A Comparison of W-Band MMIC Mixers Using InP HEMT Technology

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***Abstract*—This paper compares the performance of three different W-Band mixer designs in the same InP HEMT technology. A resistive HEMT mixer, an active HEMT mixer, and a rat-race diode mixer are designed and measured for conversion, intermodulation and noise performance for an LO frequency of 94 GHz and IF frequencies ranging from 0.5 to 5 GHz. This is the first direct comparison of three high-performance W-Band mixers fabricated in the same InP HEMT technology.**

I. Introduction

For 94 GHz missile seeker applications, the utilization of an InP-based HEMT compatible mixer provides many advantages. In addition to providing the obvious benefits of small size and weight, this type of mixer can also be directly integrated with a low-noise InP HEMT MMIC amplifier to provide optimum system performance. Because different types of mixers offer different advantages and disadvantages, the demands of the particular system will ultimately determine which mixer offers the "best" performance.

Many papers have been published on W-Band resistive FET mixers [1] - [2], active FET mixers [3], and various diode mixers [4] - [7], but direct comparisons of these different types of mixers are difficult due to the varying device technologies used. This paper addresses this issue and describes the W-Band performance of a resistive HEMT mixer, an active HEMT mixer, and a rat-race diode mixer all designed into the same InP HEMT process technology [8]. The resulting analysis highlights the trade-offs of the different designs when considering conversion, intermodulation and noise performance.

II. Resistive HEMT Mixer

The resistive HEMT mixer configuration was chosen for its superior intermodulation performance, low LO drive requirement, high dynamic range, and zero DC power consumption. For this type of mixer, the gate is biased near the turn-on voltage (V_t), and the drain is biased at 0 V. The LO signal is applied to the gate and varies the HEMT channel conductance at the LO frequency. When the RF signal is applied to the drain, across this time-varying resistance, mixing products are produced. The desired IF signal is then filtered from the drain through a diplexing network.

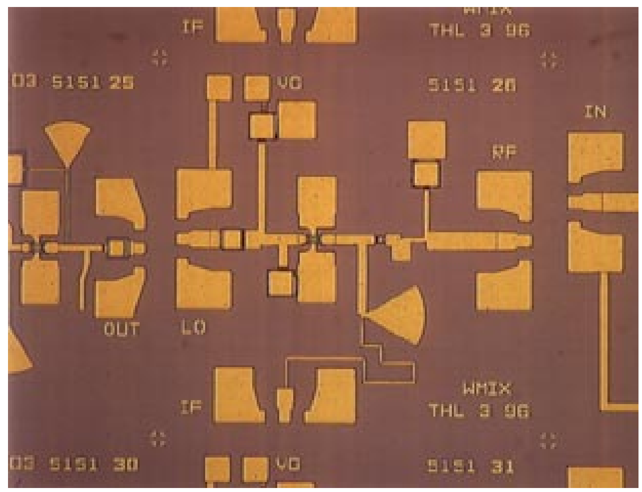

Figure 1. Resistive InP HEMT mixer. The mixer utilizes a 4 x 25 µm device, and the chip area is 1.5 x 1.5 mm^2.

The resistive HEMT mixer, shown in Figure 1, utilizes a 4 x 25 µm device, and the total chip area is just 1.5 x 1.5 mm^2. The input circuit is configured to minimize the affects of any RF voltage, which may be coupled to the gate, in order to prevent any adverse influences on the LO-controlled channel conductance. Similarly, the output circuit is designed to minimize the LO voltage at the drain while providing a structure which both matches and isolates the RF input and IF output signals [9]. As with all of the mixers presented, this design was simulated using HP-EEsof's LIBRA™,

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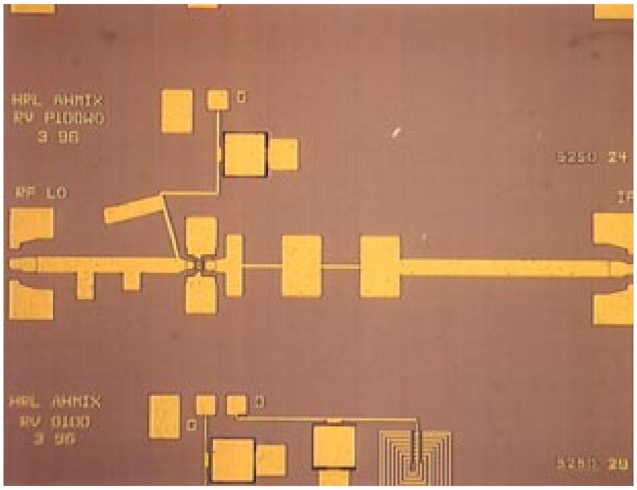

Figure 2. Active InP HEMT mixer. The mixer utilizes a 4 x 25 μm device, and the chip area is 1.2 x 2.3 mm^2.

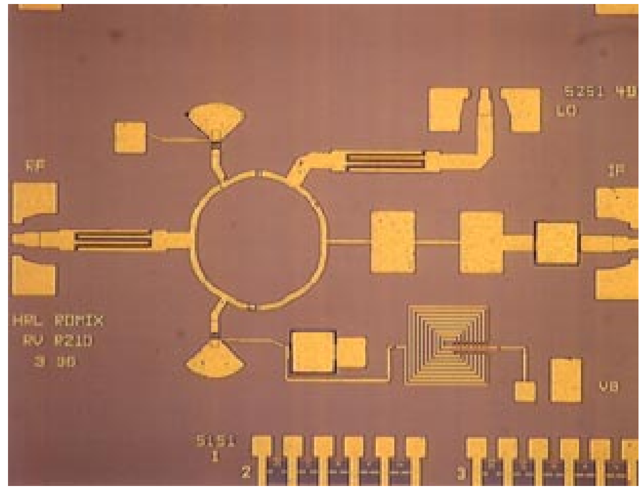

Figure 3. Rat-race diode mixer. The mixer utilizes the gate-source junctions of two 2 x 10 μm devices as the mixing diodes, and the chip area is 1.6 x 3.1 mm^2.

where analyses were performed on the critical discontinuities utilizing Sonnet's *em*™, for an LO frequency of 94 GHz and a desired IF bandwidth of 0.5 - 2.5 GHz.

III. ACTIVE HEMT MIXER

The active HEMT mixer was chosen for its superior conversion and noise performance. For this mixer, the gate is biased near V_t, and a moderate voltage is applied to the drain. The LO and RF signals are externally combined and applied to the gate of the HEMT where the LO drive generates a time-varying transconductance that mixes with the RF signal.

The input circuit is designed to provide a conjugate match at the RF frequency while short-circuiting the IF frequency. The output matching circuit at the drain is designed to present a large real impedance at the desired IF frequency, while short-circuiting the RF, LO and their undesired harmonic and mixing frequencies [10]. Matching the large output impedance of this mixer is difficult for low IF frequencies, due to the limited chip area available for tuning structures, but the use of an off-chip transformer at the output has been shown to improve the conversion gain substantially [11]. Figure 2 shows an active mixer which utilizes a single 4 x 25 μm InP HEMT, where the total chip area is 1.2 x 2.3 mm^2.

IV. RAT-RACE DIODE MIXER

The rat-race diode mixer was chosen for its moderate intermodulation performance and ease of design. For this type of single-balanced mixer, both the LO and RF signals are applied over the terminals of the two diodes through a rat-race hybrid circuit, composed of six quarter-wave sections at the LO frequency. The LO drive "pumps" the diodes 180° out of phase to generate a time-varying conductance in each diode, at the LO frequency, which mixes with the applied RF signal. The desired IF mixing products are then combined from the terminals of the diodes via the hybrid circuit and isolated through a filter at the output.

The rat-race diode mixer, shown in Figure 3, utilizes the gate-source junctions of two 2 x 10 μm HEMT devices as the mixing diodes. The devices are oriented so that a DC bias can be applied to reduce the required LO drive. The LO and RF signals are applied through interdigitated capacitors, while a stepped-impedance filter is used at the output to extract the desired IF signal. The resulting chip area is 1.6 x 3.1 mm^2.

V. RESULTS AND MIXER COMPARISONS

The mixers were measured for conversion performance as a function of IF frequency and LO drive. The RF and LO signals were injected to each circuit through a Model 120 Picoprobe®. In the case of the active HEMT mixer, the LO and RF signals were first combined using an external waveguide coupler. For each mixer, the IF output was obtained via a Cascade™ ACP probe and external bias "tee" which provided the desired drain bias for each of the HEMT mixers.

The measured conversion loss as a function of IF frequency is shown in Figure 4 for the three different configurations (f_{LO} = 94 GHz). The active mixer offers the lowest conversion loss at 0.8 dB for f_{IF} = 500 MHz (V_g = -0.64 V, V_d = 1.5 V, I_{dq} = 0.5 mA, P_{LO} = +9.7 dBm). Considering that the conversion should substantially improve when incorporating an off-chip transformer, to match the large IF output impedance of the mixer, this result compares favorably with an existing design [3] which utilizes an off-chip matching filter to perform this function. Both the resistive HEMT mixer

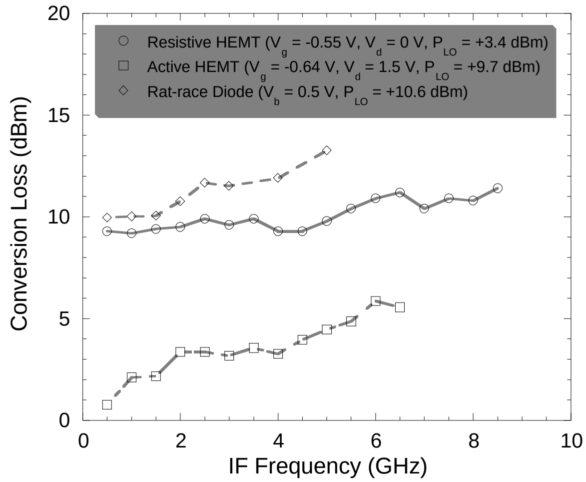

Figure 4. Measured conversion loss as a function of IF frequency for the resistive HEMT mixer (V_g = -0.55 V, V_d = 0 V, P_{LO} = +3.4 dBm), the active HEMT mixer (V_g = -0.64 V, V_d = 1.5 V, P_{LO} = +9.7 dBm), and the rat-race diode mixer (V_b = 0.5 V, P_{LO} = +10.6 dBm). The LO frequency is held constant at 94 GHz.

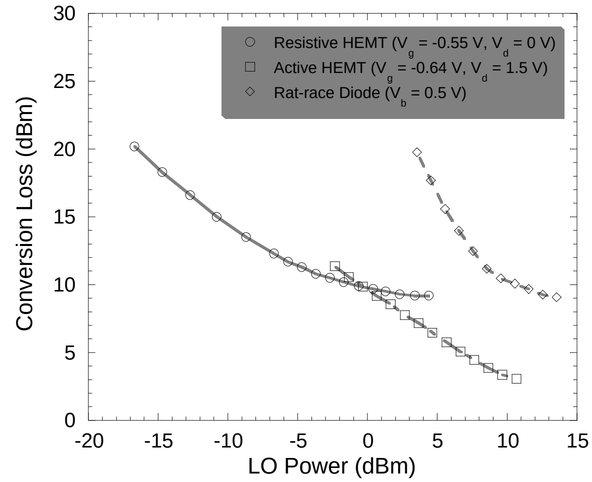

Figure 5. Measured conversion loss as a function of LO drive for the resistive HEMT mixer (V_g = -0.55 V, V_d = 0 V), the active HEMT mixer (V_g = -0.64 V, V_d = 1.5 V), and the rat-race diode mixer (V_b = 0.5 V). The LO and RF frequencies are held constant at 94 and 96 GHz, respectively.

(V_g = -0.55 V, V_d = 0 V, P_{LO} = +3.4 dBm) and the rat-race diode mixer (V_b = 0.5 V, P_{LO} = +10.6 dBm) also show conversion losses of 9 - 10 dB for the lower IF frequencies (< 2 GHz). This performance is comparable to the design goals and previously published results [1], [2], [4] - [7]. The rat-race mixer conversion loss and LO drive requirement can both be improved by ~ 1 dB by adjusting the lengths of the interdigitated capacitors at the RF and LO input ports. Direct measurement of these DC blocking structures revealed that the desired minimum insertion loss was shifted in frequency.

Even when accounting for the loss in the DC blocks, the resistive HEMT mixer still requires substantially less LO drive than the rat-race diode mixer. Part of this difference is due to the fact that the single-balanced mixer must split its LO drive over two diodes, but in general, a resistive HEMT mixer requires much lower LO drive to achieve its respectable conversion efficiency (and impressive intermodulation performance). This characteristic is highlighted in Figure 5 where the measured conversion loss is shown as a function of LO drive for each of the mixers, where the LO and RF frequencies are held constant at 94 and 96 GHz, respectively. Both the active HEMT and rat-race diode mixers require LO drives larger than +10 dBm to approach their optimal conversion efficiencies while the resistive HEMT mixer requires less than 0 dBm.

The mixers were also measured for intermodulation (IM) performance. Figure 6 shows the measured fundamental output (P_{out}) and two-tone 3rd-order intermodulation (P_{IM3}) power as a function of RF input power for each mixer, where the LO frequency and drive are held constant at 94 GHz and +10 dBm, respectively. As expected, the resistive HEMT mixer shows the lowest distortion with an Input 3rd-Order Intercept Point (IP3) of +19.8 dBm. The active HEMT mixer has an IP3 of +8.2 dBm. The rat-race diode mixer has a 3rd-order IM level which increases at ~2 dB per dB increase in RF input power (much different than the expected 3 dB/dB seen with the resistive and active HEMT mixers). This slope indicates that the nonlinearities of degree higher than three contribute significantly to the 3rd-order IM generation in this diode mixer.

Because the resistive HEMT mixer utilizes a very linear channel conductance, which varies at the LO frequency, to perform mixing, it provides the lowest intermodulation levels. Although the diode mixer distortion is somewhat larger, its IM level is still significantly lower than that of the active mixer because the diodes are biased such that the junction is strongly conducting and effectively short-circuited during most of the LO cycle. IM distortion is generated only while the diode is conducting a moderate current, where its *I/V* characteristic is significantly nonlinear. For an active HEMT mixer, IM distortion is generated over the entire positive half-cycle of the LO voltage, when the gate voltage is larger than V_t, leading to the distortion performance exhibited in the figure.

The noise figure of the active HEMT mixer was also measured. Over the IF band from 0.5 to 7 GHz, the measured SSB noise figure was 10 ± 1 dB with a minimum of 8.5 dB at 2.5 GHz. Anticipating a noise figure comparable to the conversion loss for the two resistive mixers, the active mixer doesn't appear to offer the predicted advantage in noise performance. This dif-

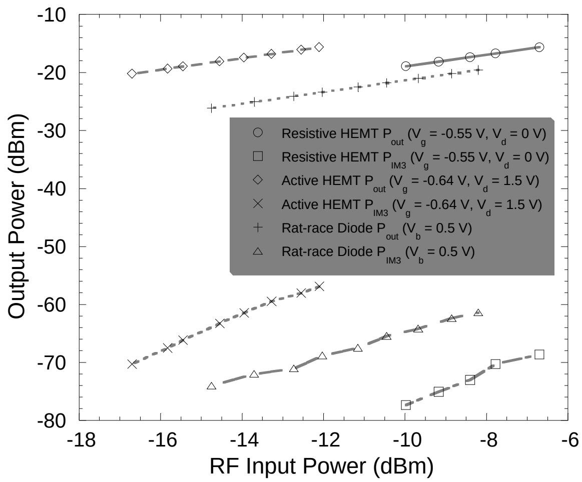

Figure 6. Measured fundamental output (P_{out}) and two-tone 3rd order intermodulation (P_{IM3}) power as a function of RF input power for the resistive HEMT mixer (V_g = -0.55 V, V_d = 0 V), the active HEMT mixer (V_g = -0.64 V, V_d = 1.5 V), and the rat-race diode mixer (V_b = 0.5 V). The LO frequency and drive are held constant at 94 GHz and +10 dBm, respectively.

ference is most likely due to the fact that the model used in the active mixer design, which was originally developed for a power InP device for < 40 GHz, did not provide an adequate representation of the low-noise InP device at W-Band. This model is also responsible for the magnitude of the LO drive required to operate the active HEMT mixer.

VI. Conclusion

In the interest of obtaining optimal W-Band system performance, a study of mixers, compatible to an InP HEMT technology, was conducted. The resistive HEMT mixer offered a respectable conversion loss, while offering the advantages of a low LO drive, the best intermodulation performance, and the least DC power consumption, all in the smallest area. The active HEMT mixer displayed the best conversion efficiency but did not offer any substantial noise advantage while requiring a moderate LO drive and demonstrating the highest IM levels. The active mixer conversion performance could be further improved through the use of an external transformer, and the use of a better W-Band device model should result in a mixer design with a better noise performance and a lower LO power requirement. The rat-race diode mixer occupied the most area, but it provided an adequate conversion performance and offered a lower IM level than the active mixer, although higher order nonlinearities contributed significantly to the measured distortion.

Acknowledgment

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