MIXING EXPERIMENTS AT W-BAND USING HIGH-TC JOSEPHSON JUNCTIONS

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Abstract—We report on the mixing properties of high-T_c superconductor (HTS) Josephson junctions. Direct radiation and heterodyne mixing experiments in the frequency range 78 GHz-119 GHz have been performed using $YBa_2Cu_3O_{7-x}$ (YBCO) step-edge junctions (SEJ) and bicrystal junctions (BCJ) on $LaAlO_3$ and MgO substrates. Under external radiation our junctions showed harmonic phase synchronization (Shapiro steps) up to 1.88 THz. Junctions with current voltage characteristics (IVC) close to predictions of the resistively shunted junction model (RSJ) were mounted into a heterodyne mixing setup. Under the radiation of two monochromatic signals we obtained conversion efficiencies around -14 dB in the 11 GHz intermediate frequency (IF) band. In the fundamental mixing regime we observed response at IF at working temperatures up to 72K . We demonstrated the operation of HTS Josephson junctions in the self-mixing mode. The experimental results are in good agreement with simulations using the RSJ model.

I. INTRODUCTION

Mixers based on the Josephson mixing scheme require overdamped junctions. Most of HTS Josephson junctions are naturally overdamped and therefore suitable for this application. Moreover, because of the relatively high energy gap, the operation of mixers based on HTS junctions up to THz frequencies is expected. In contrast, the performance of conventional low-T_c (SIS) mixers degrades above 0.7 THz.

Several groups reported successful mixing experiments using HTS junctions [1,2,3]. In this paper we present an experimental study of the mixing properties of two different types of HTS structures on two different substrates: SEJs prepared on $LaAlO_3$ and MgO substrates and junctions prepared on MgO bicrystal substrates. The aim of our investigations was to compare the heterodyne mixing properties of different HTS Josephson junction types with results of simulations made by using the RSJ model.

II. EXPERIMENTS

A. Samples and fabrication procedure

SEJs and BCJs were fabricated on (100) $LaAlO_3$ (ε_r = 20-24) and (100) MgO (ε_r = 9.6) substrates using laser ablation for film deposition, standard photolithographic processing and ion beam etching for patterning of structures [4]. The junctions were integrated into two different bow-tie antenna designs for a broadband high-frequency coupling (see Fig. 2). This antenna type exhibits a frequency independent impedance characteristic. The antenna structures contained usual microstrip low pass filters with cut-off frequencies between 11 GHz and 100 GHz. The patterned microbridge in the center of the antenna consists of one 2 μm wide Josephson junction.

B. DC and AC junction characterization

Typically, our SEJs on $LaAlO_3$ substrates had a characteristic voltage $V_c=I_cR_n$, where I_c is the critical current and R_n is the normal resistance of junction, in the range between 1 mV and 1.8 mV at 4.2 K. The normal resistance R_n, which is the important parameter for optimization of the impedance matching, was in the range between 10 Ω and 50 Ω. A reduced oxygen concentration in the barrier region of the junction generally results in reduced critical temperature T_c, higher R_n and lower I_c [5]. To achieve optimal junction parameters, e.g., to adjust V_c, a microwave oxygen plasma treatment can be applied (for details see [4]). The BCJs on MgO had R_n from 1 Ω to 4 Ω, I_c between 1.6 mA and 2 mA at 4.2 K. All bicrystal junctions were superconducting up to temperatures close to T_c of the YBCO film (88 K), with I_c=60 μA-90μA at 80 K. Using the simple voltage-frequency relation $f_c=2eV_c/h$, characteristic frequencies f_c in the range between 400 GHz and 1 THz were estimated.

We also investigated the high frequency response to applied microwave radiation with frequencies between 78 GHz and 117 GHz of several junctions on $LaAlO_3$ and MgO. Fig. 1 shows a typical IVC of a MgO-bicrystal junction under 104.5 GHz radiation using a W-band waveguide setup. In the presence of microwave power, the curve exhibits well developed

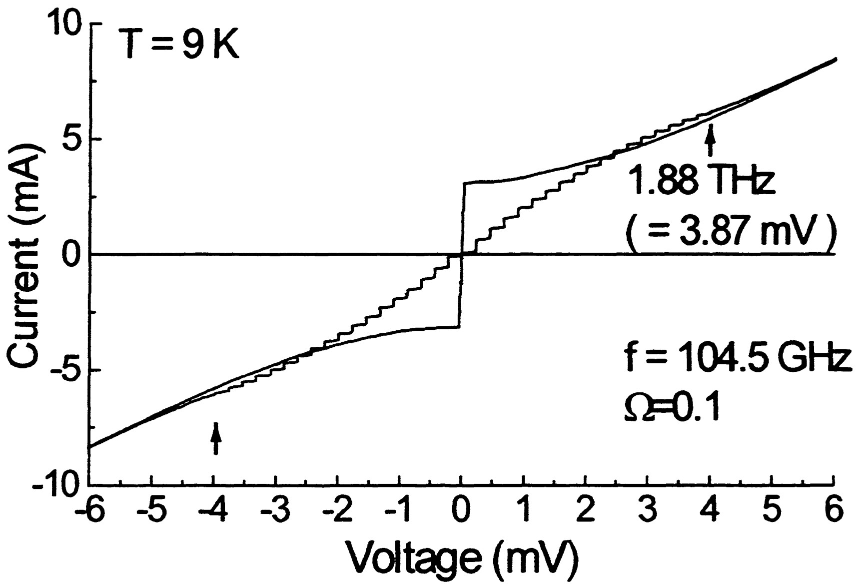

Fig.1. AC characterization of a BCJ on MgO

Shapiro steps at voltages V_n=nhf/2e up to n=18 (≅ 1.88 THz). Here n is the number of the harmonics of the Josephson radiation. This result promises operation of these junctions at THz frequencies. The normalized frequency $\Omega = f/f_c$ was 0.1 in this experiment.

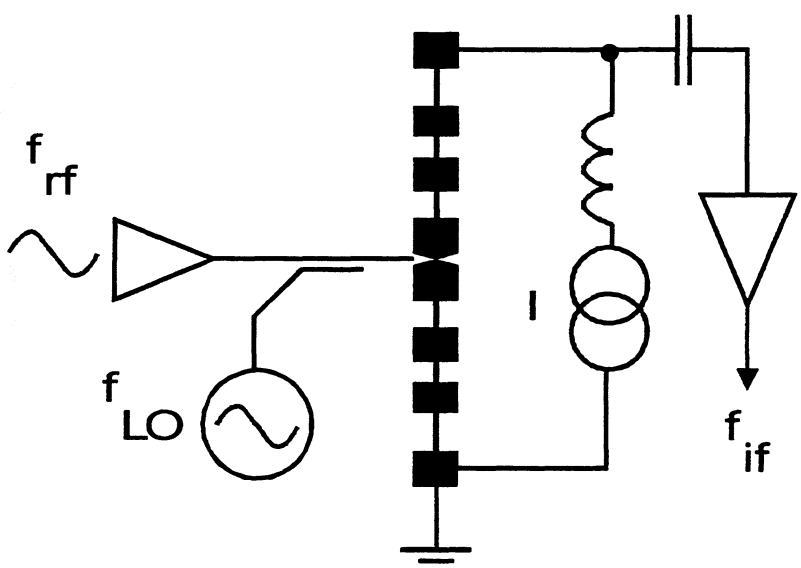

Fig. 2. Scheme of the heterodyne mixer setup

C. Heterodyne Josephson mixing: simulation and experiments

In order to simulate the Josephson mixing we solved numerically the differential equations of the RSJ model including two AC current terms oscillating with f_{rf} and f_{LO}. The obtained time dependencies were transformed into the frequency domain using FFT and the power at $f_{IF}=|f_{rf}-f_{LO}|$ was extracted from the frequency spectrum. In Fig. 3, a result of a complete simulation for different current bias points is plotted. The IVC with Shapiro steps induced by the LO are shown together with clear IF signal maxima between two Shapiro steps. In the heterodyne mixing experiments we used junctions with R_n of 1-50 Ω and V_c of 1 - 2.4 mV. A scheme of our setup is displayed in Fig. 2. In Fig. 4, results obtained for SEJ on $LaAlO_3$ are shown. Under irradiation by a Gunn-oscillator at f_{LO}=90 GHz and a weak signal from a klystron generator at f_{rf}=100.8 GHz, the intermediate frequency power P_{if} detected at 11 GHz shows clear signal peaks up to the 11 th harmonics (990 GHz) of the local oscillator line. SEJs on MgO showed heterodyne mixing response up to the 12^{th} harmonics (1.08 THz) of the local oscillator. With MgO-bicrystal junctions we obtained similar data. Because of the relatively low impedance of these junctions, higher power levels are required to overcome the impedance mismatch. The optimum biasing point for Josephson mixing was located in the middle between two steps in accordance with theoretical prediction.

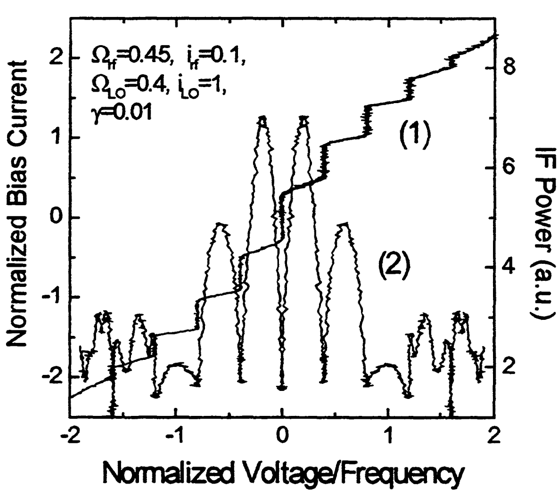

Fig. 3 RSJ model simulation of heterodyne mixing: (1) IVC, and (2) power at IF.

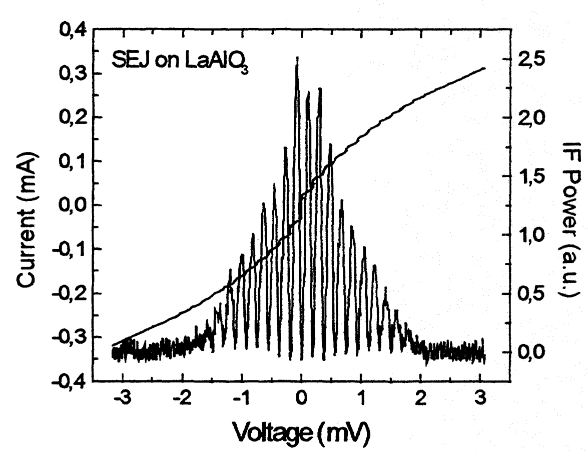

Fig. 4 Mixing experiment using a SEJ at 4.2 K, F_{LO} = 90 GHz, F_{rf} = 100.8 GHz.

D. Temperature effects

Since the characteristic frequency f_c of a Josephson junction is a function of temperature, the normalized frequency Ω, which is the ratio between the incident frequency f and fc, can be influenced by adjusting different working temperatures. Fig. 5 shows the simulated I-V

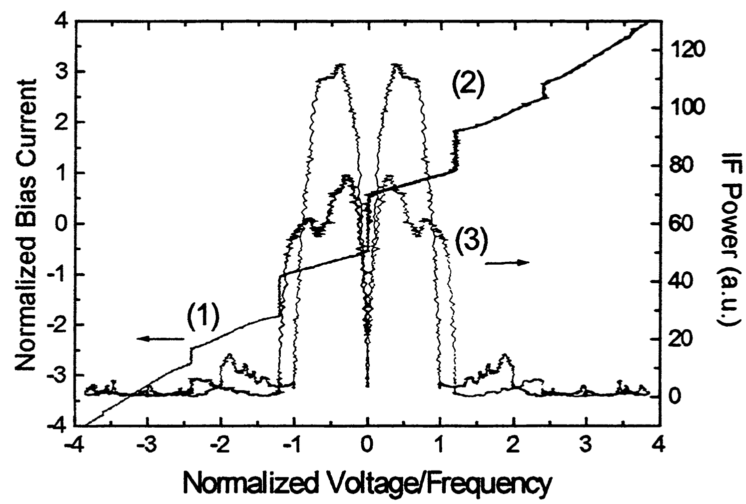

Fig. 5. Simulation of the power at IF for $\Omega = 1$ (2), and $\Omega = 1.2$ (3), IVC for $\Omega = 1.2$ (1)

curve and the power at the IF for Ω =1 and Ω =1.2. Fig. 6 displays typical results of mixing experiments using a MgO BCJ at various temperatures between 60 K and 72.4 K. In the experimental and simulated results the IF power follows the differential resistance as indicated by the basic mixer theory based on the RSJ model (e.g., see [6]).

The clearly observable reduction of the available power at the IF with increasing of temperature is due to the increase of the normalized frequency Ω (reduction of f_c). Equivalent to this experiment similar results will be obtained if the working frequency will be increased, keeping the temperature constant.

At temperatures below 60 K, this junction exhibited very high dynamic resistance between the steps, complicating an adjustment of a stable biasing point. This is typically observed if the radiation frequency is much smaller than the characteristic frequency f_c=2eV_c/h of the junction. This shows that the junction parameters (I_c, R_n, V_c) must be optimized for a given operation frequency. At the same time the value of R_n in the range 30 Ω-100 Ω is important for impedance matching.

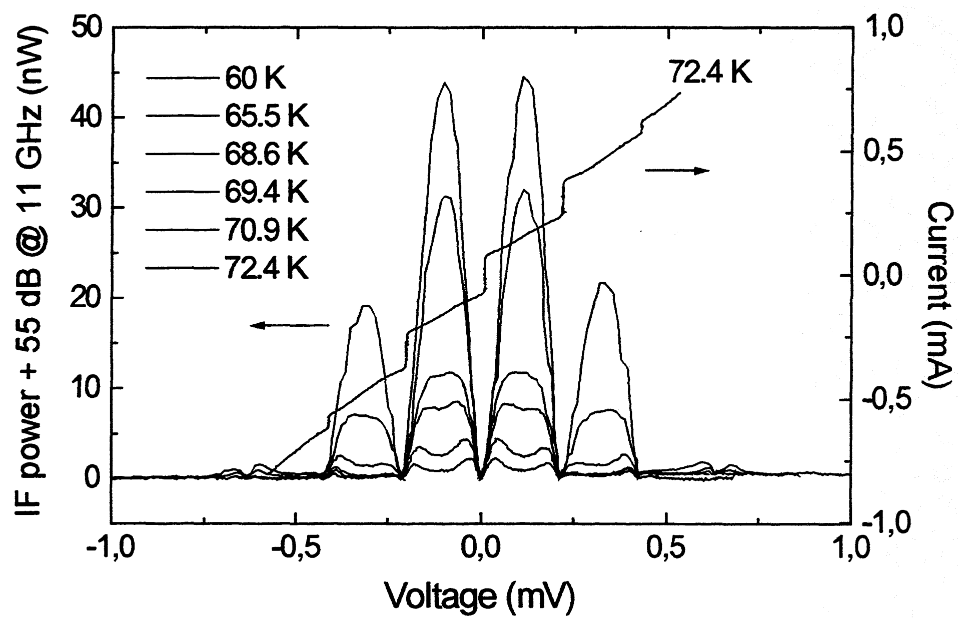

Fig. 6. Measured temperature dependence of Josephson mixing using a BCJ on MgO

E. Conversion efficiency and LO requirements

From mixing experiments using a well matched high ohmic SEJ on $LaAlO_3$ we calculated conversion efficiencies $\eta = P_{if}/P_{rf}$ to be around -14 dB (including losses in the IF matching part). An IF signal response was observed up to a minimum rf-input signal power of approximately 1 pW.

The optimal LO power level for the Josephson mixing process was investigated by measuring the power at the IF for different suppressions of the critical current I_c. The value of the suppressed current I_o depends on the LO power level.

Fig. 7 displays the result of a measurement done by using a MgO-BCJ. The temperature was 70 K, the LO frequency was 101.4 GHz and the signal frequency was 90 GHz. The measured dependency between the available IF power and the ratio of I_o/I_c shows that the optimum ratio I_0/I_c is approximately 0.5. The LO power consumption in this point was around 40 nW.

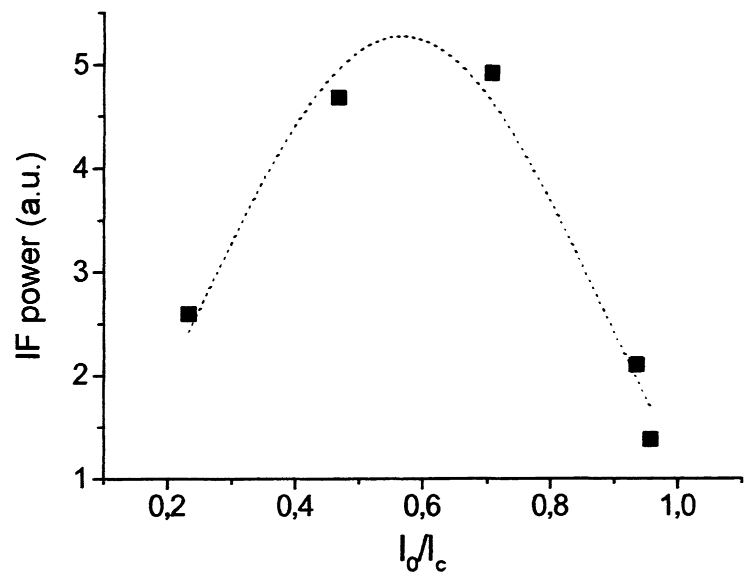

Fig. 7. Power at IF vs normalized suppression of I_c

F. Self-oscillator mixing

An interesting feature of Josephson junctions is the mixing response even without an external local oscillator - the so called self mixing. A typical characteristic of frequency down-conversion with the internal Josephson oscillator radiation is presented in Fig. 8. The MgO-bicrystal junction ($R \approx 4\ \Omega$, $V_c \approx 2.4$ mV at 4.2 K) gives, if irradiated by an external signal (only the first Shapiro step is visible) at 101 GHz, an 11 GHz IF-signal with two clear peaks around each step (101 ± 11 GHz).

The power related to these peaks was around 2 fW. The external microwave power which induced the first step was around 200 nW. The positions of the IF peaks on the voltage scale are well related to the condition for mixing at the first harmonic of the internal Josephson oscillation. The two broader peaks around the 0th Shapiro step represent the radiation of the internal Josephson oscillation detected at 11 GHz (≅ 22 μV on the voltage scale).

The linewidth of the down converted signal in this mixing mode is determined by the linewidth Δf of the internal Josephson oscillations. In the case of our Josephson junction Δf was about 2 GHz which is still too high for receiver applications. Arrays of Josephson junctions integrated into suitable resonator structures could overcome this drawback.

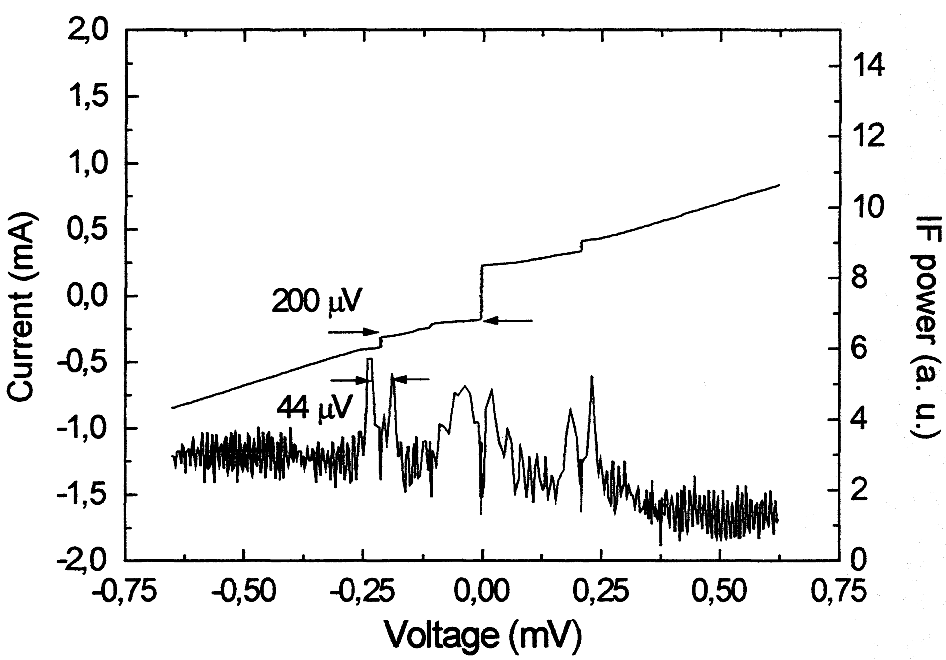

Fig. 8. Self oscillator mixing

III. Conclusion

We investigated the high frequency and mixing properties of step-edge junctions prepared on $LaAlO_3$ and MgO substrates and bicrystal junctions prepared on MgO substrates in the temperature range between 4.2 K and 72 K. These types of junctions showed a behavior in accordance with RSJ model predictions. Using bicrystal junctions on MgO, harmonic phase synchronization up to 1.88 THz was observed under irradiation by microwaves at 104.5 GHz. We performed heterodyne mixing experiments in the W-band and obtained harmonic mixing response up to frequencies higher than 1 THz with SEJ on MgO. Using high resistance SEJ on $LaAlO_3$ the conversion efficiency of our mixer was -14 dB including the IF losses. IF signal response was observable up to working temperatures around 72 K using a low resistance BCJ on MgO. For the same junction, the required LO power of 40 nW was relatively low. The lowest detectable signal using our receiver system was 1 pW. This fact indicates that further optimization of the impedance matching between the mixer and the HF environment will be necessary.

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