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# Series YBCO grain boundary Josephson junctions as a terahertz harmonic mixer

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## Abstract

Josephson devices have demonstrated the capability to work as harmonic mixers at terahertz frequencies. Low temperature devices, in particular Nb-Nb point contacts have proven particularly successful. However, practical applications of these devices have been limited by the need of utilizing liquid helium. To overcome this limitation we have investigated the use of high-$T_c$ devices. In this paper, we report mixings up to the 154th harmonic at zero-bias in a series of $YBa_2Cu_3O_{7-\delta}$ (YBCO) grain boundary (GB) Josephson junctions. We have integrated a meander series of three bicrystal YBCO Josephson junctions with a log-periodic antenna. When properly operated, this configuration allows to reach a harmonic number much higher than what possible with a single junction. This shows that the mixing performance benefits from the synchronous operation which also results in an improvement of dynamic range. We believe that the integration of a higher number of phase-locked junctions may further improve the mixer's performance. Future studies should investigate the effect of higher number of junctions on the mixer performances, as well as the effect of the meander length.

Keywords: series Josephson junctions, Josephson junction array, terahertz harmonic mixing, zero bias

## 1. Introduction

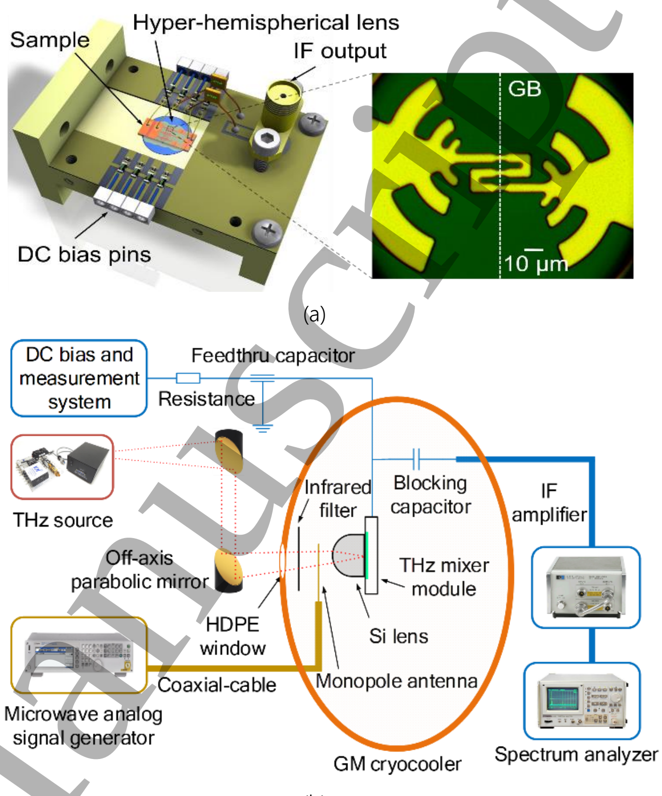
Josephson devices based on Josephson effects can have unique harmonic generating and mixing properties, which have been used in mixing experiments since the late 1960s. At liquid helium temperatures, in particular Nb-Nb point contacts have proven particularly successful. The largest harmonic number being 825 was from an Nb-Nb point-contact Josephson junction [1]. However, practical applications of these devices have been limited by the need of utilizing liquid helium. To overcome this limitation, Gao and Du *et al*. have reported many works on high-$T_c$ superconducting (HTS) $YBa_2Cu_3O_{7-\delta}$ (YBCO) step-edge Josephson junction mixers at terahertz (THz) band recently [ 2-6]. It shows that the largest harmonic number is around 30, much lower than that in low temperature devices. On the other hand, sizes of Josephson harmonic mixers have to be very small at THz frequency. A saturation problem of harmonic-mixer would be risen with increase of signal frequency, effective bandwidth and harmonic order. Matsui and Komiyama *et al*. performed harmonic mixing at 105.9 GHz with a series array of eleven Josephson junctions at liquid helium temperature [7]. 5 dB heightening was obtained in the signal-to-noise ratio (SNR) of intermediate frequency (IF) output in the 11th harmonic mixing. They attributed it to the enhancement of dynamic range by using the series array structure. Later, Konopka and Wolf *et al*. accomplished 7th harmonic mixing for 670 GHz detection by a series array of twenty YBCO step-edge Josephson junctions [8]. Regarding direct current (DC) bias, they mentioned the IF amplitude was very weakly dependent on the biasing point of the superconducting structure. Efficient mixing without biasing was also observed [9]. Thus, zero-bias operation is feasible for Josephson junction mixer and has a great advantage of not requiring a DC supply and thus no heating effect or shot noise is produced in the junction due to DC bias. Also, Du *et al*. fabricated the arrays of fifty YBCO step-edge Josephson junctions in series [10]. In their report, Shapiro steps beyond the zeroth order could not be unambiguously resolved, maybe resulting from the critical current variations in the array junctions or the non-uniform microwave current distribution in the array. And Burkhardt *et al*. attributed such a cause to non-phase locking [11].

HTS array-based devices for different applications have been developed in voltage standard [12-14], wave generators [15-16], detectors and fundamental mixers [17-18]. However, harmonic mixers of HTS Josephson junction series arrays (JJSAs) with high harmonic numbers have not been investigated yet.

In this paper, we integrate a meander series of three bicrystal YBCO Josephson junctions integrated with a log-periodic antenna. The harmonic mixing experiments based on three-Josephson-junction-in-series (3JJS) mixers are carried out at different bath temperatures. The synchronizations and the mixing performances are also studied in detail.

## 2. Experimental details

80-nm thick YBCO films covered with 20 nm *in situ* Au films were deposited via pulsed laser deposition on bicrystal magnesium oxide (MgO) substrates with a misorientaion angel of 24°. YBCO film has a critical current density $J_c$ of 2.5 MA cm$^{-2}$ and a critical temperature $T_c$ of 85.7 K. Three Josephson junctions in shape of 6-μm-long and 2-μm-wide bridges crossing the grain boundary (GB), are in series with a meander then to be embedded into a log-periodic antenna, as seen in the zoomed photo in figure 1 (a). The meander has a total length of 108 μm, a width of 4 μm and a gap of 3 μm. The log-periodic antenna has a maximal outer radius of 164 μm and a minimal inner radius of 7 μm with the ratio of outer radius to inner radius being $\sqrt{2}$ [19]. The mixers are patterned by standard photolithography and Ar-ion beam etching techniques. Mixers can be fabricated on the same 10×3 mm$^2$ MgO bicrystal substrate. A silicon (Si) hyper-hemispherical lens with a diameter of 9 mm and a thickness of 0.7 mm is attached to the back of the substrate with cryogenic glue to enhance the coupling of THz radiation. The DC bias lines on the mixer chip are connected to the DC bias pins through gold wires and silver epoxy. The filter module composed of resistors and capacitors on the DC bias pins is applied to isolate the DC and IF signals. All of these are packaged in a sample holder, shown in figure 1 (a) as well. IF output shares the path on the mixer chip with the DC bias, isolated through two capacitors.



(a)

(b)

Figure 1. (a) Josephson mixer on a sample holder with packaged modules. (b) Schematic diagram of the measurement setup for harmonic mixing.

Measurements are carried out in a Gifford-McMahon (GM) cryocooler at the bath temperature from 4.5 K to 70 K. Figure 1 (b) shows the schematic diagram of the mixing setup. The THz signal is generated from a commercial VDI-Tx-S140 made by Virginia Diodes Inc. and propagates along the quai-optical link to the sample holder with the Si lens facing to the window of the GM cryocooler. The LO pumping is from an Agilent MXG analog signal generator N5183A and radiated out through a frequency-dependent monopole antenna with a length of 1.95 cm. The frequency dependence of radiant efficiency has been calibrated by a vector network analyzer. The down-converted IF output signal is amplified by HP 8447D 011 Dual Amplifier with a gain of around 50 dB over the frequency band of 0.1-1300 MHz and then recorded in an Advantest R4131D spectrum analyzer.

## 3. Results and discussion

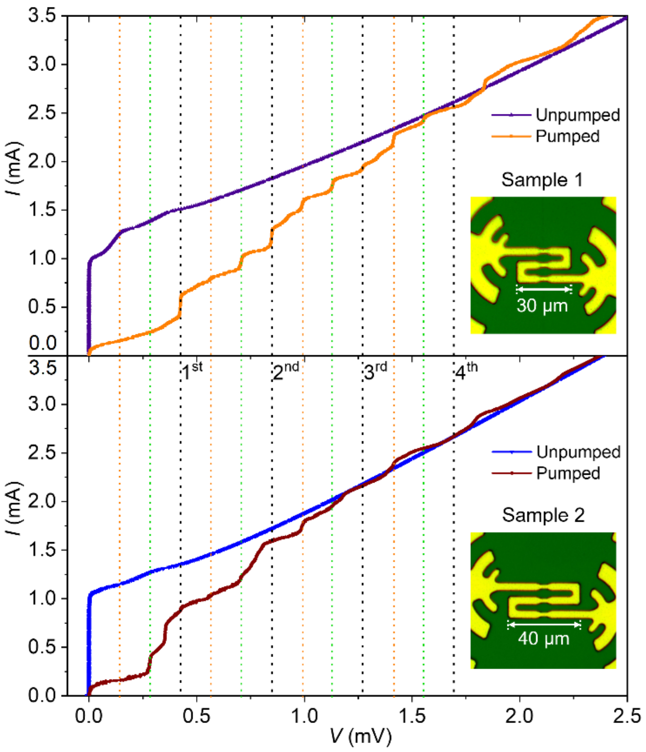


Figure 2. Measured IVCs of two 3JJS mixers with different meander lengths with and without the radiation at ~210 GHz and the bath temperature around 4.5 K. The voltages have been normalized to a single junction.

Figure 2 shows the measured current-voltage characteristics (IVCs) of two 3JJS mixers with different meander lengths with and without the radiation at ~210 GHz. In order to investigate the synchronous states of the series junctions, the voltages are normalized to a single junction, namely, divided by 3. Clear transitions are shown in the IVCs due to the variations of individual junction critical currents. Sample 1, with the meander center length of 30 μm, has a critical current ($I_c$) of ~1 mA with other transitions at ~1.3 mA and 1.5 mA, plotted in a purple line. When the mixer is radiated with a signal at ~210 GHz, the IVCs in the orange line show many Shapiro steps. We mark the voltages that satisfy the Josephson voltage-frequency relationship [20] in black dashed lines, the voltages at 1/3 of the step voltages in orange dashed lines, and the voltages at 2/3 of the step voltages in green dashed lines. Now it is clearly seen that the steps, corresponding to phase-locked states [21], are all at m /3 (m = 1,2,3,…) of the step voltages that satisfy the Josephson voltage-frequency relationship. The phase-locked state here refers to the synchronization, resulting from resonance with the rf current, driven by an external microwave source. Thus, the m /3 step voltages indicate that different numbers of junctions operate synchronously at different bias currents. For example, the first step locates at 1/3 of the voltage related to the radiation frequency, which means that only one junction operates. With higher bias currents, the number of operating junctions could be changed. Note that the voltage of 0.43 mV ($\approx\Phi_0 f_{THz}\approx$210 GHz/483.6 GHz mV$^{-1}$) where the first order Shapiro step locates means that all junctions work synchronously, obviously, for Sample 1. The blue and wine dotted lines display the IVCs of the other 3JJS mixer with a 10-μm-longer meander center length. Its $I_c$ is ~1 mA with another transition at 1.23 mA, indicating that two of the junctions have closer $I_c$ values. As the first step is located at 0.28 mV, the 2/3 of the frequency dependant step voltage, it shows that only two junctions work simultaneously at first. However, more uniform junctions do not mean the increase of the numbers of the synchronous junctions in the mixer. This may happen when there is a non-uniform microwave current distribution over the array. As the log-periodic antenna is a resonant antenna, the electric field distribution along the meander line is not uniform. Thus, the length of the meander should be carefully designed and experimentally checked in order to synchronize the series junctions. The optimal length of the connection to the junctions is worthy to study in our follow-up work.

The mixing experiments with zero bias are performed with these two mixers. In order to detect the maximal harmonic number, we kept LO power $P_{LO}$ at a higher level, like 12 dBm, and adjusted the frequency from 3 GHz with -0.001 GHz step. The best result is obtained from the mixer with three junctions working synchronously. Shown in figure 3 is the spectrum of the 154th harmonic mixing between a LO at a frequency of 1.35 GHz and the THz signal at ~210 GHz. For a down-conversion mixer, $f_{IF} = | f_{THz} - n f_{LO} |$, the THz frequency $f_{THz}$ is 154 × 1.35 GHz − 106.6 MHz ≈ 207.8 GHz. The largest harmonic number of 154 from the 3JJS mixer is much higher than that obtained from a single junction with the harmonic numbers up to 46 when coupled with a log-periodic antenna in our previous work [22]. The minimal requiring $P_{LO}$ for the 154th harmonic mixing from Sample 1 is ~3 dBm, shown in figure 4 with a blue squared line, and the optimal $P_{LO}$ is ~13 dBm for the maximal IF amplitude $P_{IF}$ of -44.8 dBm. On the other hand, the maximal harmonic number we can detect from the other mixer is 116, in which two-thirds of junctions play a role in the harmonic mixing with zero bias, under the requiring $P_{LO}$ higher than 11 dBm. The lower border of $P_{LO}$ for 116th harmonic mixing is a bit high that we cannot find the optimal $P_{LO}$, which is limited by the LO. The dependences of $P_{IF}$ on the $P_{LO}$ at 1.805 GHz for the 115th harmonic mixing are recorded in figure 4 with a red dotted line. The optimal $P_{LO}$ for the 115th harmonic mixing from Sample 2 is ~12 dBm to get a maximal $P_{IF}$ of -39 dBm. Data plotted in figure 4 are oscillating, caused by the changes in IVCs due to the radiated LO signal with different power. Different $P_{LO}$ changes the IVCs, resulting in different nonlinearities and dynamic resistances. Thus, $P_{IF}$ changes because of different nonlinearities, and changes of impedance matching between dynamic resistances and IF output impedance (50 Ω). The $P_{IF}$ from Sample 2 with 115th harmonics is higher than that from

Sample 1 with 154th harmonics, corresponding to the relationship of $P_{IF}$ (mW) $\propto n^{\alpha}$, and the scaling factor $\alpha$ has been reported between -2 to -3.3 for HTS junction millimeter and THz mixers [6, 23-25]. The maximal harmonic number from Sample 1 is larger than that from Sample 2, may due to one more junction contributing to the synchronous operation thus the improvement of dynamic range by the JJSA [7].

Figure 3. Measured IF frequency spectrum with the largest harmonic number being 154 from a 3JJS mixer for Sample 1 at zero-bias and the bath temperature around 4.5 K.

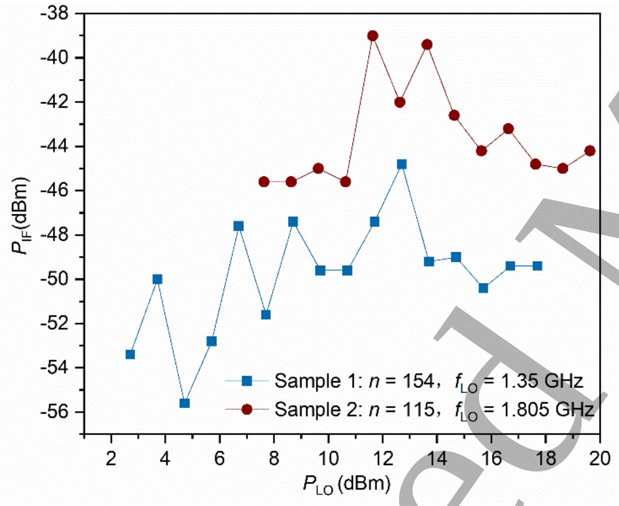
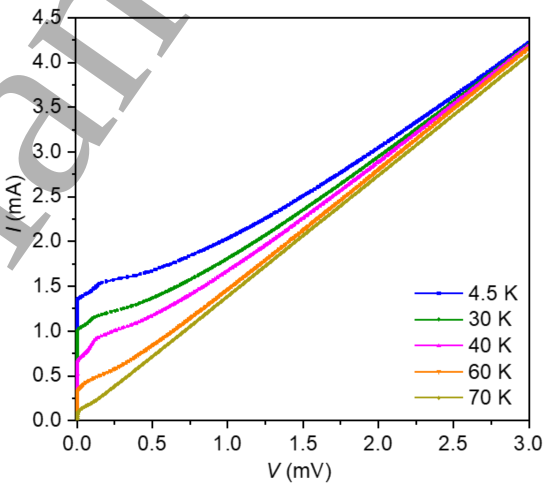


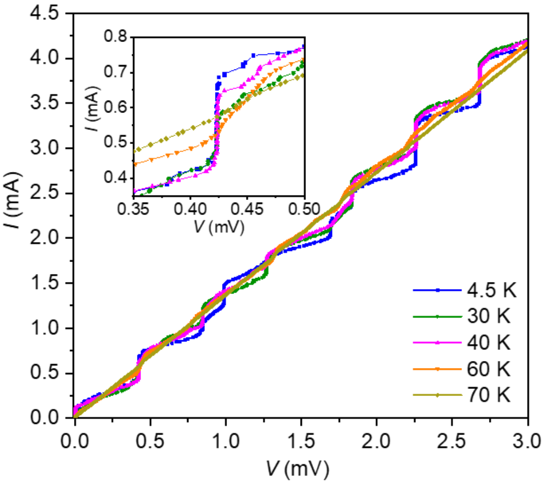
Figure 4. The dependences of IF output power on the LO power in harmonic mixing from two 3JJS mixers with different meander lengths.

Extra experiments of harmonic mixings at different bath temperatures have been performed from Sample 1, while the sample has been degraded with the $I_c$ of ~1.35 mA and another transition current of ~1.6 mA at 4.5 K. Figure 5 (a) shows the IVCs of the 3JJS mixer at the bath temperature $T$ from 4.5 K to 70 K. The $I_c$ decreases from ~1.35 mA at 4.5 K to ~78 µA at 70 K. And another current transition becomes indistinguishable when the $T$ arises to 70 K. Under the THz radiation at 207.8 GHz, as seen in figure 5 (b), the 3JJS mixer shows different IVCs with the $I_c$ suppressed and a series of m/3 of the step voltages that satisfy the Josephson voltage-frequency relationship induced. The first steps locate at 0.43 mV where the first order Shapiro steps locate, consistent with the result in figure 2. However, the steps become gradient at 60 K, and even difficult to identify at 70 K (shown in the inset).

Figure 5 (c) and (d) show the dependences of $P_{IF}$ on the $P_{LO}$ in the 150th harmonic mixing and 92nd harmonic mixing at different bath temperatures with zero bias, respectively. For the 150th harmonic mixing, the maximal $P_{IF}$ of -41.2 dBm can be attained at both 4.5 K and 40 K with the $P_{LO}$ of ~14 dBm. In addition, the $P_{IF}$ at 40 K are higher than that at 4.5 K under some specific $P_{LO}$, may caused by the improved sensitivity of the mixer as the $I_c$ decreases with the higher $T$. When $T$ arises to around $T_c$, the energy gap of the junction decreases, leading to a weaker nonlinearity in the *I-V* curve. Thus, the $P_{IF}$ decreases at 60 K and the IF output cannot be detected at 70 K for the 150th harmonics. As to the 92nd harmonic mixing, the maximal $P_{IF}$ of -26.2 dBm is attained at 4.5 K with the $P_{LO}$ of ~13 dBm. This may result from the stronger nonlinearity of the mixer at lower $T$. What's more, the maximal $P_{IF}$ at 30 K and 40 K are attained with the $P_{LO}$ of ~13 dBm as well. The IF output cannot be detected with the $P_{LO}$ higher than 6 dBm at 70 K, on account of the increased background noise.



(a)



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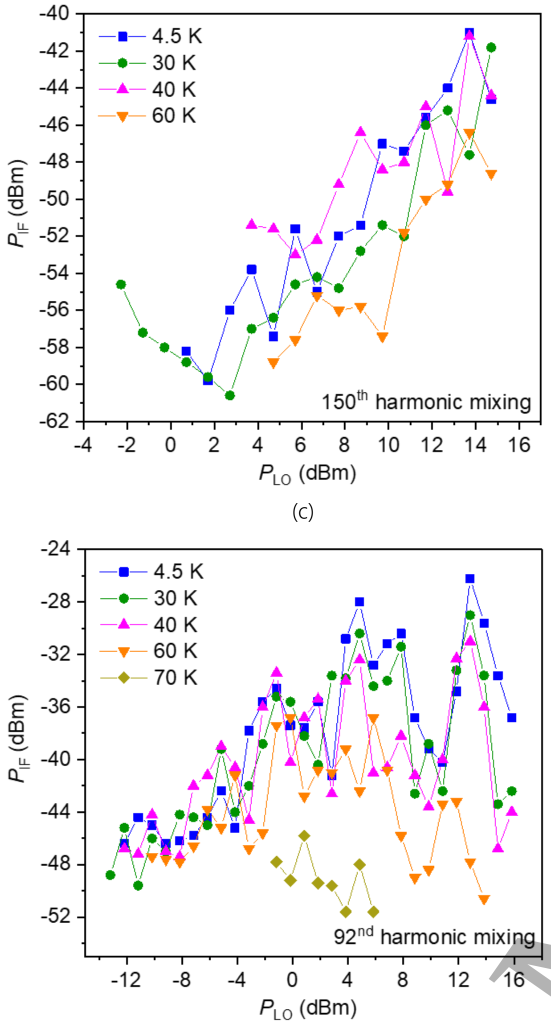

(c)

(d)

Figure 5. IVCs of the 3JJS mixer for degraded Sample 1 (a) without and (b) with the radiation at 207.8 GHz; The dependences of IF output power on the LO power in the (c) 150th harmonic mixing and (d) 92nd harmonic mixing at different bath temperatures. The voltages have been normalized to a single junction.

In a higher-order harmonic mixer, many harmonics of LO frequency and wide-band background noise cause the low saturation power and limited dynamic range in small-single Josephson junctions [26]. Now this problem can be solved by a series array structure to increase its dynamic range. The superiority of the 3JJS mixer in our experiments benefits from the synchronous operation which also improves the dynamic range. When N identical Josephson junctions in series behave in-phase, the voltage across the array is divided by N. Thus, mixer dynamic range increases in proportion to the square of series number N. We believe that the mixer performance will be more outstanding and promising in the application with more series phase-locked junctions. Future studies should investigate the effect of larger number of junctions as well as the meander length on the mixer performances.

## 4. Conclusion

This paper has successfully demonstrated a one-dimensional JJSA mixer, consisting of three series HTS bicrystal YBCO Josephson junctions operated synchronously at zero bias. The maximal harmonic number has reached up to 154, the largest harmonic number in a HTS series-junction mixer up to now and much higher than that obtained in single-junction mixers. The excellent performance benefits from the synchronous operation which also results in an improvement of dynamic range. Furthermore, with the zero-bias operation, the mixer needs no DC bias supply and thus no heating effect or shot noise is produced in the junction due to DC bias, which is dominant and compact for THz integration. The new-type harmonic mixer with JJSA at zero bias will be predominate in THz application.

## Acknowledgments

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