO junction. The ac current induced in this junction was about 0.9 mA and the (time averaged) power dissipated in the YBCO junction was estimated to be $\approx$1.8 μW.

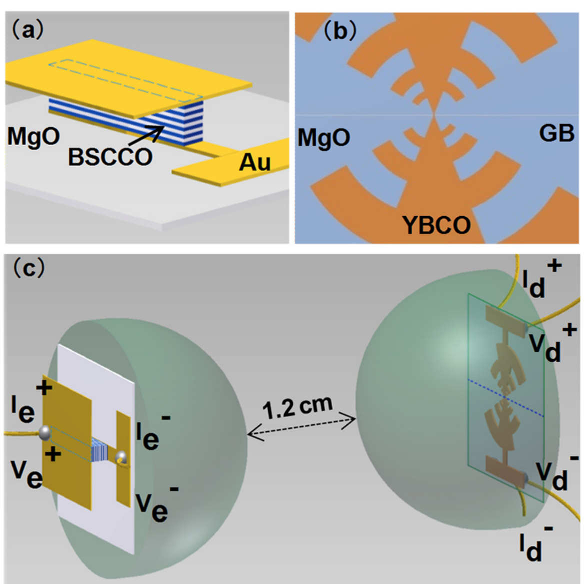

FIG. 1. Setup combining a BSCCO intrinsic junction stack emitter and a YBCO grain boundary junction detector. (a) Schematic of BSCCO stack, (b) YBCO detector, (c) detector and emitter mounted on hyper-hemispheric Si lenses. Current (I_d^+, I_d^- for detector, I_e^+, I_e^- for emitter) and voltage leads (V_d^+, V_d^- for detector, V_e^+, V_e^- for emitter) are indicated in (c). In (b) the grain boundary (GB) is indicated by a solid white line.

The IJJ emitter was fabricated from a slightly underdoped BSCCO single crystal with $T_c = 84$ K. The fabrication process of the IJJ emitter is very similar to the one for a Au/BSCCO/Au structure developed earlier.[46] In short, a 200 nm thick gold layer was deposited onto the surface of a cleaved BSCCO single crystal which was fixed on a substrate. A 1.2 μm thick *T*-shaped mesa was patterned by photolithography and argon ion milling, contacted with a second (MgO) substrate with epoxy, and then transferred to the second substrate by cleaving, with its gold-covered face downward. The stand-alone *T* had a vertical stroke of $\sim$400 μm long and 60 μm wide. The sample was subsequently covered with a 100 nm thick gold layer. A piece of rectangular photoresist was put photolithographically over the vertical stroke, and the whole sample was etched down to the bottom gold by ion milling. The resulting mesa is 320 μm long, 60 μm wide, and 1.2 μm thick.

The YBCO grain boundary junction, integrated with a logarithmic periodic antenna, was patterned by photolithography into a 100 nm thick YBCO film deposited via pulsed laser deposition on a MgO bicrystal substrate with a misorientation angle of 24°. The junction had a width of 1.5 μm, and the antenna had an outer diameter of 0.45 mm.

The BSCCO emitter, already mounted on the Si lens, was pre-characterized in terms of transport and THz emission measurements in Tsukuba, using a similar setup as described in Ref. 7. The combined emitter/receiver system, described above, was measured in Nanjing. All measurements were performed in an electrically shielded room.

Fig. 2 shows the IVC, as measured near 25 K, together with the emission power detected by the Si bolometer. The contact resistance of 2.4 Ω is subtracted in the IVC. The maximum emission signal was found at a current of 15.7 mA (voltage: 0.785 V) where the maximum *detected* power was 25 μW, which is 3 orders of magnitude larger than the values we have detected with the same bolometer for IJJ mesas not mounted to a Si lens. The large signal of the stand-alone mesa appears in the high bias regime where all junctions are resistive and presumably a hot spot has formed already. At this bias the emission frequency, as detected by our Fourier spectrometer, was 0.51 THz, corresponding to $N \sim 744$ emitting junctions. Over the main emission peak between 11 mA and 18 mA the emitted frequency varied between 0.48 THz (high current) and 0.52 THz (low current). This

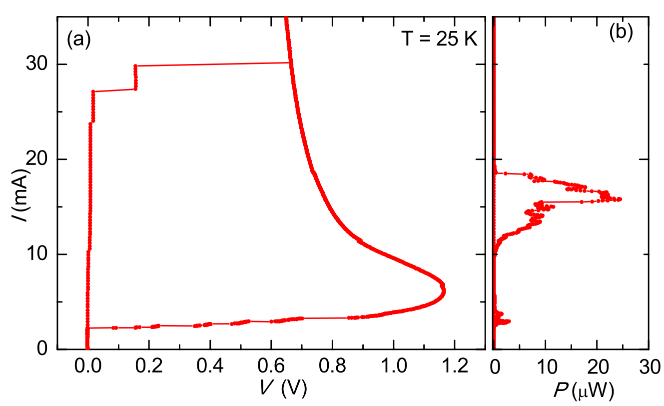

FIG. 2. Properties of the THz emitter. (a) Current voltage characteristic and (b) THz emission power vs bias current, as detected by a Si bolometer.

variation is less than the change of voltage in this regime, which is between 0.74 V (high current, $N \sim 750$) and 0.88 V (low current, $N \sim 820$). Thus, when decreasing the current from 18 mA to 11 mA the number of junctions taking part in coherent emission seems to increase by 10%. We also note that emission was observable up to currents of more than 30 mA. However, for currents larger than 18 mA the emitted power was on the order of or below 1 μW. On the power scale of Fig. 2(b) this emission is not even visible. At $I = 33$ mA the emitted frequency was 0.44 THz. Thus, although the overall tunability is around 20%, only a small range of frequencies is associated with high power. We further made preliminary linewidth measurements of this sample, using the Nb SIR. The linewidth near the emission maximum was found to be ~20 MHz.

Fig. 3(b) shows by a black line the IVC of the YBCO junction, while the emitter is off. The critical current is about 0.42 mA, and the normal state resistance is 4.2 Ω. The upper inset of this graph compares the same IVC to a simulated curve, using the resistively and capacitively shunted junction (RCSJ) model.[47,48] For the simulation the following input parameters have been used: Stewart McCumber parameter $\beta_c = 2\pi C I_0 R_n^2/\Phi_0 = 0.85$ and noise parameter $\Gamma = 2\pi k_b T/I_0\Phi_0 = 0.02$. Here C, R_n, and I_0 denote the junction capacitance, resistance, and critical current, respectively, Φ_0 is the flux quantum, and k_B is Boltzmann's constant. Matching the current and voltage axes of the measured and calculated curves yields $I_0 = 0.423$ mA and a product $I_0R_n = 1.78$ mV. The characteristic frequency $f_c = I_0R_n/\Phi_0$ is 0.86 THz. When the emitter is on, the detector exhibits the IVC shown by a red line in Fig. 3(b). The critical current is suppressed by 30%, and the first Shapiro step is visible but small. The second step has a large amplitude, and steps 3 and 4 are also clearly visible. The derivative dV/dI is shown in Fig. 3(a). Here, also Shapiro steps 5, 6, and even 7 can be seen. As a function of ac current I_{ac} passing the junction, the critical current and the amplitude of the Shapiro steps oscillate (the amplitude of the nth step is roughly proportional to the nth Bessel function, where the argument of the Bessel function is proportional to I_{ac}). The fact that in the irradiated curve in Fig. 3(b) the amplitude of the second step is larger than the amplitude of the first step while the critical current is not suppressed very much is indicative that I_0 has already passed its first minimum and is near the first side maximum. To analyze this further and find a value for the induced ac current we also simulated this curve within the RSCJ model, using the same junction parameters as for the non-irradiated IVC. The result for $I_{ac} = 0.93$ mA is shown as a green line in the lower inset of Fig. 3(b) in comparison with the experimental curve (black line). The theoretical IVC for $I_{ac} = 0.93$ mA does not completely agree with the experimental curve; however, it is about the best what can be done within the RCSJ model describing the ac drive as a current source (the parameters quoted above are accurate to about 10% within the RCSJ model; outside this window IVCs are produced which are inconsistent with the measurements). The model does, in fact, not take into account the finite impedance of the antenna ($Z \approx 189\,\Omega$).[49] Nonetheless we can, within a 10% accuracy, state that an ac current of around 0.9 mA has been induced in the YBCO junction, leading to a time averaged ac power $P_{ac} = I_{ac}^2 R_n/2 \approx 1.8\,\mu$W. This is not extremely different from the power picked up by the bolometer, cf. Fig. 2(b), considering losses, different solid angles, and imperfect impedance matching. Note, however, that the power picked up by the antenna is $I_{ac}^2 Z/2 \approx 82\,\mu$W. This significantly exceeds values of emission power reported before.

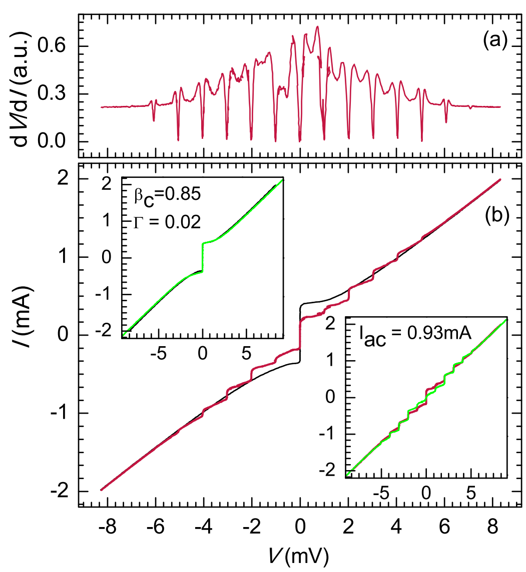

FIG. 3. Properties of the THz detector: (a) differential resistance when irradiated by emitter, (b) current voltage characteristic with emitter on (red line) and off (black line). Upper inset in (b) compares experimental IVC with emitter off (black thick line) to simulated curve (green thin line). Lower inset compares experimental IVC with emitter on (red thick line) to simulated curve (green thin line, ac current $I_{ac} = 0.93$ mA). Model parameters are $\beta_c = 0.85$, $\Gamma = 0.02$. Matching current and voltage axes of experimental and calculated curves yield a critical current $I_0 = 0.42$ mA and a normal state resistance $R_n = 4.2\,\Omega$.

In summary, we have realized a BSCCO intrinsic Josephson junction stack, which was fabricated in the form of a stand-alone stack contacted by Au and mounted face down to a hyper-hemispheric Si lens. This THz emitter emitted at frequencies near 0.5 THz, with a maximum emission power of 25 μW as detected by a Si bolometer. This emission power was strong enough to induce up to 7 Shapiro steps in a YBCO grain boundary Josephson junction acting as a detector. The detector junction was integrated with a self-similar logarithmic-periodic antenna and mounted on a similar lens as used for the BSCCO emitter. The ac current induced in this junction was $I_{ac} = 0.9$ mA, and the (time averaged) power dissipated in the YBCO junction was ≈1.8 μW. Although our setup is far from being optimized it may be considered as a first step towards an integrated high-T_c receiver.

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