

A High LO-to-RF Isolation E-band Mixer with 30 GHz Instantaneous IF Bandwidth in 90nm CMOS

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Abstract—This paper demonstrates a single-ended down-conversion mixer with a wide IF bandwidth. The proposed mixer utilizes a modified cascode topology, consisting of a CS amplifier transistor and a cold-biased ($V_{ds}=0$) mixing transistor. The cold-biased mixing transistor enables wide IF bandwidth, while the CS transistor operates as an RF amplifier to boost conversion gain. Additionally, the LO-to-RF isolation is improved by two pairs of LC resonators. When pumping by an 8-dBm LO power at 60-GHz, the mixer exhibits 30 GHz IF bandwidth. Over the full E-band, the measured conversion loss is between 9 and 12 dB. The measured LO-to-RF isolation is 40.8 dB, while the RF-to-IF isolation is better than 38 dB. The IP_{1dB} ranges from -2 to 4 dBm in the full E-band.

Keywords—mixer, wideband, CMOS, radio astronomy, astronomical observation.

I. INTRODUCTION

In radio astronomy, the instantaneous bandwidth of the heterodyne receiving system plays a major role in observation efficiency. With identical receiver sensitivity, observing speed for spectral line survey and continuum observations will be doubled when the instantaneous bandwidth is doubled [1]. Signals at microwave, millimeter-wave, and submillimeter-wave bands are down-converted to several GHz in receivers by mixers. Both superconductor- and semiconductor-based mixers with up to 16 GHz instantaneous IF bandwidth or wider for radio astronomy applications were reported [2, 3, 4, 5]. Further increment in mixer IF bandwidth is desired for more efficient performance.

In the GaAs pHEMT technologies, a variety of wide IF bandwidth mixers was proposed. Most of them such as the star mixer [6], ring mixer [7], and sub-harmonically pumped mixer [3], are passive mixers. Despite the zero dc power consumption, they all have inadequate isolation and require high LO power. For active mixers, in order to provide a wider IF bandwidth with a lower LO power, a modified cascode mixer was implemented [8], but the poor LO-to-RF isolation problem persisted. One suggestion to improve LO-to-RF isolation is to replace the CS (common-source) amplifier with a cascode amplifier, which makes the entire circuit into a triple-cascode mixer [4]. Unfortunately, IP_{1dB} degrades significantly in this topology as a result of the high RF gain. On the other hand, an ultra-wideband mixer was proposed in the CMOS process [5]. Although it provides extremely wide RF coverage of 30-90 GHz, with 16 GHz instantaneous IF bandwidth, several LO tunings are required to cover full RF bandwidth.

In this paper, a modified cascode CMOS mixer with both wide RF and IF bandwidth is proposed. 30 GHz instantaneous

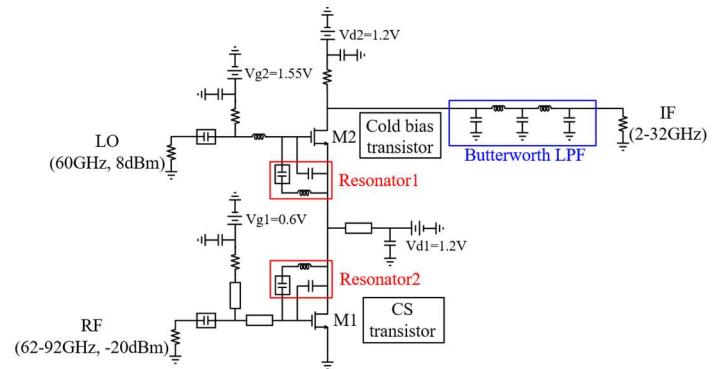


Fig. 1. Circuit schematic of the broadband mixer

IF bandwidth provides entire RF coverage of 62-92 GHz in a single observation. Embedded LC resonators are employed to improve isolation without significantly sacrificing IP_{1dB} .

II. CIRCUIT DESIGN

The proposed mixer was implemented by TSMC 90-nm CMOS. The topology of the mixer is shown in Fig. 1.

A. Wide Band Design

For high conversion gain mixers, conventional cascode structures were utilized. However, it is a challenge to achieve a wideband output matching network due to the high output impedance of the conventional cascode mixer. For wide IF bandwidth mixer design, a modified cascode mixer was therefore proposed [8]. The bias condition of two transistors can be independently controlled by connecting a stub with a bypass capacitor which provides an ac-short to the source of the mixing transistor.

The bias condition for the CS amplifier transistor was selected by a trade-off in gain and power consumption, resulting in $V_{g1}=0.6$ V and $V_d=1.2$ V. The drain and the source of the mixing transistor are biased with the same voltage, 1.2 V, which satisfies the cold-bias criterion. The mixing transistor operates as a voltage-controlled resistor and the output impedance is equal to its channel resistance. Hence, compared to the output impedance of a conventional cascode mixer, the output impedance of a modified cascode architecture is lower and less frequency-variable. Moreover, biasing the gate of the mixing core with 1.55 V, that is a $0.35\text{-}V_{gs}$, can reduce the third harmonic gain of the mixing transistor, and the linearity can be improved.

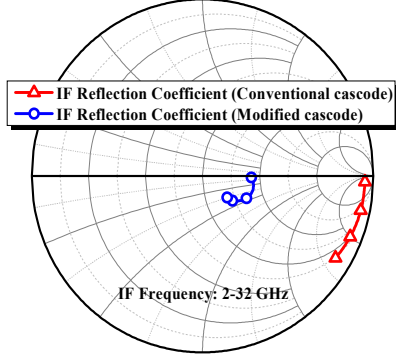


Fig. 2. The reflection coefficient at IF port of cold-biased schematic

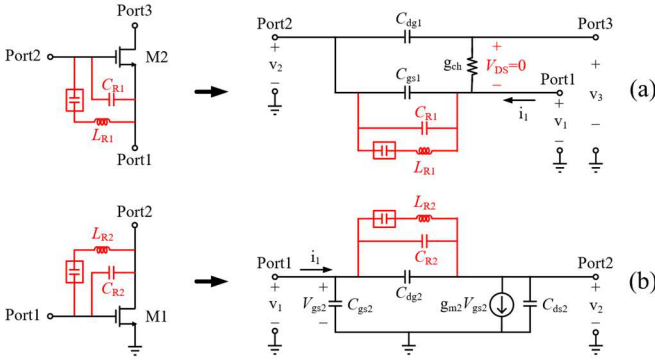


Fig. 3. The small signal equivalent circuit of (a) resonator in the mixing stage; (b) resonator in the g_m stage.

The size of the mixing transistor was selected to achieve a 50-ohm output impedance for wide IF bandwidth designs. In contrast to a conventional cascode, the modified cascode with specified transistor size exhibits reflection coefficients at the IF port that is less frequency-dependent and is closer to the Smith chart's center, as shown in Fig. 2. This simplifies the design work for a wideband output matching network. Without significantly reducing bandwidth, a shunt-first Butterworth low-pass filter (LPF) is used to block high-frequency RF and LO signals from the IF port.

The compensation for gain in the higher frequency is required since the CS transistor has a higher gain at low frequencies. Circuit components including RF port matching network, inter-stage matching network, and LPF were all designed with higher loss at low frequencies in order to maintain the gain flatness over the whole frequency range.

B. LO-to-RF Isolation Improvement

Single-ended mixers typically have poor isolation. In this down-converting modified-cascode mixer, the high-frequency RF and LO signals are blocked from the IF port by the LPF. However, because of the closeness of the LO and RF frequencies, the matching network is unable to sufficiently isolate the LO and RF ports. LC resonators are therefore necessary to enhance LO-to-RF isolation [9].

Fig. 3 (a) shows the small-signal equivalent circuit for the cold-biased mixing transistor with an LC resonator embedded between gate and source terminal. The parasitic capacitances

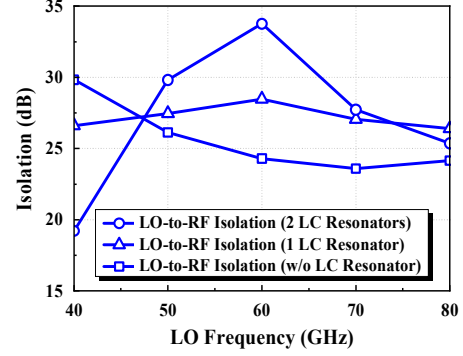


Fig. 4. Simulated LO-to-RF isolation with different numbers of resonators

from drain to gate and gate to source are denoted by C_{dg1} and C_{gs1} , respectively. g_{ch} represents the transconductance of the cold-biased transistor. The resonator capacitance and inductance are denoted by C_{R1} and L_{R1} .

Assuming the dc block capacitor is large enough to give negligible reactance in comparison to the resonator inductor, the admittance between gate and source terminal is:

$$Y_{12} = \frac{i_1}{v_2} \Big|_{v_1=0} = -j2\pi f \left(C_{R1} + C_{gs1} - \frac{1}{4\pi^2 f^2 L_{R1}} \right). \quad (1)$$

The mixer will operate with a single LO frequency of 60 GHz. Thus, the admittance between two ports must be minimized at 60 GHz in order to reject the LO signal from coupling to port 1. Assuming $Y_{12} \approx 0$, the relationship between resonator inductance and capacitance value is:

$$L_{R1} = \frac{1}{4\pi^2 f^2 (C_{R1} + C_{gs1})} \quad (2)$$

The small-signal equivalent circuit of the CS transistor with an LC resonator embedded between drain and gate terminal is shown in fig. 3 (b). The parasitic capacitances from drain to gate, gate to source, drain to source are denoted by C_{dg2} , C_{gs2} , and C_{ds2} respectively. g_{m2} represents the transconductance of CS transistor. C_{R2} and L_{R2} denote the resonator capacitance and inductance. The admittance between drain and gate is:

$$Y_{12} = \frac{i_1}{v_2} \Big|_{v_1=0} = -j2\pi f \left(C_{R2} + C_{dg2} - \frac{1}{4\pi^2 f^2 L_{R2}} \right). \quad (3)$$

For the purpose of rejecting the LO signal coupling from port 2 to port 1. The admittance between the two ports shall be minimized to 0 at 60 GHz. Thus, the correspondence between resonator inductance and capacitance value is:

$$L_{R2} = \frac{1}{4\pi^2 f^2 (C_{R2} + C_{dg2})} \quad (4)$$

The parasitic capacitances of the 2-um \times 16-finger transistor are extracted from the TSMC model, and C_{gs}/C_{gd} are 25.3/10.8 fF, respectively. Due to the low parasitic capacitance, if the resonators only contain inductors and parasitic capacitors, the fabrication of correspondingly large inductance to resonate at 60 GHz is infeasible. To increase the overall capacitance, additional capacitors (C_{R1} , C_{R2}) must be embedded in parallel with the parasitic capacitance of the corresponding transistor ports. The tiny capacitors are constructed with edge-coupled MOM capacitors to minimize the influence of process variation. The final values in this design are C_{R1} =20 fF, L_{R1} =150 pH, C_{R2} =25 fF, and L_{R2} =200 pH.

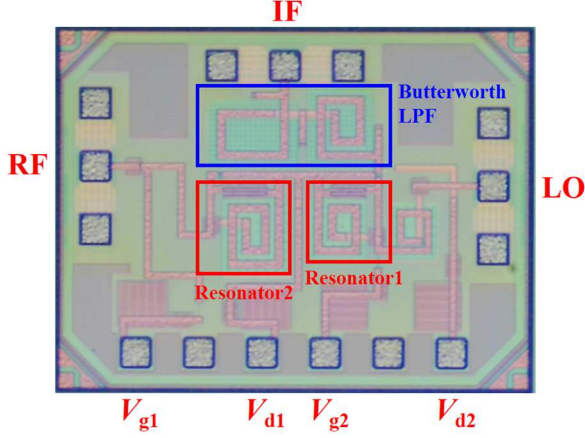


Fig. 5. Chip photo of wide IF bandwidth mixer

Fig. 4 demonstrates the simulated LO-to-RF isolation for 40-80 GHz LO signals, with the IF frequency fixed at the center frequency, 15 GHz. The LC resonators have been fine-tuned using Sonnet EM simulation tool. The figure shows that the original mixer without an LC resonator has a 24 dB LO-to-RF isolation with a 60-GHz LO signal, which is too low for system use. When one LC resonator is applied, the LO-to-RF isolation increases to 28 dB. After using two LC resonators, the LO-to-RF isolation with a 60-GHz LO signal increased to a decent level of 34 dB.

III. MEASUREMENT

A. Measurement setup

Fig. 5 shows the chip photograph of the proposed mixer. The mixer was measured by on-wafer probing. Keysight E8257D signal generators are used to generate LO and RF signals. The RF signal lower than 70 GHz was generated directly by the signal generator. Beyond 70 GHz, the RF signal is generated with a $\times 2$ frequency multiplier (Spacek Labs W-2X) and a W-band power amplifier (SAGE Millimeter SBP-7531142515-1010-E1). The output IF signal is detected by the Keysight N9041B spectrum analyzer.

B. Measurement result

Fig. 6 presents the results of the simulated and the measured conversion gain. With an 8-dBm 60-GHz LO, the mixer achieves a conversion loss of 9 to 12 dB in the RF frequency range of 62 to 92 GHz, which shows consistent tendencies. The measured RF-to-IF isolation is higher than 38 dB, as shown in Fig. 7. Discontinuity between 67 and 70 GHz was caused by the frequency limitation of the probes. With a 60-GHz LO, the measurement shows an exceptional LO-to-RF isolation of 40.8 dB. The IP_{1dB} at 90 GHz is 2.4 dBm as shown in Fig. 8. The IP_{1dB} ranges from -2 to 4 dBm for every frequency point across the full RF frequency band, as illustrated in Fig. 9.

The performances of this mixer and other selected wide-band mixers are summarized in Table I. The proposed mixer achieves the widest instantaneous IF bandwidth when compared with the published mixers.

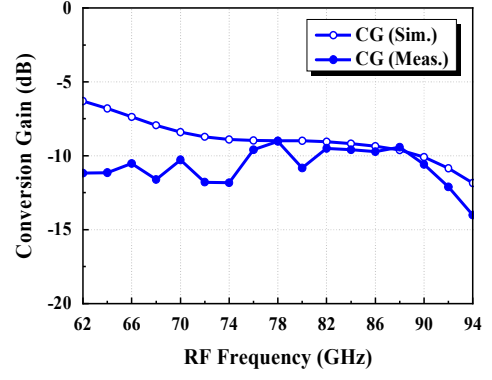


Fig. 6. Simulated and measured conversion gain

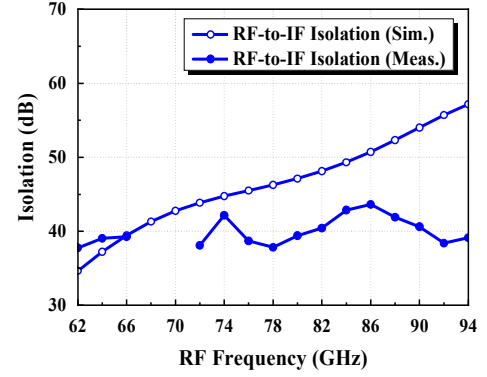


Fig. 7. Simulated and measured RF-to-IF isolation

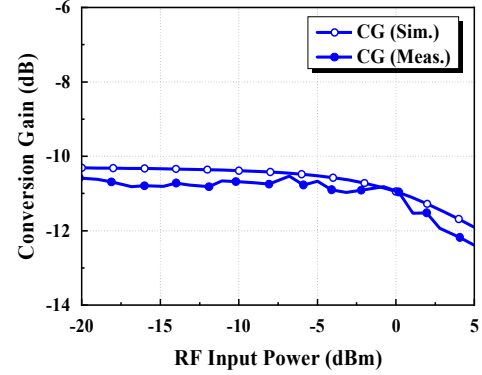


Fig. 8. Large signal simulated and measured result at 90 GHz

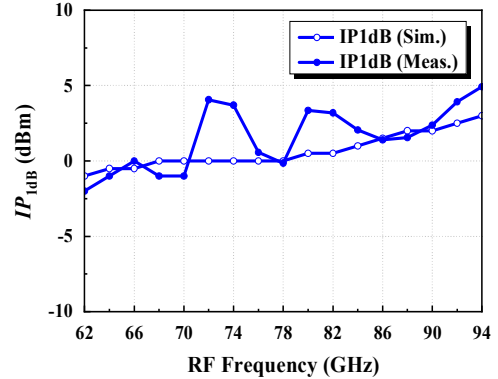


Fig. 9. Simulated and measured IP_{1dB}

Table 1. Performance Comparison of Published Mixer

Ref.	Process	Topology	RF freq (GHz)	IF freq (GHz)	CG* (dB)	IP_{1dB} (dBm)	LO-to-RF ISO [#] (dB)	P _{dc} (mW)	LO power (dBm)	Area (mm ²)
[6]	0.25- μ m GaAs pHEMT	Star mixer	17-34	0.1-13	-6.6--15.2	N/A	22.6	0	14	0.8
[7]	0.15- μ m GaAs pHEMT	Ring mixer	40-50	DC-10	-9.2--11.9	N/A	20	0	15	1.2
[3]	0.15- μ m GaAs pHEMT	Subharmonically pumped diode	75-105	DC-21	-4.7	N/A	15	0	11	2
[8]	0.15- μ m GaAs pHEMT	Modified cascode	27-47	DC-15	0	N/A	N/A	N/A	4	1.5
[4]	0.15- μ m GaAs pHEMT	Modified triple cascode	75-120	DC-24	-10 - -17	N/A	41.5	24	7	1
[9]	0.1- μ m GaAs pHEMT	Modified cascode	34-53	3-13	-2--4	-2--4	37	36	0	2.3
[10]	GaAs	Double balanced	18-50	DC-21	-8.7	9	39	0	12-22	16
[5]	90nm CMOS	Fundamental drain/gate pumped	30-90	DC-16	-7.2--13.7	2	30.2	0.6	4.2	0.4
This work	90nm CMOS	Modified cascode	62-92	2-32	-9--12	-2-4	40.8	8.1	8	0.4

*Conversion gain, # LO-to-RF isolation

IV. CONCLUSION

In this paper, a modified cascode mixer with LC resonators fabricated by 90 nm CMOS is presented. This mixer features wide IF bandwidth, good conversion gain flatness, and high isolation. The LC resonators are utilized to improve the LO-to-RF isolation, while the cold biasing technique is the primary cause to achieve wide IF bandwidth. Both spectral line survey and continuum observation will benefit from its wide IF performance.

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