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Engineering the Cavity modes and Polarization in Integrated Superconducting Coherent Terahertz Emitters

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***Abstract*— On-chip, solid-state terahertz (THz) devices based on superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) can coherently and continuously radiate electromagnetic waves with frequencies tunable between 100 GHz and 11 THz. Their huge frequency tunability observable by the application of an applied voltage of as small as $0 < V_{dc}$ (V) <1.5 covers the entire THz gap. Here, we report on a novel approach towards engineering the THz waves in such devices, with pentagonal cavities, by performing the numerical simulations/analytical calculations of the cavity resonances. We investigate the radiation of the intense and coherent THz waves in pentagonal emitters by keeping the bias feed point in the middle and changing the device geometry. We compare the results with the experiment and find a good agreement.**

I. INTRODUCTION

At terahertz (THz) frequencies, f= 100 GHz - 10 THz in the electromagnetic spectrum, the available components, such as antennas, emitters, waveguides, detectors, and receivers, are generally inefficient and impractical. Hence, a gap exists between mature microwave and developed optical technologies [1-22]. THz offers wide bandwidth, and it makes the high data transfer rates possible. The THz band is vital for the realization of 6 G mobile wireless networks, with a data transfer rate at terabits per second. Moreover, THz can empower the implementation of the internet of things (IoT), with a system of many communicating devices. Therefore, the realization of integrated, low-cost, and efficient generation, waveguiding, detection, and manipulation of THz waves are highly demanding.

Based on the quantum tunneling of electron pairs across the stack of intrinsic Josephson junctions (IJJs), that are naturally present in a single crystal of the layered high-T_c superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO), one can realize integrated, broadly tunable, and powerful quantum sources that coherently radiate THz waves between 0.1 and 11 THz (potentially extendable to 15 THz limited by the superconducting gap frequency) and with a potential output power of > 1 mW. Such devices have been found to be especially promising solid-state THz sources capable of bridging the entire THz gap.

Here, we discuss techniques to engineer THz waves in IJJs devices. Our focus will be on the devices with pentagonal cavities. We show that how the fundamental cavity resonance modes of the pentagonal antennas depends on the geometry of the devices. We first investigate the fundamental cavity modes in superconducting THz antenna with a standard pentagonal shape cavity. We then slightly change the standard pentagonal cavity by rounding two edges and finally by rounding all edges. In all cases, the current bias feed point is located in the middle of the superconducting THz antennas.

II. RESULTS

In this section, we examine the effect of device geometry on the radiation of intense and coherent THz waves in superconducting THz devices [2]. We are particularly interested in pentagonal cavities because they can radiate circular polarized THz waves with only one single bias-feed point. We perform numerical calculations and investigate the antennas' S-parameters and emission power spectrum at frequency ranges between 300 GHz and 4 THz, and observe sharp resonances. The side length and thickness of our THz devices with regular pentagonal cavities are 60 µm and 1 µm, respectively, which are consistent with the dimension presented in [2,3].

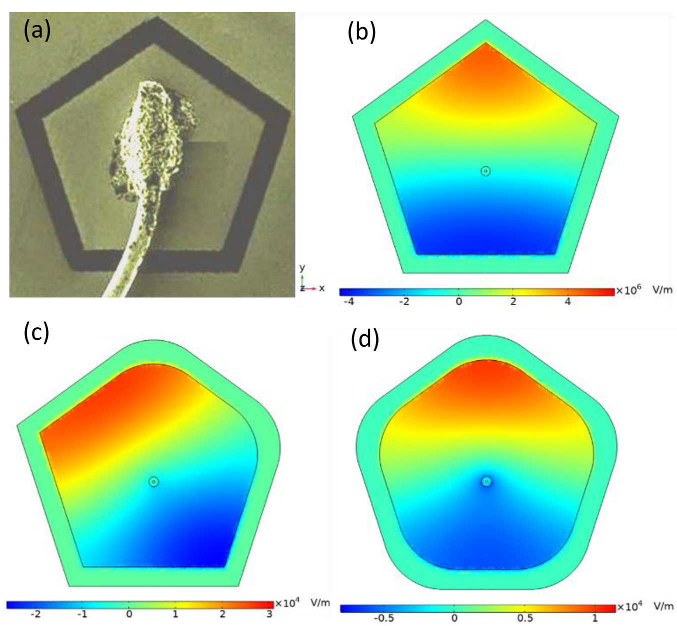

Fig. 1. (a) A false color scanning ion microscope image of the superconducting THz emitter with regular pentagonal cavity. The current bias feed is located in the middle of the device. Sketch of the pentagonal THz devices together with the electric field E_z map at f = 0.46 THz., for (b) regular pentagonal geometry similar to that fabricated THz device shown in (a), (c) for regular pentagonal cavity with two rounded edges, and (d) for regular pentagonal cavity with all rounded edges. In (b-d) a single-feed point is chosen to be in the center.

In this work, we report only the sharp resonance appears around frequency f= 0.462 THz as this frequency is almost equal to the peak frequency observed in the experiment on reported in [2,3].

Figure 1 (a) is a false color scanning ion microscope image of the THz emitter, with a regular pentagonal cavity, made from high-T_c superconducting BSCCO with a transition temperature $T_c \cong$ 68.6 K.. The current bias feed is located in the middle of the device. Figure 1 (b) shows the snapshot of the electric field amplitude E_z, at f= 0.462 THz for single-feed pentagonal THz antenna. We can see that the THz device with a regular pentagonal cavity shows a standing wave mode that is symmetric across the y-axis. The results are in good agreement with the data reported previously from a different method [2].

By rounding only two corners of the regular pentagonal THz device, see Fig. 1 (c), the standing wave becomes slightly asymmetric. When all edges are rounded, see Fig. 1 (d), the mode becomes symmetric again but with less intensity compared to the regular pentagonal cavity. We also investigate the angular distribution of the THz emission from these devices at f= 0.462 THz and study the polarization conversion from linear to circular polarization by calculating the antennas' axial ratio (dB). These results will be discussed in detail elsewhere.

III. Summary

We introduced a novel approach towards engineering the cavity modes in on-chip superconducting coherent THz emitters. We investigated the radiation of the intense and coherent THz waves in pentagonal emitters by keeping the bias feed point in the middle and changing the device geometry. We compared our results with the experiment and found a good agreement.

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