

A Wideband Gate Mixer Using 0.15 μm GaAs Enhancement-Mode PHEMT Technology

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Abstract—This paper presents a wideband gate mixer using 0.15 μm GaAs enhancement-mode pseudomorphic high electron mobility transistor (E-mode PHEMT) process. The proposed mixer is based on a single-ended gate mixer topology. Proper input matching networks are used to ensure good conversion gain as well as a wide frequency band. A $\lambda/4$ open stub at local oscillator (LO) frequency and a low-pass filter at the drain terminal do great help to enhance LO-IF and RF-IF isolation performance. A Lange coupler is used to maintain LO-RF isolation in a wide frequency band. The measured results show that the mixer operates in wide RF frequency of 17–26 GHz and IF frequency of 0.8–1.7 GHz with a conversion gain of 5–8 dB. The 1 dB compression point ($P_{1\text{dB}}$) is $-1 \sim 1$ dBm, and the needed LO power is only 1 dBm. The LO-IF, RF-IF, and LO-RF isolations are about 45, 45, and 20 dB, respectively. This represents excellent performance for GaAs PHEMT mixer in terms of frequency bandwidth, conversion gain, isolation, and $P_{1\text{dB}}$ performance.

1. INTRODUCTION

Recently, there has been an increasing demand on communication systems that work in K-band and above as they could provide wide bandwidth to achieve a high data rate. Devices operating in the K-band are widely used in short-range systems for distance measurement such as industrial positioning systems, LMDS (Local Multipoint Distribution Services) systems, and automotive systems [1, 2]. In a receiver system, down-conversion mixer is one of the most important parts for converting a received signal to a low-frequency signal. The success of receiver systems needs mixers with good performance and low cost [3].

Any nonlinear device with strong nonlinearity can be used as a mixer. In microwave mixer designs, both passive and active mixers have been proposed. Generally, passive mixers (diode mixers or resistive FET mixers) need a higher LO while active mixers, with an external dc bias, require lower power LO or even exhibit a positive conversion gain instead of conversion loss [4]. However, a high power LO is expensive and difficult to achieve as the oscillating frequency increases. Thus active mixers show great potential for both commercial and military applications.

For active mixers, heterojunction bipolar transistors (HBTs) and high electron mobility transistors (HEMTs) are used with MMIC process. The main way for HBT microwave mixer design is the Gilbert mixer. Recent developments of the well-known Gilbert mixers have been demonstrated using SiGe or GaAs HBT technology [5, 6]. As a double-balanced active mixer, the Gilbert mixer benefits from high conversion gain and good port-to-port isolation. However, it consumes much more dc power. In the microwave regime, HEMTs with good frequency performance are quite popular. A number of gate mixers using GaAs or InP-based HEMTs have been investigated and employed [7, 8]. The gate mixer

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could achieve a better conversion gain. Due to the higher conversion gain, the requirement for a low noise amplifier preceding the mixer may be eliminated in certain applications.

Compared with CMOS process, GaAs-based devices exhibit better noise and linearity performance. E-mode PHEMTs are suitable for modern wireless mobile communications due to their single voltage supply, low knee voltage, and high linearity characteristic [9, 10]. In this paper, we propose a wideband gate mixer using 0.15 μm GaAs E-mode PHEMT process. The measurement results show that the mixer can achieve quite good conversion gain, isolation, and P1dB performance in quite a wide RF and IF frequency band. The mixer can be used for K-band receiver systems applications.

2. MMIC PROCESS AND CIRCUIT DESIGN

This circuit is designed using a 0.15 μm GaAs E-mode PHEMT process provided by the WIN Semiconductors Corp. The E-mode PHEMT device typically exhibits a maximum oscillation frequency f_{max} of 150 GHz and current gain cutoff frequency f_T of 85 GHz when being biased at the maximum dc transconductance of about 1000 mS/mm. In this MMIC process, E-mode PHEMT device, diode, slot VIA hole, thin film resistor, metal-insulator-metal (MIM) capacitor, spiral inductor, and microstripline are available.

For a common source active FET mixer, two different configurations are quite common, gate mixer and drain mixer. Generally, gate mixer can achieve much higher conversion gain than the latter one; therefore, gate mixer is studied here. The frequency conversion mainly comes from device nonlinearity. The nonlinearity in an HEMT includes conductance, transconductance, and capacitances, and the dominant nonlinearity is the transconductance. When the gate is biased near the pinch-off region, the transconductance approaches zero. A small positive gate voltage variation can cause a large change in transconductance, leading to a nonlinear response. The LO voltage can be applied to the gate to pump the transconductance to switch the HEMT between high and low transconductance states, thus providing the desired mixing function. In this gate mixer design, a common source E-mode PHEMT with a size of $2 \times 75 \mu\text{m}$ (2 gate fingers and the unit gate width of $75 \mu\text{m}$) is used. The transistor is biased at a drain voltage of 4 V and the gate voltage of 0.3 V, with the quiescent drain current near 0 mA.

The proposed wideband HEMT gate mixer is based on the single-ended design as shown in Figure 1. For single-ended gate mixer, both the RF and LO signals are supplied to the gate terminal without electrical separation, and this makes it difficult to maintain isolation between LO and RF signal ports. In order to provide better isolation performance, a Lange coupler is applied to the gate. A Lange coupler can easily achieve 3 dB coupling ratios, with quite a broad bandwidth and high port-to-port isolation while it occupies a smaller area than a branch line coupler [11]. According to our simulation, the designed Lange coupler achieves port-to-port isolation of no less than 20 dB as well as an insertion loss of less than 4 dB in 15–30 GHz.

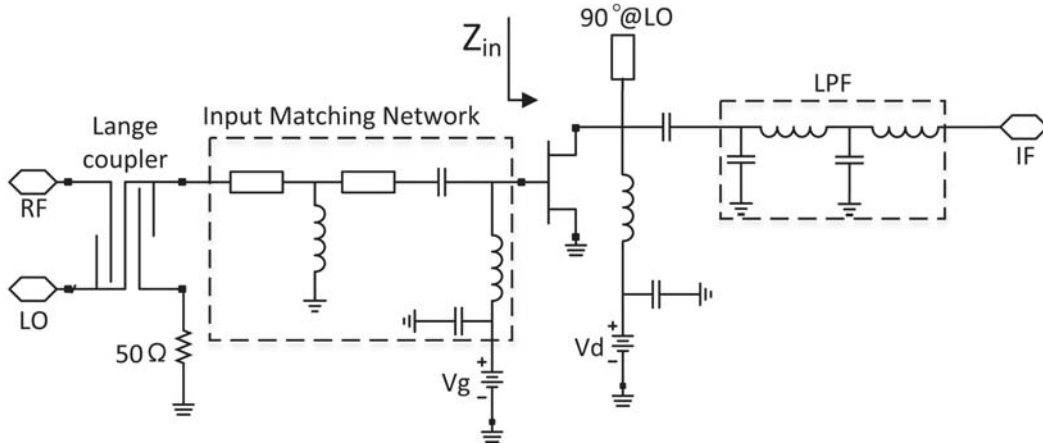


Figure 1. The circuit schematic of the mixer.

To obtain a good conversion gain characteristic in a broad band, a combined T-shape and L-shape input matching network is employed as shown in Figure 1. Both microstrip and lumped inductors are employed to achieve broadband matching. When designing the Lange coupler, the typical ports impedance is selected as $50\ \Omega$. Z_{in} is the input impedance looking into the gate terminal of PHEMT device at RF frequency. The input matching network between the transistor and Lange coupler provides a proper impedance transformation from Z_{in} to $50\ \Omega$. Since the inductance connected with V_g is small for the IF, one more objective of this matching network is to provide a short-circuit condition for the IF signal. This prevents IF signal from leaking into the RF and LO port.

The IF output was extracted from the drain terminal. The MIM capacitor at the drain serves not only for DC blocking, but also for IF impedance matching. At the drain terminal, a low-pass filter is used to enhance the LO-IF and RF-IF isolations. The filter is composed of two series spiral inductors and two MIM capacitors shunted to ground. In order to further improve the LO-IF and RF-IF isolations, a $\lambda/4$ open stub at LO frequency is utilized at the drain terminal. As LO and RF frequencies lie close together, it behaves as a short circuit for both RF and LO signals. With this LO short circuit, the drain voltage remains nearly constant throughout the LO cycle. In this case, it guarantees the transistor's large-signal stability even under hard LO input drive by minimizing feedback at the LO frequency and its harmonics.

The circuit simulation is performed using the Keysight Advanced Design System (ADS). The whole passive layout simulation has been performed and optimized by a 2.5D planar EM-simulator (Momentum). Then the transistor model is added and co-simulated with the S -parameters of the passive layout. The harmonic balance simulation is used to verify the mixer performance such as conversion gain, P_{1dB} , and port-to-port isolation. A chip photo is shown in Figure 2, including DC and RF pads.

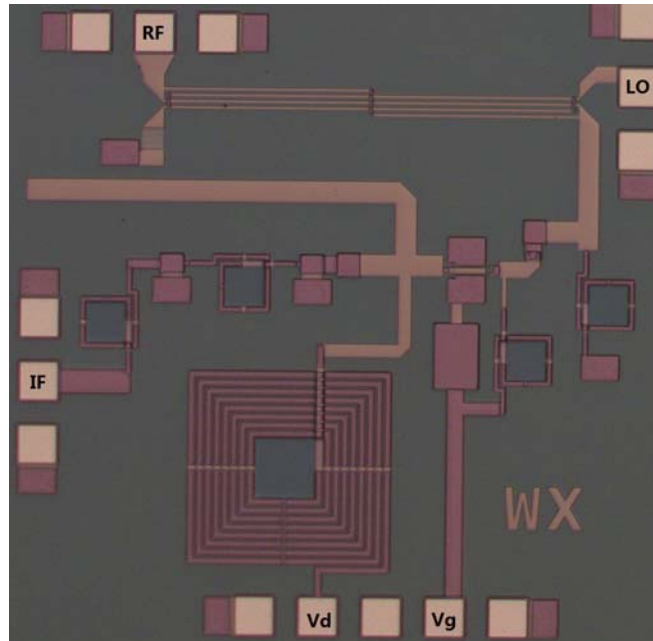


Figure 2. Chip photo of the mixer with a chip size of $1500\ \mu\text{m} \times 1500\ \mu\text{m}$, including RF and DC bias pads.

3. EXPERIMENT RESULTS

The E-mode PHEMT gate mixer MMIC was fully characterized via on-wafer probing with DC and RF probes. Both the RF and LO signals are provided by the Agilent signal sources, and the signal in IF port is measured by the Agilent N9030A PXA signal analyzer. The insertion loss of the cables and

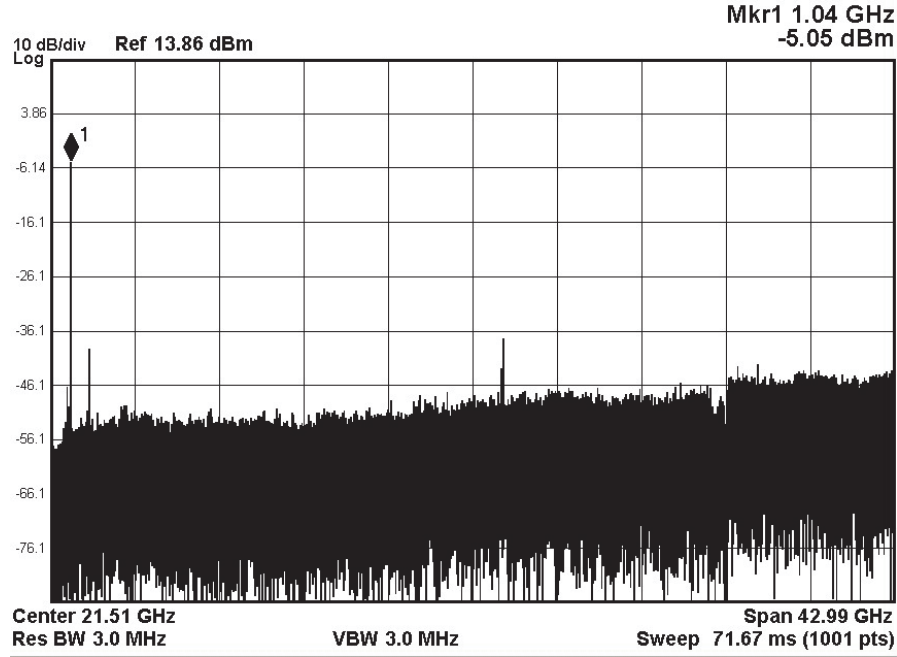


Figure 3. The measured output spectrum.

probes in the measurement setup is about 3 dB in this frequency band. Figure 3 shows the raw data of the measured spectrum when RF = 22 GHz, LO = 23 GHz, and IF = 1 GHz with 50 Ω standard load. The input RF power is -10 dBm, and LO power is 1 dBm. From Figure 3 the IF output power is -5 dBm. Taking the insertion loss of the cables and probes into consideration, the corrected output power is -2 dBm, corresponding to a conversion gain of 8 dB.

Figure 4 shows the simulated and measured conversion gains versus LO power at the RF frequency of 22 GHz and LO frequency of 23 GHz. The measured conversion gain is a bit lower than the simulated results. This discrepancy could be attributed to three reasons. Firstly, the device large-signal model is not sufficiently accurate. As the device model handbook provided by WIN Semiconductors Corp shows [12], the device model predicts higher output power and gain than the measured data. Thus it is

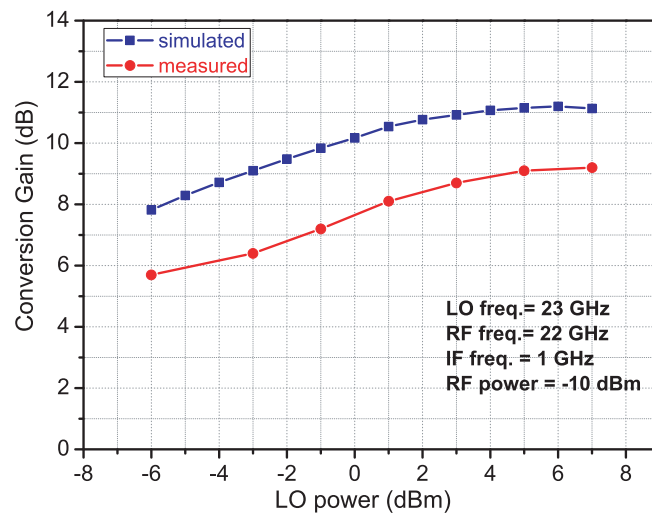


Figure 4. The simulated and measured conversion gain versus LO power.

reasonable that the simulated gain of the mixer is higher than the measured one. Secondly, the device model is optimized for power amplifier (PA) design when V_{gs} is 0.45–0.75 V, while the proposed mixer is biased near pinch-off ($V_{gs} = 0.3$ V). This means that the device large-signal model is not perfectly suitable for our design. Thirdly, the passive part of the layout was performed by a 2.5D planar EM-simulator instead of a 3D simulator. This could save a lot of simulation time, but also introduced some discrepancy between simulation and measurement. Therefore, the difference between simulation and measurement results is acceptable and reasonable. In addition, the simulation and measurement results have basically the same trend, which approves the feasibility of the circuit design method.

Figure 5 shows the simulated and measured conversion gains versus RF input power. We can see that the measured 1 dB compression point P_{1dB} is -1 dBm. Actually in the whole frequency band, the maximum P_{1dB} can be as high as 1 dBm. The measured conversion gains versus RF frequency and IF frequency are shown in Figure 6. A conversion gain over 5 dB is obtained in 17–26 GHz with a maximum value of about 8 dB, which means a 3 dB bandwidth of 9 GHz. This is a relative RF bandwidth of 41.9%. At a fixed LO frequency, a conversion gain of 5–8.5 dB is achieved when the IF is

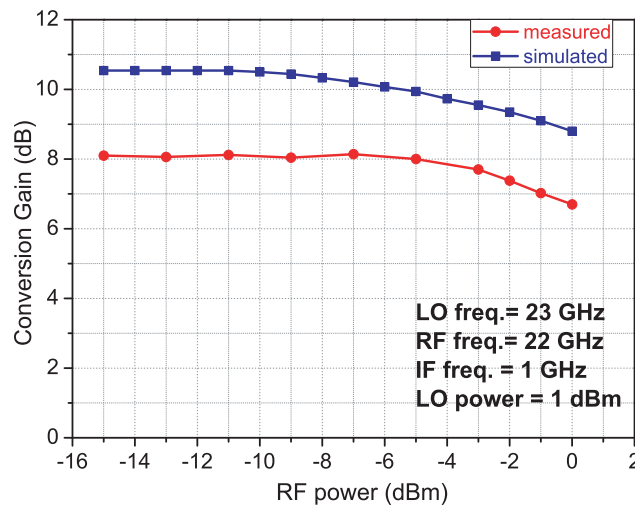


Figure 5. The simulated and measured conversion gain versus RF power.

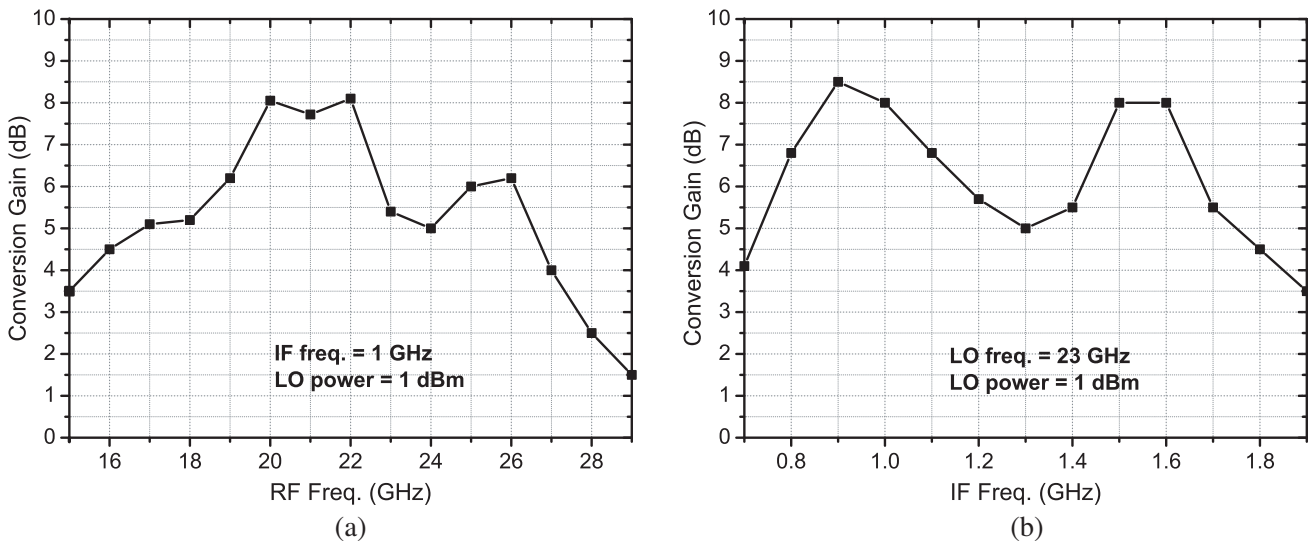


Figure 6. The measured conversion gain, (a) versus RF frequency, (b) versus IF frequency.

between 0.8 GHz and 1.7 GHz. This means an IF bandwidth of 0.9 GHz, corresponding to a relative IF bandwidth of 72%. Although quite high conversion gains are obtained, the flatness is not so excellent. For optimum conversion gain, the input network must provide conjugate matching at the RF and LO, while the output network must conjugate match the device at the IF. Since the matching is done at a broad band, the return losses have fluctuations at different frequencies. This will ruin the flatness of conversion gain.

As shown in Figure 7, the measured results of LO-RF, RF-IF, and LO-IF isolations are about 20, 45, and 45 dB, respectively. The LO-IF and RF-IF port isolations are quite good thanks to the employed low-pass filter and the $\lambda/4$ open stub at LO frequency. The LO-RF port isolation is also good because of the optimized Lange coupler.

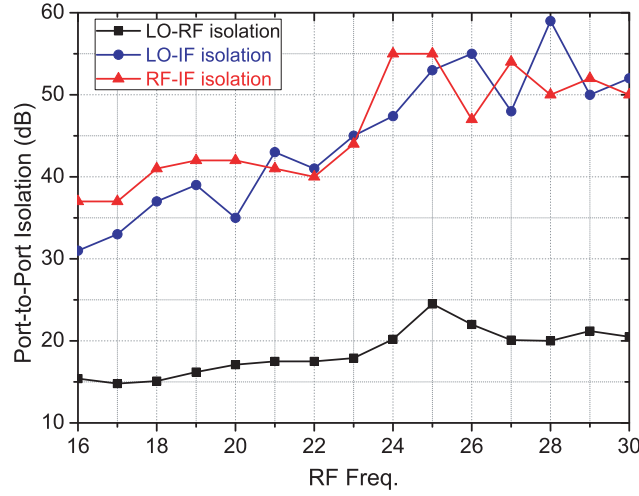


Figure 7. The measured isolation versus RF frequency.

The comparison between our design and other reported mixers is listed in Table 1. Among the listed results, the proposed mixer demonstrates a wide bandwidth, quite good conversion gain, as well as high $P_{1\text{dB}}$. Moreover, the needed LO power is only 1 dBm, which is lower than many others. The excellent performances of this mixer demonstrate good potential for microwave system applications.

Table 1. Comparison of some reported mixers.

Ref.	Process	Conversion Gain (dB)	RF Freq. (GHz)	IF Freq. (GHz)	LO Power (dBm)	$P_{1\text{dB}}$ (dBm)
[11]	0.18 μm GaAs PHEMT	0.6	39	3	2	-4
[13]	MACOM diode	-15 ~ -7	25 ~ 39	1.1 ~ 2.6	12	-
[14]	GaAs diode	-12 ~ -7	24.1 ~ 25	0.1 ~ 0.9	12	-
[15]	90 nm CMOS	10 (with LNA)	21.6 ~ 27	-	-4	≤ -8.5
[16]	0.18 μm CMOS	-5.1 ~ -3.9	23 ~ 25	-	5	-6
This work	0.15 μm GaAs PHEMT	5 ~ 8.5	17 ~ 26	0.8 ~ 1.7	1	-1 ~ 1

4. CONCLUSION

In this paper, a wideband gate mixer has been successfully developed using a 0.15 μm GaAs E-mode PHEMT process. The Lange coupler and the reasonable input matching network contribute to the good conversion gain performance in quite wide RF and IF bandwidths. In addition, the mixer exhibits other excellent performances such as high $P_{1\text{dB}}$, isolation, and low LO power. The excellent measurement results indicate that the mixer has great potential for K-band receiver systems applications.

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