*Invited Paper*

# Modulating the emission properties of superconducting terahertz emitters

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**Abstract**: Developing compact, tunable sources for terahertz (THz) generation is a highly active field of research. It was found that intrinsic Josephson junction (IJJ) stacks, naturally formed in single crystals of the cuprate superconductor $Bi_2Sr_2CaCu_2O_8$ (BSCCO), can emit coherent radiation in the THz range. With appropriate design, superconducting THz emitters with strong emission power have been fabricated over the last years. To make these emitters versatile for practical applications, e.g. in radio astronomy or for high-speed tele-communication, it is necessary to modulate and tune the THz emission power. We demonstrate two modulation methods. The first method is to use a three-terminal configuration. At high bias currents a hot spot, having a local temperature higher than the superconducting transition temperature, forms in the stack due to Joule-heating. The appearance and the position of the hot spot can be controlled by varying the ratios of the injected currents from two bottom electrodes. The second modulation method is to shine a focused laser beam onto the sample. Also with this method the emission power can be modulated in the high bias regime by moving the laser beam on the surface of the stack.

**Keywords**: Intrinsic Josephson junctions, Superconducting terahertz emitter, Manipulation of emission

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## 1. Introduction

Coherent terahertz (THz) radiation from superconducting terahertz emitters, made of intrinsic Josephson junctions (IJJs) naturally formed in the high critical temperature ($T_c$) cuprate superconductor $Bi_2Sr_2CaCu_2O_8$ (BSCCO), has attracted a lot of research interests recently [1-50].

A Josephson junction can be created by combining two superconducting layers with an interlayer so that the two superconductors are weakly coupled. The interlayer can, e.g., be an insulator or a normal metal. When a dc voltage $V$ is applied to a single Josephson junction, the supercurrent across the junction oscillates at the Josephson frequency $f=V/\Phi_0$, where $\Phi_0$ is the flux quantum; $\Phi_0^{-1}$ = 483.6 *GHz/mV*. Intrinsic Josephson junctions occur naturally in the layered high-$T_c$ superconductor BSCCO. In this material superconducting $CuO_2$ double layers are separated by insulating BiO and SrO layers. As a result, a BSCCO single crystal forms a stack of a large number of these junctions, cf. Fig. 1(a). Each IJJ has a thickness of about 1.5 *nm*. Fig. 1(b) shows the equivalent circuit of an IJJ stack with lateral sizes much greater than the Josephson penetration depth ($\lambda_J$, typically of the order of 0.5 $\mu m$).

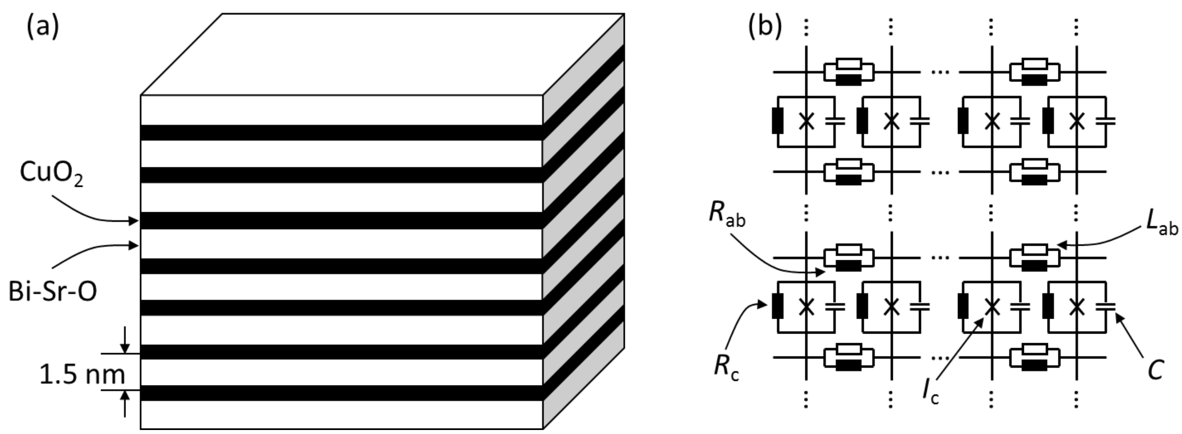


Fig. 1 (a) Schematic illustration of $Bi_2Sr_2CaCu_2O_8$ intrinsic Josephson junctions. (b) 2D equivalent lumped circuit of intrinsic Josephson junctions. The in-plane resistor $R_{ab}$ and inductor $L_{ab}$ represent the in-plane quasiparticle current and supercurrents in the superconducting layers. The resistor $R_c$, capacitor $C$ and critical current $I_c$ represent the interlayer currents.

To create a superconducting THz emitter one patterns a stack of hundreds of IJJs from a single crystal. The stack is typically several μm thick, about 300 $\mu m$ long and 50 $\mu m$ wide. It is usually current biased and operated in a state where all IJJs in the stack are resistive. The excitation of geometrical resonant modes utilizing the whole stack as a cavity is important for synchronizing the phases of the IJJs in the stack [3, 4, 7, 12, 13, 14, 15].

There is a large variety of emitter structures. The mesa structure, fabricated on the top of a BSCCO base crystal, was frequently employed in early experiments. Later on, all-superconducting z-type stacks and stand-alone stacks embedded between Au layers were also developed [25-27, 33, 40, 48]. The emission power obtained from the stand-alone stacks (the structure shown in Fig. 2(a)) is often much higher than the one from mesas, reaching values up to 82 $\mu W$ [27, 33].

The maximum voltage across the stack, an indicator of the maximum possible emission frequency $f_e$, is limited by Joule-heating. The BSCCO out-of-plane resistivity strongly decreases with increasing temperature. Consequently, in the resistive state as shown in Fig. 2(b), when increasing the bias current from zero at a given bath temperature $T_b$, the voltage $V$ initially increases but starts to decrease when Joule-heating becomes dominant [7, 13, 14, 29, 31, 36, 43]. For typical emitters, the maximum voltage per junction is 1--2 *mV*, limiting emission frequencies to the sub-THz regime. Further, at high bias, the current and temperature distributions in the stack become strongly non-uniform. A high-temperature region, the so-called hot spot as shown in Fig. 2(a), coexists with a cold region which is still superconducting. This inhomogeneity has been verified experimentally with low-temperature scanning laser microscopy (LTSLM) and other techniques [7, 13, 14, 31].

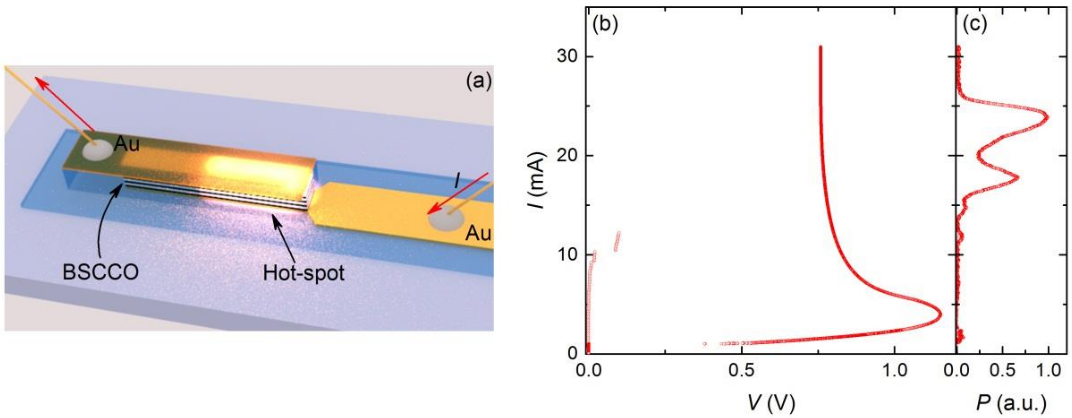


Fig. 2 (a) Schematic illustration of a stand-alone emitter operated in the high bias regime. The bias current is indicated by the red arrows. Graphs (b) and (c) show, respectively, a typical current-voltage characteristic of the emitter at $T_b = 20$ *K*, and the dependence of the terahertz emission power on bias current.

In our experiments, we have found a few merits by operating the emitters in the hot spot regime. For example, the linewidth of radiation is much lower in the high bias regime than in the low bias regime [22]. Also the strongest radiation power from a single stack was achieved at high bias [27, 33]. These observations indicate that the hot spot contributes to phase synchronization.

To obtain a practical emitter appropriate tuning of the THz emission power is desired. Here, we report two methods that may be useful for applications.

## 2. Experimental methods

We briefly describe the fabrication process of a general stand-alone emitter. First, one cuts a single crystal into pieces and glues a flat piece onto a Si substrate with epoxy. By mechanical exfoliation, a fresh surface is created and a ~120 *nm* thick Au layer is evaporated on the surface immediately after exfoliation. Then, a rectangular pattern defining the width of the stack is transferred to the photoresist on the crystal surface by photolithography. Next, a ~1 $\mu m$ thick mesa is formed by ion milling and an MgO substrate is glued to the mesa top with epoxy. The two substrates are subsequently separated, making the stack stand-alone on the MgO substrate.

After a second exfoliation, a 30 *nm* thick Au layer is deposited on this stack as a ground terminal (top electrode in our experiments). A second photolithography and ion milling step is performed to define the length of the stack and to remove the residual BSCCO on the bottom electrode.

To measure the emission properties we mount the sample with terahertz transparent glue onto a hemispheric sapphire lens, used to collect the emission. To achieve the operation temperature (usually 10 *K* to 70 *K*), the sample is cooled in a helium-flow cryostat. The THz wave collected by the sapphire lens radiates through a Teflon window in the cryostat. A home-made Fourier transform infrared spectrometer and a low temperature Si bolometer are used to measure the radiation spectra and the emission power.

To perform LTSLM, we focus a laser spot with diameter of ~1 $\mu m$ on the surface to locally heat up the sample. The wavelength of the laser in our setup is 1310 *nm*. The scanning area can cover the whole sample with a resolution better than 1 $\mu m$. The laser is modulated with a 10 *kHz* square signal and one records the laser-induced changes $\Delta V(x_L, y_L)$ of the voltage across the stack with a lock-in technique while the sample is biased at a constant current. Here $(x_L, y_L)$ denotes the position of the laser spot. We have integrated a compact low temperature scanning laser microscope into the helium-flow cryostat and are thus able to measure emission properties, electrical transport and $\Delta V(x_L, y_L)$ simultaneously.

## 3. Modulation of emission power using three-terminal devices

The fact that the emission properties in the high-bias regime are affected by the hot spot suggests that moving the hot spot is a way to modulate the emission power. To realize this idea, we fabricated a stand-alone stack with three terminals as shown in Fig. 3(a). The fabrication process was similar to the fabrication process of the general stand-alone stack described above, only we removed partially the bottom Au layer with a KI solution to form two individual bottom electrodes.

The lateral size of the three-terminal THz emitter is about $50 \times 300$ $\mu m^2$. Bias currents $I_1$ and $I_2$, as indicated in Fig. 3(a), are injected into two separated bottom electrodes individually. The total current $I_t = I_1+I_2$ is collected at the top electrode. In standard configurations the hot spot usually forms near the electrode injecting the bias current [13, 14]. Thus, in order to move the position of the hot spot, we vary the ratio $I_2/I_t$ of the current injected into the "$I_2$" electrode to the total current while keeping $I_t$ at a constant value. LTSLM is performed to identify the hot-spot position.

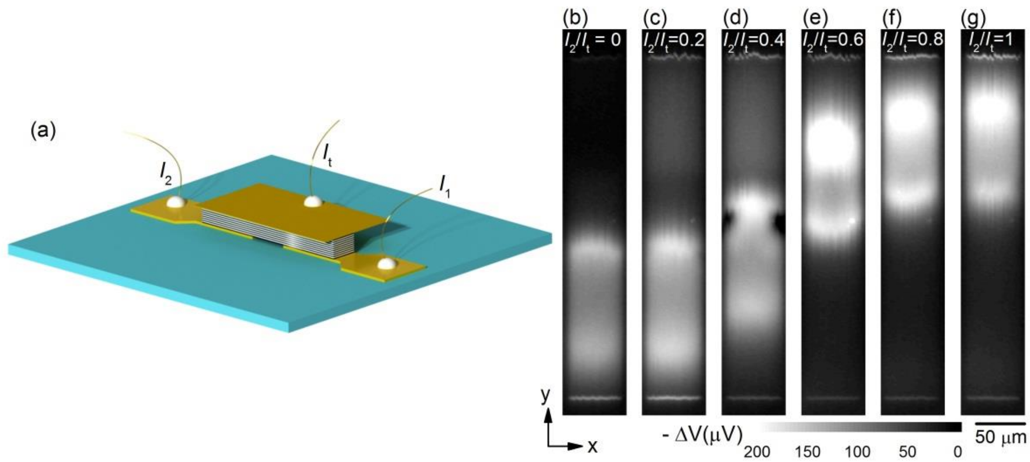


Fig. 3 (a) Sketch of a three-terminal stand-alone emitter on an MgO substrate. The injection currents $I_1$, $I_2$ and the collected total current $I_t$ are indicated. Graphs (b) to (g) are Low Temperature Scanning Laser Microscopy (LTSLM) images for six ratios of $I_2/I_t$ at $I_t = 16$ *mA* and $T_b = 20$ *K*.

Figures 3(b) to (g) show a series of LTSLM images taken at $I_t = 16$ *mA* and a bath temperature $T_b = 20$ *K* for six different ratios $I_2/I_t$ as indicated in the figures. A hot-spot area has formed at this total bias current. In LTSLM, the signal $-\Delta V$ induced by a hot spot is usually largest near the hot-spot edges. A big enough hot spot thus appears as a ring-shaped feature with a moderate signal in its interior and almost no signal in the cold part of the stack. In Figs. 3(b) and (c), where $I_1$ is larger than $I_2$, the hot spot is located in the part of the stack, where $I_1$ is injected (bottom part in the graphs). For $I_2/I_t = 0.3$, cf. Fig. 3(d), the hot spot starts to move upwards, and for larger ratios of $I_2/I_t$ it is situated in the upper half of the stack, cf. Figs. 3(e), (f) and (g). Thus by varying $I_2/I_t$ from 0 to 1 the hot spot can be moved along the whole stack.

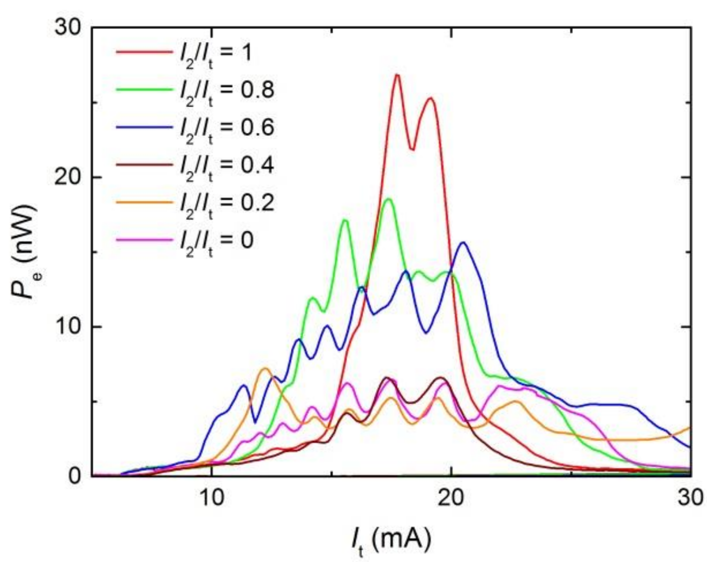


Fig. 4 Emission power vs. total bias current $I_t$ for six ratios of$I_2/I_t$ and $T_b = 20$ *K*.

To check whether the movement of hot spot changes the emission properties, we measured the emission power $P_e$ for six different injection ratios. For each measurement, we fix the ratio $I_2/I_t$ at a constant value and measure $P_e$ while increasing the total current $I_t$. Figure 4 shows $P_e$ vs. $I_t$ for six values of $I_2/I_t$. The total bias current $I_t$ varies from 5 *mA* to 30 *mA* and is taken in the regime where the hot spot has formed. The overall variation of $P_e$ with respect to $I_t$ and $I_2/I_t$ are drastic. For a fixed $I_2/I_t$, $P_e$ exhibits short-period oscillations on top of an envelope that depends on $I_2/I_t$. The short-period modulations have been observed before. Presently, it is unclear whether they are intrinsic in origin or arise from interferences caused by the environment (substrate, sample holder, lens, etc.). Apart from the oscillation, one observes that, for $I_2/I_t$ =1, $P_e$ exhibits a peak for $I_t$ values between 15 *mA* and 21 *mA*. When decreasing $I_2/I_t$ to 0.8 and further to 0.6, the emission peak broadens while the maximum intensities decrease to roughly half of the maximum emission power obtained for $I_2/I_t$ =1. Although a systematic explanation is still needed for the power oscillation and the dependence on the ratio $I_2/I_t$, the data clearly show that $P_e$ depends strongly on injection ratio $I_2/I_t$, demonstrating that it is possible -- and actually necessary for optimizing the emission power -- to tune the emission properties with a three-terminal configuration.

## 4. Modulation of emission power by a strong laser spot

We next discuss the possibility to manipulate the emission power using a strong focused laser spot. As shown in Fig. 5, the laser beam, causing a local temperature increase, is focused onto the top electrode of a stand-alone emitter. The setup configuration is similar to LTSLM but uses a strong beam power, so the laser is operated in a manipulation mode rather than in a probe mode. We mainly focused the laser on different positions along the central length. We found that the laser could not induce a hot spot by itself when the sample is operated in low bias regime. However, when a hot spot was formed by Joule heating, the laser was able to increase the inhomogeneity in the temperature distribution and thus modulate the emission.

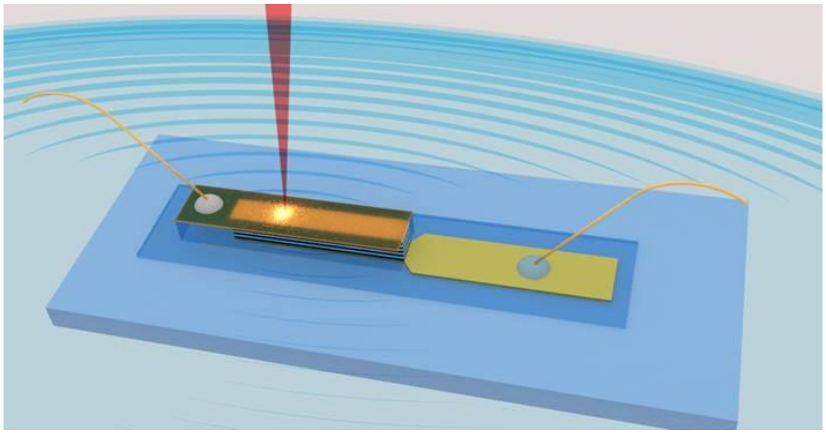

Fig. 5 Schematic illustration of modulating the terahertz emission from the BSCCO stack with a strong laser beam.

Here we show the results obtained for a stand-alone stack with lateral dimensions of about $50 \times 290\ \mu m^2$ and a thickness of about 1 $\mu m$. The wavelength of the laser was 1310 *nm*. The beam power arriving at the stack was estimated to be about 2-5 *mW*. We investigated the variation of $P_e$ for different positions of the laser spot along the stack, for bias currents in the hot-spot regime. For measurement, while the stack is biased with a constant current, we place the laser spot at a given value $x_L$ for a time of 150 *ms*, measure the emission $P_e$, and then vary $x_L$ in steps of 1 $\mu m$ along the central length of the stack. By increasing the bias current and repeating the measurement, we get the dependence of emission $P_e$ on the laser position $x_L$ and the bias current $I$.

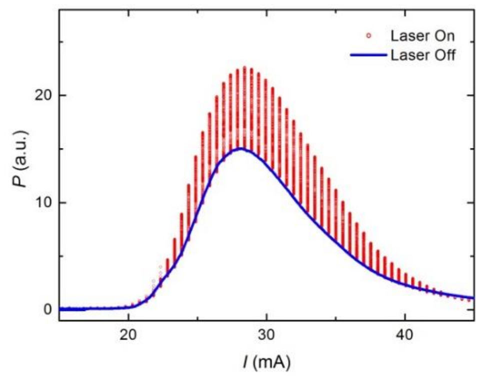


Fig. 6 Emission power vs. bias current when the laser position is varied (red circles) and the laser is turned off (blue line), and $T_b = 22\ K$.

Fig. 6 summarizes how $P_e$ varies with $I$ from 15 *mA* to 45 *mA* at $T_b = 22\ K$. In the graph, we also plot the $P_e^{off}$ vs. $I$ by a blue line, as measured when the laser is turned off. The vertical red lines indicate for each current the additional emission power that is laser-induced. As can be seen, the emission power is enhanced for almost every bias current and reaches values between 50% and 80% for currents between 23 *mA* and 39 *mA*.

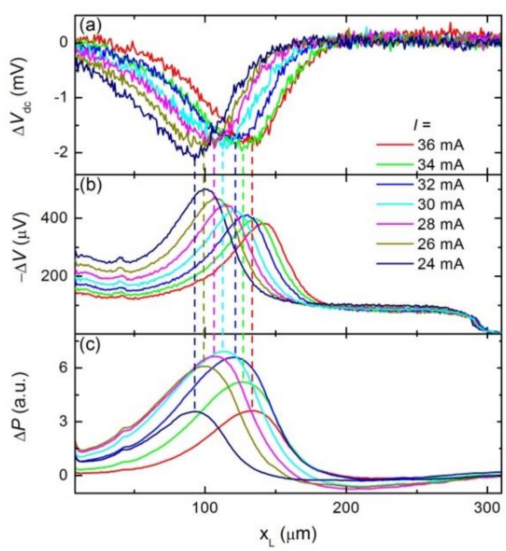


Fig. 7 (a) Response of the IJJ stack vs. laser beam position, recorded for different bias currents. (a) laser-induced changes in the dc voltage, (b) LTSLM signals and (c) laser-induced changes in emission power.

In Fig. 7, we plot (a) the laser-induced changes $\Delta V_{dc}$ in the dc voltage across the stack, (b) the LTSLM signals -$\Delta V$ and (c) the laser-induced changes in emission power $\Delta P$ for seven selected bias currents. The maximum changes in the emission power occured when the laser-induced change in dc voltage reached its maximum. This is also near the position where -$\Delta V$ has its maximum and the local temperature is near $T_c$ [24]. Thus one can conclude that the strong laser beam can strongly modulate the emission power when its location is close to the edge of the hot spot, presumably changing the location of the hot-spot edge.

## 5. Conclusions

In summary, we investigated two methods -- variable current injection in three-terminal devices and local heating by a laser beam -- to tune the THz emission properties of superconductor terahertz emitters. Both methods utilized the manipulation of a hot spot which forms in the emitters at high bias currents because of strong Joule heating. Although more efforts are necessary to control the emission precisely, we have seen that both methods work in principle. Particularly the three-terminal configuration is easy to realize and may be useful for future applications.

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