Tuning the Terahertz Emission Power of an Intrinsic Josephson-Junction Stack with a Focused Laser Beam

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We report on tuning the THz emission of a Bi2Sr2CaCu2O8 (BSCCO) intrinsic Josephson-junction stack by a focused laser beam which is scanned across the stack. The emission power $P_e$ increases by up to 75% upon laser irradiation for a bath temperature near 22 K. The laser-induced changes in the voltage $V_{dc}$ across the stack and in the emission power are measured simultaneously. The maximum of the laser-induced changes in emission power $\Delta P_e$ is achieved by irradiating the stack on the location where the local temperature is about the critical temperature $T_c$. However, $\Delta P_e$ is found to be proportional to the laser-induced global voltage change $\Delta V_{dc}$, irrespective of the laser position. This unexpected global response is likely to be related to a change in the average stack temperature and is consistent with the change in $P_e$ when increasing the bath temperature by about 0.2 K. This tuning method can be employed in the application of BSCCO THz sources.

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I. INTRODUCTION

Developing compact, tunable sources for THz generation is a highly active field of research [1,2]. Recently, it was found that intrinsic Josephson-junction (IJJ) stacks, naturally formed in the cuprate superconductor Bi$_2$Sr$_2$CaCu$_2$O$_8$ (BSCCO), can emit coherent radiation at submillimeter wavelengths [3]. In Ref. [3], stacks consisting of about 700 IJJs with a typical length of 300 μm are realized as mesa structures on top of BSCCO single crystals. An emission power $P_e$ of up to 0.5 μW is detected for emission frequencies $f_e$ between 0.5 and 0.8 THz. A lot of work has been performed following this discovery [4–48]; for a recent review, see Ref. [49]. $P_e$ is raised to 82 μW with stand-alone structures, which are no longer patterned on a BCCSO base crystal [27,33]. By synchronizing three mesas patterned on the same base crystal, $P_e$ is increased to 610 μW [30]. The linewidth of radiation can be as low as 6 MHz [44] and the maximum emission frequency reaches 1.6 THz [48]. In the IJJ stacks, THz emission is generated by the ac Josephson effect, yielding an emission frequency $f_e = 2eV_{dc}/Nh$, where $N$ is the number of junctions and $V_{dc}$ is the total dc voltage across the stack. This relation assumes that the voltage drop $V_{dc}/N$ is the same for all junctions. Furthermore, the Josephson relation suggests that $f_e$ is freely tunable by the applied voltage (0.4836 THz per mV across each IJJ), perhaps up to the superconducting energy gap, which would yield a maximum emission frequency of some 10 THz. However, in real systems, there is strong Joule heating, leading, e.g., to the formation of hot spots (regions heated to temperatures above the critical temperature $T_c$) in the stack [7,13,14,29,31,36,43] and also limiting the maximum voltage per junction to values less than 3 mV. Furthermore, collective cavity modes utilizing the whole stack as a resonator seem to play an important role for synchronizing the IJJs [3,13,14].

Understanding—and ideally also controlling—the relations between THz emission, the inhomogeneous temperature distribution in the stack, and the mechanism of synchronization is a key issue in optimizing the device, not only with respect to $P_e$, $f_e$, and the linewidth of emission but also with respect to the tunability of both $P_e$ and $f_e$. A series of papers addresses the issue of thermal management [6,17,24,40,41,45–48]. In particular, it is proposed that $P_e$ can be enhanced by using a focused laser to locally increase the temperature variation in the stack, thereby strongly exciting plasma waves in the stack [41]. This method is used in the present work, although...
with the difference that, in Ref. [41], an initially homogeneous temperature distribution is assumed while, in our experiment, the sample investigated emits THz radiation in the presence of a hot spot. Measurements are done on an IJJ stack embedded between two gold layers, the gold-BSCCO-gold (GBG) structure [40]. By scanning the laser at half width along the length of the stack in the hot-spot regime, we succeed in changing $P_e$ continuously at a constant bias current $I$. The variations in $P_e$ are strongest when the laser is focused on a location where the local temperature in the stack roughly equals $T_c$.

Very recently, a similar experiment was performed using mesa structures. Also here, an increase of $P_e$ is observed and appears when the hot-spot position is moved to a mesa end by locally heating the mesa surface with an 80 mW laser beam.

II. EXPERIMENTAL METHOD

A schematic diagram of the GBG structure is shown in Fig. 1. The lateral dimension of the sample studied in this work is about $290 \times 50 \ \mu m^2$. The sample is mounted on a hemispheric sapphire lens. A laser with wavelength $\lambda = 1310 \ \text{nm}$ and a spot diameter of about $1 \ \mu m$ is focused onto the surface of the stack. The laser can scan across the surface of the stack with submicrometer precision. Using a Si bolometer, we measure the emission power of the sample from the other side of the hemispheric lens while keeping the laser on at the same time. The power detection and frequency measurement are similar to our previous work [14]. By modulating the laser power with a 10 kHz square signal and detecting the global differential voltage response $\Delta V$ of the stack with a lock-in technique while the sample is biased at a constant current, the setup can also be used as a low-temperature scanning laser microscope (LTSLM) [7,13,14,24]. In the present study, we use a comparatively strong beam power; thus, the LTSLM is operated in a manipulation mode rather than an imaging mode. In fact, we estimate that the maximum power of the laser beam arriving at the sample is in the range 2–5 mW. However, most of this intensity is reflected from the Au layer covering the mesa. From the change in the dc voltage across the stack upon laser irradiation, we estimate that a power of 100 $\mu$W or less (depending on the laser position and bias current) is absorbed by the mesa.

III. RESULTS AND DISCUSSIONS

In Fig. 2(a), the outermost branch of the current-voltage characteristic, at a bath temperature $T_b = 22 \ \text{K}$, is shown by a solid red line, and the emitted power, for the laser beam turned off, is presented in Fig. 2(b) as a function of bias current. Terahertz emission is only detected at the high-bias regime, from $(I, V_{dc}) \sim (50 \ mA, 0.93 \ \text{V})$ to $(20 \ mA, 0.88 \ \text{V})$. For the peak in $P_e$ at $(I, V_{dc}) = (28 \ mA, 0.883 \ \text{V})$, the emission frequency is found to be about 690 GHz, corresponding to $N \approx 620$ IJJs in the resistive state. By its color scale, Fig. 2(a) also shows the LTSLM signals $-\Delta V$ for a family of LTSLM linescans recorded for a large number of bias currents. The linescans are taken along the length of the stack at half of its width. In the graph, the two vertical dashed lines indicate the left and right boundaries of the stack. For currents below 20 mA, there is a strong signal near the left edge of the stack. This edge is not covered by the top Au layer and is much more sensitive to laser irradiation than other areas. One further observes that, near $I \approx 7 \ mA$, the strong LTSLM response extends significantly from the left edge of the stack toward the center of the stack. In this bias regime, where $V_{dc}$ starts to bend back, a hot spot nucleates and is, presumably, to some extent, moved toward the interior of the stack by the laser beam during scanning. A similar effect (i.e., a laser-induced shift of the hot-spot position) is seen in Ref. [47]. For larger currents, $-\Delta V$ is more restricted to the left part of the stack and develops a local maximum inside the stack, which shifts to the right with increasing current (cf. the tilted, dashed line). This kind of maximum is typical for the edge of a hot spot [24]; i.e., we observe that, for currents above 12 mA, a stable hot spot forms in the left part of the stack and the hot spot increases in size with increasing current. In this regime, the reaction of the hot spot on the laser beam is close to the standard imaging mode; i.e., it slightly increases in size but its position remains fixed [24]. This seems natural because, with increasing dc input power, the relative contribution of the laser beam to local heat production becomes smaller.

Next, we investigate how $P_e$ varies when the laser is positioned at different locations $x_L$ along the stack. For the measurement, we place the laser at a given value $x_L$ for 150 ms, measure $P_e$, and then vary $x_L$ in steps of 1 $\mu m$. Figure 3(a) shows the resulting $P_e$ vs $x_L$ for $T_b = 22 \ \text{K}$ and $I = 28 \ mA$. The lower horizontal dashed line in the graph...
To study this further, we compare, in Fig. 4, for \( T_b = 22 \) K and four selected bias currents, (a) the laser-induced change in dc voltage \( -\Delta V_{dc} \), (b) the LTSLM signal \( -\Delta V \), and (c) the laser-induced change \( \Delta P_e \) in emission power. Note that \( \Delta V_{dc} \) and \( \Delta V \) would be the same if the laser is modulated arbitrarily slowly, rather than with 10 kHz. For measuring \( \Delta V_{dc} \) and \( \Delta V \), the laser, while still modulated, is kept at a fixed position \( x_l \) for 150 ms. Thus, \( \Delta V_{dc} \) measures laser-induced temperature changes which occur within 150 ms of (modulated) laser irradiation while \( \Delta V \) gives the short time response. Not very surprisingly, the overall amplitude of \( \Delta V_{dc} \) is larger than the amplitude of \( \Delta V \) and the positions of the minima (the hot-spot edges) are slightly shifted to the left for \( \Delta V_{dc} \) compared to \( \Delta V \). More importantly, the shape of \( -\Delta V \) vs \( x_L \) is basically the same as the shape of \( \Delta P_e \) vs \( x_L \). In Fig. 4(d), we plot \( \Delta P_e \) vs \( -\Delta V_{dc} \) for the four bias currents and all values of \( x_L \); i.e., \( x_L \) runs as a parameter in this graph. In the plot, we exclude the data from the edge peaks, because here the time delay of the Si bolometer relative to the voltmeter causes a significant phase shift between \( \Delta P_e \) and \( \Delta V_{dc} \). For the rest of the \( x_L \) values, one obtains straight lines for all currents, confirming the proportionality of \( \Delta P_e \) and \( \Delta V_{dc} \). Note that the slopes \( \Delta P_e/\Delta V_{dc} \) amount to about \(-3\) nW/mV for
bias currents of, respectively, 24 mA and 36 mA and to about −6 nW/mV for bias currents 28 mA and 32 mA. The large values of $|\Delta P_e/\Delta V_{dc}|$ are in fact obtained near the center of the emission peak in $P_e$ vs, respectively, $I$ and $V_{dc}$; cf. Figs. 2(b), 2(c), and 3(b).

The proportionality $\Delta P_e \propto \Delta V_{dc}$ is unexpected. In view of the proposal of Ref. [41], one might assume that there is a big difference if the laser is positioned inside the hot-spot region compared to a position where the stack temperature is below $T_c$. Furthermore, when the laser is positioned near the edges of the stack, the local electric and magnetic field distribution, and thus the radiation impedance [15], might change, giving rise to a change in $P_e(x_L, y_L)$. In particular, one would expect signals in Fig. 3(c) or in Fig. 4(c) on the cold edge of the stack. This is not observed. For the experiments described in Ref. [47], performed on mesa structures, it is concluded that the laser-induced enhancement of the emission power is realized by an adjustment of the hot-spot position. Also for this case, we do not see a reason why $P_e(x_L, y_L)$ and $\Delta V(x_L, y_L)$ should be strictly proportional to each other.

Accepting the proportionality of $\Delta P_e$ to the global response $\Delta V_{dc}$, one might assume that by changing $V_{dc}$ with the amount $\Delta V_{dc}$, one simply moves toward a lower voltage in the $P_e$ vs $V_{dc}$ curve of Fig. 2(c). However, the bias currents in Fig. 4 are chosen so that in $P_e$ vs $V_{dc}$ points on both sides of the emission peak are covered; thus, one should get different signs of the response, e.g., for $I = 24$ mA and 36 mA. With the laser turned on, there is also a slight increase in the average stack temperature which to some extent is equivalent to an increase of the bath temperature. For the sample, we find that, for the bias currents of interest, $V_{dc}$ changes by about 3–4 mV/K. Thus, the laser-induced relative change in voltage corresponds to a change in $T_b$ of about 0.2 K. By changing $T_b$ for fixed values of the bias current, we find that $P_e$ in fact oscillates as a function $\Delta V_{dc}$ and, near the bath temperature of 22 K, increases by more than a factor of 5 when increasing $T_b$ by only 2 K. A 0.2 K laser-induced temperature change is thus compatible with the increase in $P_e$ that we observe.

**IV. SUMMARY**

In summary, we investigate the response of a BSCCO intrinsic Josephson-junction stack, embedded between two gold electrodes, to a focused laser beam which is scanned across the stack. The laser-induced changes in the voltage $V_{dc}$ across the stack and in the THz emission power $P_e$ are measured simultaneously. The study is motivated by the recent theoretical study [41] proposing that a laser beam locally heating the stack, thereby causing a critical current inhomogeneity, can give rise to a strong enhancement of $P_e$ in comparison with the homogeneous state. In our experiment, the sample does not emit in the low-bias regime, neither in the absence nor in the presence of the laser beam. However, the laser-induced changes of the emission power are found at the high-bias regime in the presence of a hot spot. For a bath temperature near 22 K, the laser-induced changes of the emission power, in which case $\Delta P_e(x_L, y_L)$ is proportional to the voltage change $\Delta V_{dc}(x_L, y_L)$ for all values of the position $(x_L, y_L)$ of the laser beam, $\Delta V_{dc}(x_L, y_L)$ itself, and consequently also $\Delta P_e(x_L, y_L)$, strongly depends on the $(x_L, y_L)$ position, being, e.g., large near the edge of the hot spot. The laser-induced change of the voltage across the stack is essentially determined by the temperature dependence of the BSCCO c-axis conductance, as is analyzed in Ref. [24]. In fact, we would have expected that different mechanisms lead to laser-induced changes of the emission power, in which case $\Delta P_e(x_L, y_L)$ and $\Delta V_{dc}(x_L, y_L)$ should have different dependences on the local beam position. The unexpected global response is likely to be related to a change in the average stack temperature and is consistent with the change in $P_e$ when increasing the bath temperature by about 0.2 K.

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