Full EM Design Method for HTS MMIC Josephson Mixers

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Abstract—**We report the full electromagnetic (EM) design and simulation method, and applied it to develop a 34 GHz High temperature superconducting (HTS) microwave monolithic integrated circuit (MMIC) Josephson mixer. The mixer is modeled in EM simulation software, High Frequency Simulation Structural Simulator (HFSS), with the junction area modeled as an excitation port with frequency-dependent impedance. Impedance matching between the junction and RF/IF ports is then optimized accordingly. Module design is carried out for the optimized HTS Josephson mixer, and the cavity resonance issue is investigated and eliminated. The HTS mixer module was experimentally developed and measured to verify the simulation. The measured frequency response of the conversion gain agrees with the simulation results of combined RF and IF transmission loss.**

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***Index Terms*—High temperature superconducting (HTS), Josephson mixer, MMIC, EM design.**

I. Introduction

HTS materials have ultra-low surface resistance at frequencies below 100 GHz, which has been applied to make filters and resonators with superior performance [1-3]. The low–noise and high non-linearity properties of the HTS Josephson junctions make them ideal for the key component of mixers [4-7]. A series of HTS MMIC Josephson mixers, ranging from 7 GHz to 36 GHz, have been developed at CSIRO, Australia, of which the $YBa_2Cu_3O_{7-x}$ (YBCO) step-edge Josephson junctions are integrated monolithically with a series of YBCO filters to achieve better performance [8-11]. Meanwhile, modelling method of such an HTS MMIC Josephson circuit has been developed [12, 13], in which impedance matching and optimization theory between passive devices and Josephson junctions were investigated. The model has provided some theoretical guidance for the MMIC Josephson mixer circuit design, but it still has several limitations: First, the parameters of each passive components could only be tuned individually without including the effect caused by other parts of the circuit. Second, electromagnetic effect starts to be dominant and generate strong interferences between ports at mm-wave frequencies, which cannot be simulated in the modelling method consisting of ideal, lossless and interference-free components. A full EM simulation method combining the passive devices and the Josephson junction section is, therefore, highly desirable for HTS MMIC Josephson mixer design in the mm-wave range.

In this work, a full EM simulation approach is presented, and a 34 GHz HTS MMIC Josephson mixer is designed and experimentally developed for verification of our EM design theory and comparing with the simulation results. The Josephson junction in the mixer is modelled as an excitation port with a frequency-dependent impedance, which enables a comprehensive EM simulation of the whole mixer circuit. RF and IF port impedance is optimized for better matching to the junction, while isolation between different ports is also considered in the simulation. A housing is designed to accommodate the HTS MMIC mixer chip and other relevant components. Cavity resonance of the housing is investigated and eliminated by design optimization. The Josephson mixer has been fabricated, packaged and measured for comparison with the simulation results. Modeling approaches, design considerations, impedance optimization, simulated and measured frequency response of the mixer are reported.

II. HTS MMIC Mixer Design

Fig. 1 shows the layout of the proposed HTS MMIC Josephson mixer. All the passive and active devices are integrated onto a 4.5 × 4 × 0.3 mm^3 MgO substrate with a dielectric constant of

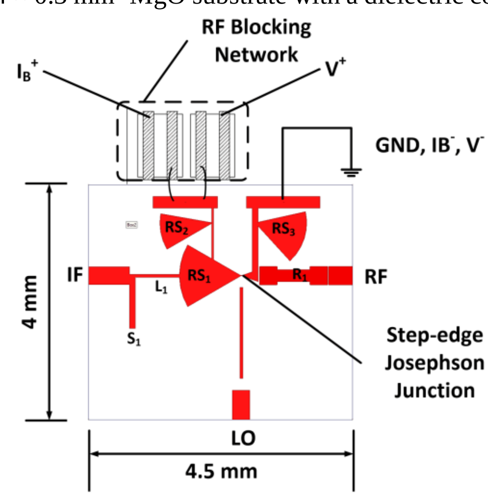

Fig. 1. Layout of the designed HTS MMIC Josephson mixer.

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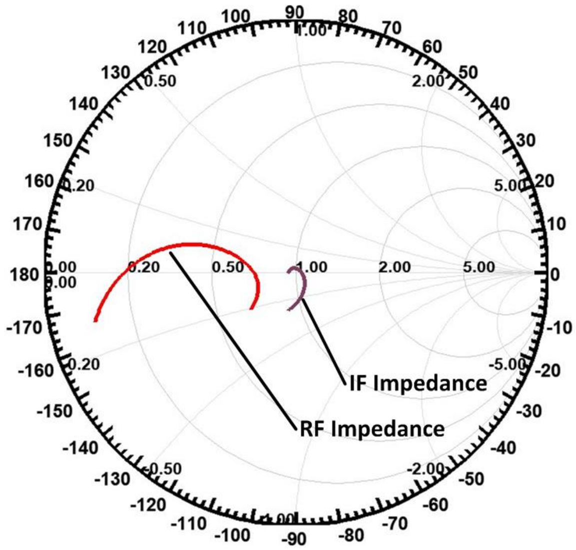


Fig. 2. Simulation result of normalized RF input impedance and IF output impedance. The junction-equivalent port impedance is 5 Ω for RF and 50 Ω for IF, respectively.

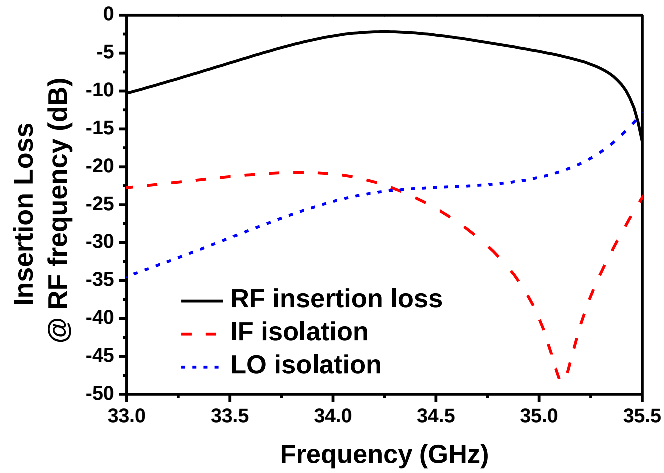


Fig. 3. Simulated insertion loss between the junction and the input/output ports at RF frequency (0.1 GHz Frequency step)..

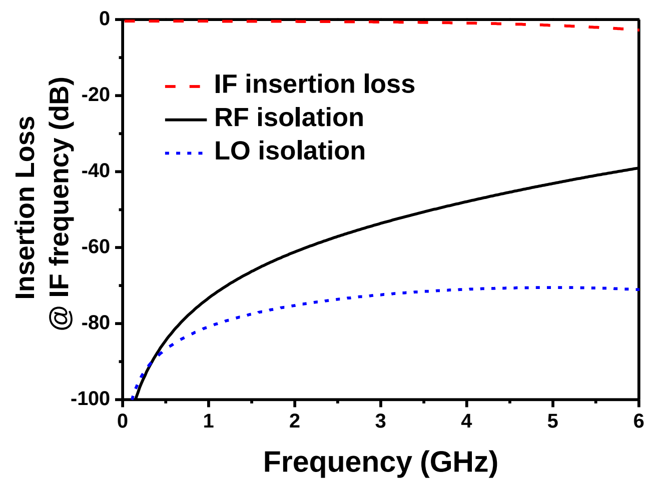


Fig. 4. Simulated insertion loss between the junction and the input/output ports at IF frequency (0.1 GHz Frequency step)..

9.7. Compactness is further improved compared with our previous work at similar frequencies [10, 11]. LO frequency is set to be 36 GHz, and the desired RF and IF frequency ranges are 33.5 to 35 GHz and 1 to 2.5 GHz, respectively.

The design of the mixer follows the modeling theory in previous papers [6, 13], and the simulation in this work is performed using HFSS. For modeling and circuit designs at RF frequencies, the junction area is considered to be equivalent to an excitation port with 5 Ω impedance, which is close to the typical step-edge junction intrinsic resistance R_n values measured previously [11]. A quarter-wavelength radius stub RS_1, is applied at the other end of the junction to provide a virtual ground for RF and LO inputs, due to the absence of physical grounding of the HTS step-edge Josephson junction's single-layer structure. A step-impedance resonator R_1 is applied at the RF input, and connected to the junction via a gap. In this way, a capacitive coupling is introduced to eliminate the impedance imaginary part introduced by the short tapered line connected to the junction for the convenience of impedance matching. The biasing network for V^- and I_B^- serves as an impedance matching stub for RF input, with a shunted radius stub RS_3 for RF blocking. In this way, RF input impedance is tuned down to around 25 Ω, as shown in Fig. 2, which results in an insertion loss around 2.5 dB. Simulation result of the insertion loss between the junction and all three ports is shown in Fig. 3. The average RF insertion loss is around 3 dB from 33.5 GHz to 35 GHz, while the isolation from LO and IF ports are all better than 20 dB. The designed RF layout has improved the insertion loss by over 3 dB, compared with a direct connection between the junction and the 50 Ω port using tapered line, which is approximately 7 dB.

Impedance matching network at IF frequency will be bulky due to longer wavelengths, compared with RF frequency. Furthermore, the impedance of IF output port should better match the junction's dynamic resistance R_d, which can be close to 50 Ω. Therefore, the circuit design consideration at IF frequency is mainly focused on RF-to-IF isolation, while the port impedance is still designed to be close to 50 Ω, as shown in Fig. 2. A low-pass filtering network is designed, consisting of a stub line S_1, a high impedance transmission line L_1, and the radius stub RS_3 mentioned above. Additionally, a number of RF suppression method are applied for the V^+ and I_B^+ biasing line, including the shunted radius stub RS_2 and the miniature RF blocking network outside the MMIC circuit. The biasing pad for V^- and I_B^- is designed to be connected to ground to provide physical earth for IF port. The biasing line itself will introduce low extra loss due to its relatively short electrical length for IF frequencies. Optimized insertion loss between the junction and IF port is around 0.5 dB below 3 GHz, and a high isolation is achieved between the junction and RF/LO ports, as shown in Fig. 4.

The designed mixer was subsequently fabricated on a single-sided $YBa_2Cu_3O_{7-x}$ (YBCO) film on MgO substrate using the CSIRO well established step-edge junction technology [14]. More detailed descriptions of the device fabrication procedures and mixer measurement set-up can be found in earlier papers [8-10].

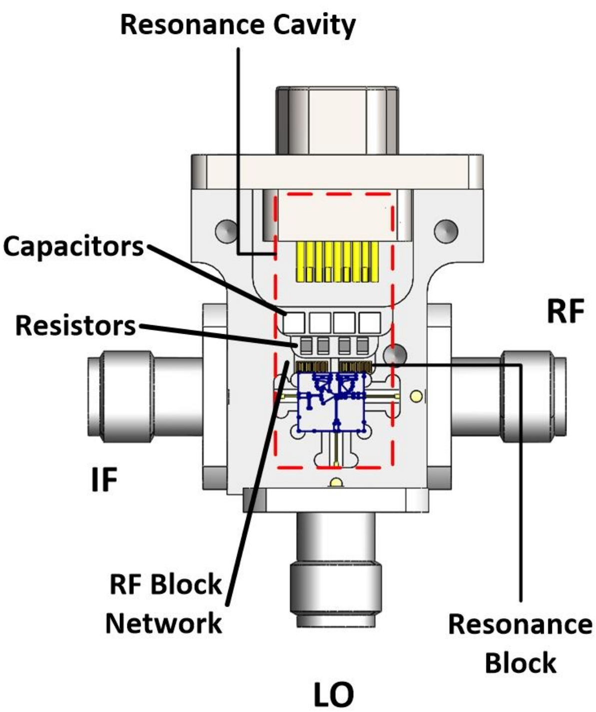
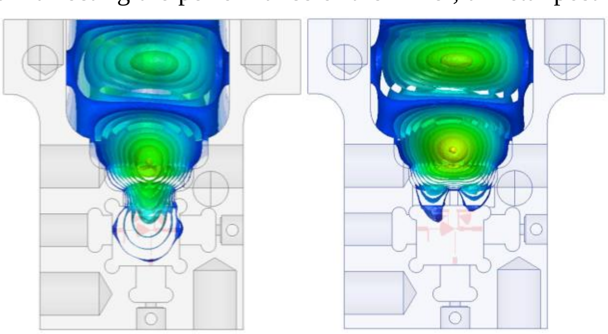


Fig. 5. Drawing of the packaged HTS Josephson mixer module.

III. Module Configuration

The fabricated HTS mixer chip was packaged into a customized metal housing, along with other lumped elements of DC biasing networks as shown in Fig. 5. The overall dimension of the module is below 25 × 20 × 15 mm^3, which is very compact. For module designs at the frequency over 30 GHz, cavity resonance can affect the performance of the whole module and can no longer be neglected. Although the dimension of the Josephson mixer has been designed small enough to avoid cavity resonance around 34 GHz, small segments for the mixer, RF blocking networks, resistors and capacitors have formed a cavity with the dimension around 5 × 10 × 2 mm^3, which would resonate at 33.5 GHz. Simulation in Fig. 6 (a) has shown that the cavity resonance at 33.5 GHz does affect the HTS MMIC mixer area (Fig. 6 (a)). This may lead to severe deterioration in transmission loss and the shape of frequency response as reported in previous work [10]. To prevent the cavity resonance from affecting the performance of the mixer, a metal post was



(a) (b)

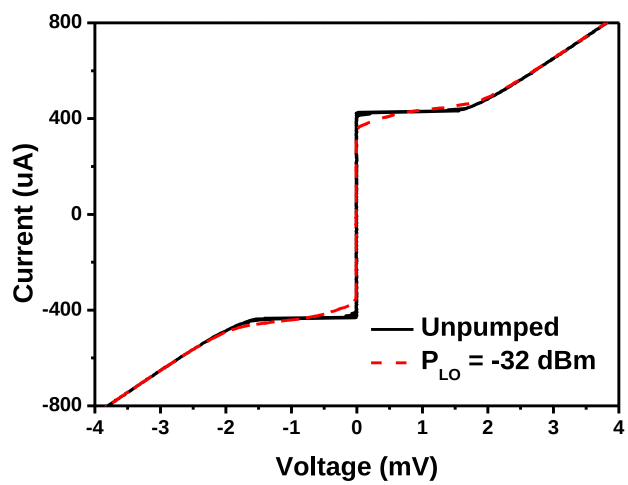
Fig. 6. Simulation of cavity resonance at 33.5 GHz: (a) without and (b) with the resonance blocker.

placed between the two pieces of RF blocking network circuits, as shown in Fig. 5. The post functions as an RF choke in the cavity, and has substantially altered the cavity resonance mode (TE_{101} mode) in the approximate rectangular cavity in Fig. 6 (a). Due to the existence of the metal post, cavity resonance of the housing only occurs outside the HTS mixer chamber, as shown in Fig. 6 (b), which ensures that the mixer performance will not be affected by the housing.

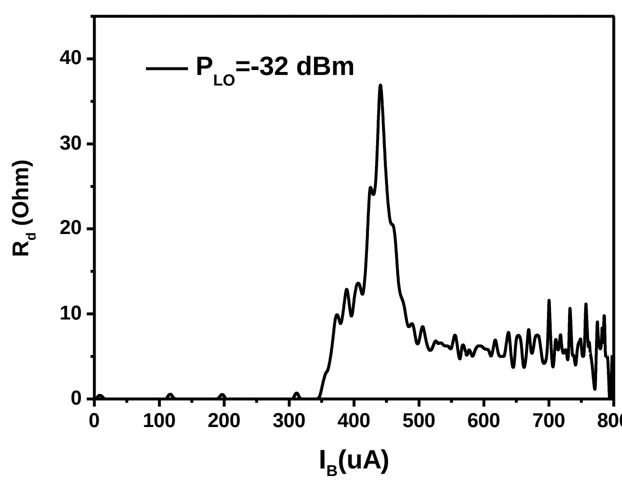
IV. Measurement and Discussion

The packaged module was cooled down to an operating temperature in 20 - 77 K with a commercial 2-stage pulse-tube cryocooler. A battery-driven DC current source was used to bias the Josephson device. The microwave RF signal generated by an Anritsu 68087C Synthesized CW Generator was applied to the RF port. An Agilent E4407B spectrum analyzer was connected to the IF port for output power measurement. The experimental results of the HTS receiver front-end at 40 K are presented here and compared with the simulated results.

Fig. 7 (a) is the measured I- V characteristic of the step-edge junction, with a partial I_c suppression when pumped by LO, and



(a)



(b)

Fig. 7. (a) Measurement result of the junction DC I-V behavior, and (b) the derived dynamic resistance R_d when pumped at P_{LO} = -32 dBm.

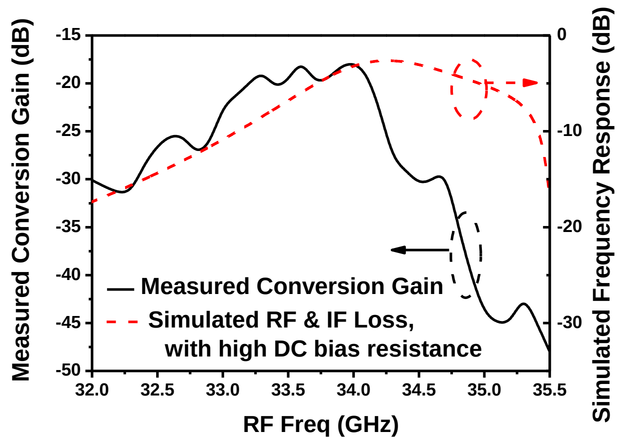
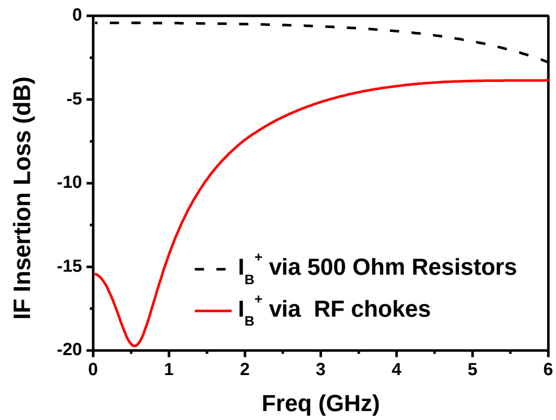


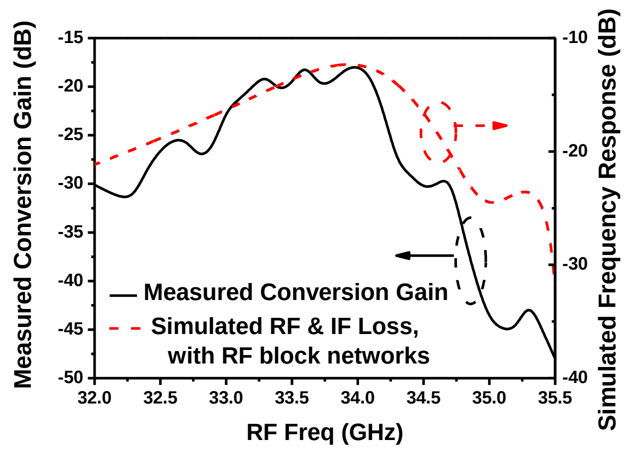
Fig. 8. Measured frequency response of the mixer conversion gain, and simulated frequency response of combined RF and IF loss (0.1 GHz Frequency step used).

(b) is its dynamic resistance R_d derived from the I-V behavior. The unsuppressed junction critical current I_{c0} is around 450 µA, and is suppressed down to 360 µA at P_{LO} = - 32 dBm. The junction normal resistance R_n, determined by the linear section of the I-V curve, is about 5 Ω, while the maximum R_d is around 40 Ω. Both R_n and R_d values are close to what has been anticipated and discussed in Section II. The I_{c0} R_n product obtained for this junction is around 2.2 mV, which is a high value compared with previous ones [8, 10].

Frequency response of the mixer IF output power was measured, and a calculated conversion gain of -17 dB is obtained as shown in Fig. 8. For comparison, simulated frequency response of combined RF and IF transmission loss is also presented in the figure. Compared with the simulated transmission loss, which is around 4 dB, the measured conversion gain is approximate 10 dB lower than that expected, with a sharper roll-off at the upper stopband around 34.5 GHz. The difference between the simulation and measurement results is believed to be due to the choice of the miniature RF blocking networks. From the supplier's datasheet [15], the RF blocking network circuit provides a cascade 10 Ω resistor, and a shunted 30 pf capacitor, instead of components with high impedance. At IF frequencies, the shunted capacitor and the 10 Ω resistors have induced a serious impedance mismatch between the IF port and the junction's dynamic resistance R_d, thus resulting increased losses. This hypothesis has now been verified using the simulation approach of IF insertion loss described in Section II and the results are shown in Fig. 9 (a). After taking into consideration of the low value impedance of the RF blocking networks, the simulated insertion loss of IF link has increased by over 7 dB between the frequencies from 0 to 2 GHz, and the flatness of the frequency response has been severely deteriorated. Consequently, the overall transmission loss of the mixer has risen to – 14 dB with a sharp roll-off at the upper stopband as the simulated result shown in Fig. 9 (b). The measurement results agree well with the simulation ones having taken into consideration of the effect of the RF blocking network circuits, which proves that the proposed simulation approach of the HTS MMIC Josephson mixer is applicable. The performance of the mixer



(a)



(b)

Fig. 9. (a) Simulated IF transmission losses comparing with a higher value resistance and the low impedance RF chokes for the assembled mixer, and (b) frequency response of the measured conversion gain and the simulated transmission response having taken into consideration of the low-impedance RF blocking networks (0.1 GHz Frequency step used).

should improve by replacing the RF blocking network circuits with 1 kΩ resistors in future designs.

V. Conclusion

Full EM modeling and design of a Ka-band HTS MMIC Josephson mixer are presented in this paper. The junction area is modeled as an excitation port, with impedance of R_n at RF frequency and IF frequency. In this way, transmission loss and impedance matching of the whole circuit can be simulated using the EM simulation software. Cavity resonance is eliminated in the module packaging design by inserting a metal post in the housing. Measured frequency response of conversion gain agrees well with the simulated transmission loss when taking into consideration of the effect of DC bias networks. The EM modeling and simulation method presented in this paper have been proven to be a good approach for HTS MMIC Josephson mixer design, which is a major improvement from the theoretical modeling developed previously [13].

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