Superconducting THz sources with 12% power efficiency

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Low power efficiency is one of the main problems of THz sources, colloquially known as “the THz gap”. In this work we present prototypes of THz devices based on whisker-crystals of a high-temperature superconductor Bi2Sr2CaCu2O8+δ with a record high radiation power efficiency of 12% at a frequency of ~4 THz. We employ various on- and off-chip detection techniques and, in particular, use the radiative cooling phenomenon for accurate evaluation of the emission power. We argue that such devices can be used for creation of tunable, monochromatic, continuous-wave, compact and power-efficient THz sources.

Tunable, monochromatic, continuous-wave (CW), compact and power-efficient sources of terahertz (THz) electromagnetic waves (EMW) are required for a broad variety of applications such as spectroscopy, environmental control, security, non-ionizing medical imaging, ultrahigh-speed telecommunication and electronics, as well as for fundamental research in various areas of science [1,2]. The key problem of THz sources, colloquially known as the “THz gap”, is a rapid decay of radiation power efficiency (RPE), i.e. the ratio of emitted and dissipated power [3], in the low THz range [1]. Despite a significant progress, achieved in development of semiconductor quantum cascade lasers (QCL’s) [4–6], the RPE of CW QCL’s drops from ~28% at f ≈ 55 THz [7] to a sub-percent at 3–4 THz [8,9] and to ~0.01% at f ≈ 1.3 THz [10]. Although QCL frequency can be tuned [4,5,9,11,12], this comes at the expense of a dramatic reduction of RPE to ~0.0001% [11] when low THz emission is obtained by mixing or downconversion of higher frequencies [11,12]. QCL’s emitting at primary low THz frequencies, on the other hand, have to be cooled down to cryogenic temperatures, kBT < hf [3,10].

Superconducting devices, based on arrays of Josephson junctions (JJ’s) have an inherent frequency tunability and provide and alternative technology for creation of tunable THz sources with tunable, monochromatic CW operation [13–30]. The Josephson frequency, fJ = (2e/h)V, is proportional to the dc-bias voltage V and is limited only by the superconducting energy gap, which can be in excess of 30 THz for high-temperature superconductor Bi2Sr2CaCu2O8+δ with a record high radiation power efficiency of 12% at a frequency of ~4 THz. We employ various on- and off-chip detection techniques and, in particular, use the radiative cooling phenomenon for accurate evaluation of the emission power. We argue that such devices can be used for creation of tunable, monochromatic, continuous-wave, compact and power-efficient THz sources.

Here we present prototypes of novel THz sources based on Bi-2212 whisker-type crystals with intermediate-size mesa structures. We employ various techniques for detection of THz radiation such as an in-situ detection by a mesa on the same whisker, an off-chip detection by electrically isolated mesa and an off-chip detection by a bolometer. Furthermore, we employ the radiative cooling phenomenon for estimation of the absolute value of the emitted power. It reveals that the RPE of our devices can reach 12% making a significant step forward towards the theoretical limit of 50%. The boost of efficiency is attributed to a good impedances matching with open-space, caused by a specific turnstile antenna-like geometry of our devices. We argue that such devices can be used for creation of tunable, and, most importantly power-efficient THz sources.

Figures 1(a) and (b) show an image and a sketch of studied devices. In the middle of each device there is a Bi-2212 whisker crystal with typical sizes (300 – 500) × (20 – 30) × (1 – 5) μm3 along crystallographic a, b and c-axes, respectively. Several metallic electrodes with the width 10 – 15 μm are made across the whisker. Beneath each electrode there is a mesa structure containing N ~ 150 – 250 intrinsic JJ’s. Devices are made by conventional microfabrication techniques. Details about sample fabrication and the experimental setup can be found in Ref. 21, 32 and the Supplementary 35.

Fig. 1(c) shows the current-voltage (I-V) characteristics of a mesa at T ≈ 3 K. It consists of multiple branches, due to one-by-one switching of JJ’s from the superconducting to the resistive state [31,33]. The total number of JJ’s, N ≈ 150 ± 10 for this mesa, is obtained by counting branches. A rough estimation, valid for all our

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mesas is \( N \approx V_{\text{max}}/10 \text{ mV} \), where \( V_{\text{max}} \) is the voltage at a maximum in the \( I-V \) curve. The maximum is caused by back-bending at high bias due to self-heating. The extent of self-heating depends on geometry and decreases with decreasing mesa sizes \([30,37]\). Sizes of our mesas are in the range \((2.5 - 10) \times (10 - 30) \mu\text{m}^2\) with areas \( 50 < A < 300 \mu\text{m}^2 \), which are significantly smaller than “large” mesas \((A > 10^4 \mu\text{m}^2)\) studied in the majority of earlier works \([16,20,23,29]\), but larger than “small” mesas \((A \lesssim 10 \mu\text{m}^2)\) studied in Ref. \([21]\). Thus, our mesas are of “intermediate size”. This enables a significant overall power \(\sim 1 \text{ mW} \) with a tolerable self-heating.

To analyze EMW emission, we start with an on-chip generation-detection scheme \([21]\) using one mesa as a generator and another mesa on the same chip as a switching-current detector. Figure 1 (d) shows evolution of the \( I-V \) of the detector at three bias points \((I_{\text{gen}}, V_{\text{gen}})\) in the generator. The \( I-V \) of the generator mesa, with marked bias points, is shown in the top panel of Fig. 2 (a). From Fig. 1 (d) it is seen that with increasing bias in the generator, critical currents in the detector are first reduced (red curve) and then get completely suppressed (blue curve) due to the EMW absorption \([21]\). Detailed dynamics of the generation-detection experiment is demonstrated in the supplementary video \([35]\).

Absorption of EMW by a JJ leads to formation of Shapiro steps in the \( I-V \) at \( V_n = n hf/2e \) (\( n \)-integer). Thus, junction response carries a spectroscopic information both about the frequency and the amplitude of EMW. In mesas with \( N \) JJ’s, the EMW emission occurs at \( f_J = 2e V_{\text{gen}}/Nh \) (provided all JJ’s are synchronized). Thus, the primary Shapiro step should appear at \( V_{\text{det}} = V_{\text{gen}}/N \). Small steps can indeed be seen in the blue \( I-V \) from Fig. 1 (d). Fig. 1 (e) shows the differential conductance for this curve. It exhibits clear peaks, corresponding to steps in the \( I-V \). The grid spacing is equal to \( V_{\text{gen}}/N \) with estimated \( N \approx 200 \) for the generator mesa, see Fig. 2 (a), and is in agreement with the observed peak separation. Some displacement of peak positions is likely caused by the fact that the detector response involves six JJ’s, see Fig. 1 (d). A certain difference between JJ’s leads to a mismatch of bias conditions for appearance of Shapiro steps. This affects both the regularity and the amplitude of Shapiro steps. Nevertheless, the data is consistent with occurrence of monochromatic emission at \( f_J \approx 4.3 \text{ THz} \) because the non-monochromatic emission would not lead to appearance of distinct steps.

To exclude possible electrical crosstalk, we performed

![Image](image-url)
FIG. 2. (Color online). Comparison of on-chip and off-chip detection schemes. (a) On-chip generation-detection with electrically connected mesas. Top panel: the $V$-$I$ of a generator mesa at $T \simeq 3$ K. Circles represent bias points for the detector $I$-$V$'s in Fig. 1 (d). Bottom: $ac$-resistance of the detector mesa as a function of the generator current. Blue/red curves represent up and down bias sweeps. (b) A setup for off-chip detection of emission by a NbN bolometer and images of the bolometer (from Refs. 39, 30). (c) Off-chip detection experiment. Top: The $V$-$I$ of the generator mesa. Bottom: the bolometer response as a function of $I_{gen}$. Vertical dashed lines in (a) and (c) indicate that emission occurs at the step in the generator $I$-$V$.

similar generation-detection experiment using electrically disconnected mesas. For this the whisker was cut by a focused ion beam in two sections, thus separating the generator and the detector mesas. The detector response remains qualitatively unchanged after such separation. Fig. 1 (f) shows the $I$-$V$ of the generator mesa, color mapped by the response of electrically disconnected detector mesa ($ac$-resistance, $R_{det}^{ac}$, measured by the lock-in technique with zero offset). It is seen that a profound, almost vertical step develops in the back-bending region of the $I$-$V$. The color code indicates that the detector response appears just at this step and disappears both above and below. In Fig. 2 (a) the same behavior is demonstrated for the on-chip generation-detection experiment with electrically connected mesas. Here a correlation between the step in the $I$-$V$ of the generator and the upturn in the detector response is clearly seen (see also the Supplementary video 35). Such a non-monotonous behavior precludes self-heating origin of the observed signal and confirms occurrence of the EMW emission 21.

To confirm EMW emission into open space we perform off-chip detection using a NbN bolometer 35. Fig. 2 (b) shows the measurement setup and images of the bolometer (from Refs. 35, 30). The bolometer is placed at a distance $\sim 1$ cm above the device. Fig. 2 (c) shows corresponding generation (top) and detection (bottom) characteristics. Vertical dashed lines indicate that the bolometer response ($lock$-in resistance $R_{bol}^{ac}$) appears at the step in $I_{gen}$-$V_{gen}$, thus confirming EMW emission. Some difference in the shapes of on-chip, Fig. 2 (a), and off-chip, Fig. 2 (c), responses is likely caused by the spectral selectivity of the double-slot antenna of the bolometer, peaked at $f = 1.6$ THz, well below the emission frequency $f_{J} \simeq 4.2$ THz for this mesa 40.

Power dissipation leads to heating, but EMW emission — to radiative cooling of the device. We use this for unambiguous estimation of the emission power, $P_{THz}$. Figure 3 (a) represents the on-chip generation-detection measurement for another device (upward bias sweep). The sample stage of our dry cryostate has a relatively small heat capacitance and a finite heat resistance, $R_{th}$, to the coldhead. Therefore, its temperature directly reflects the energy balance at the chip. Fig. 3 (b) shows the stage temperature as a function of the dissipation power, $P_{gen} = I_{gen}V_{gen}$, for the data from Fig. 3 (a). As expected from the Newton’s law of cooling, it increases approximately linearly, $T_{stage} \simeq T_{0} + R_{th}P_{gen}$, with $R_{th} = 0.508$ K/mW. However, at $P_{gen} \simeq 0.6$ mW there is a visible drop down from the linear dependence. In Fig. 3 (c) we plot this drop, $\Delta T$, vs. $I_{gen}$. It clearly follows the detector response, shown by the red line in Fig. 3 (a). The correlation between $\Delta T$ and the EMW emission provides a straightforward demonstration of the radiative cooling phenomenon. Importantly, it allows direct estimation of $P_{THz} = \Delta T/R_{th}$. The maximum drop $\Delta T = -31.5 \pm 2$ mK occurs at $I_{gen} \simeq 0.4$ mA and $P_{gen} = 0.6$ mW. This yields $P_{THz} \approx 62$ $\mu$W and RPE of 10.3 $\pm$ 0.7% for this device.

Figs. 3 (d-f) show similar measurements for another device. Fig. 3 (d) shows $V_{gen}$ (blue, left axis) and $R_{det}^{ac}$ (red, right axis) vs. $P_{gen}$ for the upward bias sweep (black lines represent similar data for the reverse sweep). The dark blue curve in Fig. 3 (e) shows $T_{stage}$ vs. $P_{gen}$ for the upward sweep. Inset shows time dependence of $P_{gen}(t)$ during this sweep. It is nonlinear due to the non-Ohmic $I$-$V$ of the generator. The nonlinearity may cause some transient effects. Therefore, to make an accurate calibration of the bare (without device) thermal response of the stage we heated it by a resistor, applying exactly the same time-dependence of the dissipation power using a
We presented prototypes of novel THz sources based on whisker-based devices. We argue that such devices can be used for creation of turnstile antenna-like geometry of whisker-based devices. Impedance matching with open space due to the specific whisker-based devices is caused by a specific turnstile antenna-like geometry. Optimization of emission requires proper microwave design for impedance matching.

The corresponding variation of T_{stage} is shown by the magenta line in Fig. 3(e). It is almost linear with the slope R_{th} \sim 0.514 K/mW. Fig. 3(f) shows the difference between T_{stage} with and without device (blue) and the radiation power efficiency RPE=−ΔT/(R_{th}P_{gen}) (red curve). It is seen that the maximum RPE for this device reaches 12%, which corresponds to the emission power of P_{THz} \sim 0.11 mW. We want to emphasize that this power is actually emitted in the far-field. Indeed, it is taken out of the range cooled by the second stage of the cryocooler (which has a small cooling power) and is dumped into the first stage (with a very large cooling power), which is 10-40 cm away. This distance is much larger that the wavelength, \lambda \sim 70 \mu m, at f \sim 4.3 THz. Therefore, the radiative cooling probe the total far-field emission. Of course, for the practical device the emission should be collected and delivered via open space to the desired place, which inevitably involve certain losses. In this respect the estimation of RPE from the radiative cooling provides the upper limit of the achievable “useful” emission.

Estimations above indicate that whisker-based THz sources can have RPE > 10%, not far from the theoretical limit of 50% [34]. This significantly exceeds the RPE for devices made on regular Bi-2212 crystals [17, 21]. Generally, the low RPE is caused by poor impedance matching with open space [34]. JJ’s are much smaller than the wave length. Especially tiny are interlayer distances \sim 1 nm. Therefore, JJ’s act as miniature dipoles with almost no emission in the far field. Essentially, the emission is facilitated by other passive but large-size elements of the device such as the Bi-2212 crystal and the electrodes, acting as matching antennas. Optimization of emission requires proper microwave design for impedance matching. In the Supplementary [35] we discuss the geometrical differences between crystal- and whisker-based devices. We argue that the reported boost of RPE in whisker-based devices is cause by a specific turnstile antenna-like geometry, which allows obviation of a large parasitic capacitance between the crystal and the electrode and facilitates good impedance matching with open space.

To conclude, a low radiation power efficiency is one of the main problems of THz sources. For cryogenic sources the emission power is limited both by the cooling power and RPE: \Pi_{THz} < \Pi_{cooling}. For portable cryocoolers with limited \Pi_{cooling}, the only way to increase the emission power is by enhancement of the RPE. We presented prototypes of novel THz sources based on Bi_2Sr_2CaCu_2O_{8+δ} whiskers with RPE up to 12%, more than an order of magnitude larger than for similar devices made on regular Bi-2212 crystals. This indicates better impedance matching with open space due to the specific turnstile antenna-like geometry of whisker-based devices. We argue that such devices can be used for creation of
tunable, monochromatic, continuous-wave, compact and, most importantly, power-efficient THz sources.

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