Design and Performance of a 45-GHz HEMT Mixer

STEPHEN A. MAAS, MEMBER, IEEE

Abstract —A 45-GHz single-ended HEMT mixer has been developed with unity gain and 7–8-dB SSB noise figure over a 2-GHz bandwidth, including an IF amplifier, and 2-dBm output intermodulation intercept. This paper describes its design, structure, and performance. High performance has been achieved by careful attention to the design of the input and output embedding networks. This is the first reported HEMT mixer and the first active mixer above 30 GHz.

I. Introduction

GaAs MESFET mixers have conversion gain and have achieved noise figures and intermodulation levels superior to those of diode mixers at microwave frequencies [1], [2]. They are particularly valuable for use in small, lightweight, integrated receivers and in GaAs integrated circuits. The use of FET mixers above 30 GHz has not been explored, however, and the usefulness of high-electron mobility transistors (HEMT's) as mixers has also not been addressed. This paper describes the design and performance of the first reported HEMT mixer and the first active mixer at 45 GHz. It shows that such mixers can achieve conversion gain, and have noise and intermodulation performance that compares favorably with that of diode mixers.

HEMT's have several demonstrable and potential advantages over GaAs MESFET's for use in millimeter-wave mixers. The major advantage is that the high mobilities achieved in the two-dimensional electron gas result in substantially higher transconductance (in this case over 300 mS/mm), hence higher conversion gain and lower noise. The large increase in transconductance with only moderate cooling may also result in very low-noise cooled mixers. The one disadvantage is that the peaked transconductance versus gate voltage characteristic of currently available devices results in intermodulation levels that are higher than those of MESFET's, but still comparable to those of diode mixers.

II. HEMT Device

The HEMT device used for this mixer was designed for low-noise amplifier applications above 30 GHz. It is described in detail by Berenz [3]. The active layer is grown at TRW by molecular-beam epitaxy, and the source and drain contacts are ion-implanted for low resistance. The dimensions of the recessed gate are 0.25 μm by 60 μm, and it is rectangular in cross section. The gate is defined by electron-beam lithography, and it is offset slightly toward the source to minimize drain/gate capacitance. The device's transconductance, as a function of gate voltage, is shown in Fig. 1; its peak value is 28 mS. Similar devices from the same manufacturing lot have achieved noise figures below 3 dB with 6-dB associated gain for a single-stage amplifier at frequencies near 40 GHz [4].

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The author was with TRW, Electronic Systems Group, Redondo Beach, CA. He is now with Aerospace Corporation, Los Angeles, CA 90009.

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III. Mixer Design

The mixer is designed according to the principles outlined in [2]. In designing the mixer's input and output matching circuits, it is important to present the optimum terminations to the HEMT gate and drain not only at the RF, IF, and LO frequencies, but at all significant LO harmonics and mixing frequencies. In particular, for a conventional downconverter, it is important to short-circuit the LO frequency and its harmonics at the drain and the IF frequency at the gate. The number of LO harmonics which are significant is sometimes problematical; however, for a 45-GHz mixer it is safe to assume that only two or at most three harmonics are significant. The input is matched at the RF frequency; no improvement in noise figure has been obtained experimentally by mismatching the input as is done in FET and HEMT amplifiers.

The IF output impedance of a gate-driven HEMT mixer is usually very high, because it is dominated by the HEMT's drain/source resistance. This resistance varies over the LO cycle from a low of several hundred ohms to an open circuit when the device is turned off. Measurements and numerical simulations using the techniques in [2] indicate that the output impedance of a well-designed, strongly-pumped FET or HEMT mixer is on the order of 1000–3000 Ω, and is in practice nearly impossible to match. In the rare instances when the IF can be matched (e.g., at IF frequencies below 100 MHz with bandwidths of a few MHz), the high load impedance may cause instability. For the broad-band microwave IF's invariably required by modern communications receivers, it is necessary to employ a different matching rationale. The IF should be designed to present a load impedance to the HEMT of 50–150-Ω resistive, depending upon the desired gain and circuit realizability limitations. The drain is biased to the same voltage that would be used in amplifier operation; the gate bias point is near the gate turn-on voltage.

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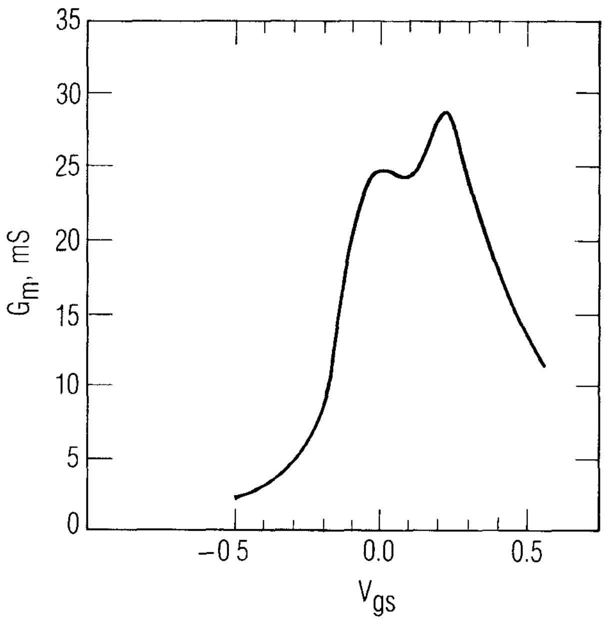

Fig. 1. DC HEMT transconductance.

The purpose of the broad-band short at the drain is twofold: first, it guarantees large-signal stability of the device even under hard LO input drive by minimizing feedback at the LO frequency and its harmonics. Second, it ensures that the drain voltage remains constant at the bias value, so the HEMT remains in its saturation region throughout the LO cycle. The drain/source resistance therefore remains high and relatively constant, and the variation of the drain/gate and gate/source capacitances, although not zero, is minimized. The result is that the dominant parameter in the frequency conversion process is the fundamental frequency component of the transconductance, and its magnitude is maximized. The gate termination at the IF frequency does not appreciably affect conversion gain if the mixer is otherwise well designed; however, it does affect noise figure significantly. Shorting the gate reduces the gain through the device at the IF frequency, and therefore prevents the amplification of noise from the input termination or the bias circuit at the IF frequency.

It is possible to estimate the conversion gain and input impedance of a MESFET or HEMT mixer very easily and with good accuracy if its input and output matching networks are well designed and its IF frequency is low compared to the RF. The RF input impedance can be estimated from device parameters as follows:

$$Z_{\text{in}} = R_{\text{in}} + \frac{1}{j\omega C_j}. \tag{1}$$

This input impedance is a good starting value for input circuit design. The conversion gain G_c is given by (8) in [1] as follows:

$$G_c = \frac{g_1^2}{4\omega^2 C_j^2} \frac{\overline{R}_d}{R_{\text{in}}}. \tag{2}$$

In this expression $\overline{R}_d$ is defined in [1] as the time-averaged drain resistance, although, since R_d is an open circuit over part of the LO cycle, it is more precisely the inverse of the time-averaged drain admittance. g_1 is the magnitude of the fundamental component of the transconductance waveform. Since (2) assumes a matched output, only half the current from the drain current source circulates in R_L. For this mixer, $R_L \ll \overline{R}_d$ so the full output current circulates in R_L and

$$G_c = \frac{g_1^2}{\omega^2 C_j^2} \frac{R_L}{R_{\text{in}}}. \tag{3}$$

Assuming that the gate is biased near the device's turn-on voltage, the transconductance waveform is a half sinusoid, and $g_1 \cong G_{m\,\max}/4$ so

$$G_c = \frac{G_{m\,\max}^2}{16\omega^2 C_j^2} \frac{R_L}{R_{\text{in}}} \tag{4}$$

where $G_{m\,\max}$ is the maximum transconductance, R_L is the IF load impedance at the drain of the device, R_{in} is the total resistance in the input loop of the device, the sum of gate, source, and intrinsic resistances, C_j is the gate/source capacitance at the turn-on voltage, and ω is the RF radian frequency. Equation (4) is valid only for the optimum short-circuit terminations discussed above. Equation (4) also assumes that the voltage drop across the source resistance R_S is negligible (satisfied if $g_1 R_S \ll 1$) and the gate/drain capacitance is negligible. The latter is satisfied if the drain terminations are short circuits.

Equation (4) shows that FET mixers, unlike FET amplifiers, achieve higher gain as the gate width is increased, because $G_{m\,\max}$ increases in proportion to width and the device can be designed so that $\omega C_j R_{\text{in}}$ stays approximately constant. The limit to gain improvement by increasing gate width is that input impedance drops with increasing gate width, and matching becomes progressively more difficult in practice to achieve. Gain also increases with R_L. The limit to increasing R_L, other than circuit realizability limitations, is that the mixer may become unstable. For the HEMT mixer, $R_{\text{in}} = 7.8\ \Omega$, $C_j = 0.074$ pF, $R_L = 110\ \Omega$, and $G_{m\,\max} = 0.028$ S, (4) predicts approximately 2-dB conversion gain. This is very close to the 1.5-dB measured gain, which necessarily includes circuit losses. More accurate conversion gain and input/output impedance calculations, or calculations for other types of mixers (e.g., upconverters) can be obtained using the methods in [2].

One should recognize that (4) predicts conversion gain achievable in practice, not the maximum available gain (MAG), which is usually unachievable, and is defined only if the circuit is unconditionally stable. Numerical simulations which include all the device parasitics, especially the gate/drain capacitance, indicate that FET mixers are often only conditionally stable. A load resistance below 150 Ω, however, is almost invariably adequate to insure stability.

It is clear from (4) that a wider device would be preferable to that used here. Also, it appears likely that conversion gain can be achieved with similar devices at even

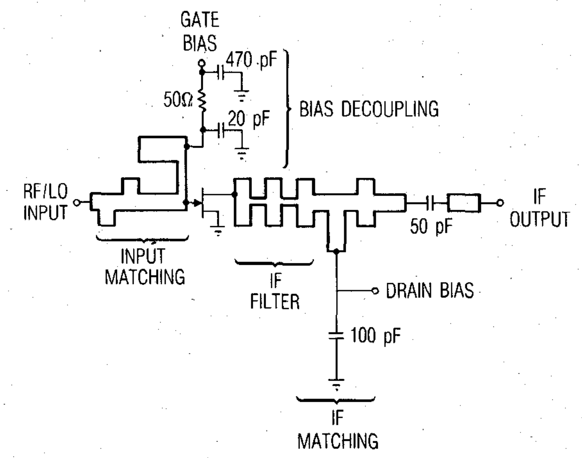

Fig. 2. HEMT mixer circuit.

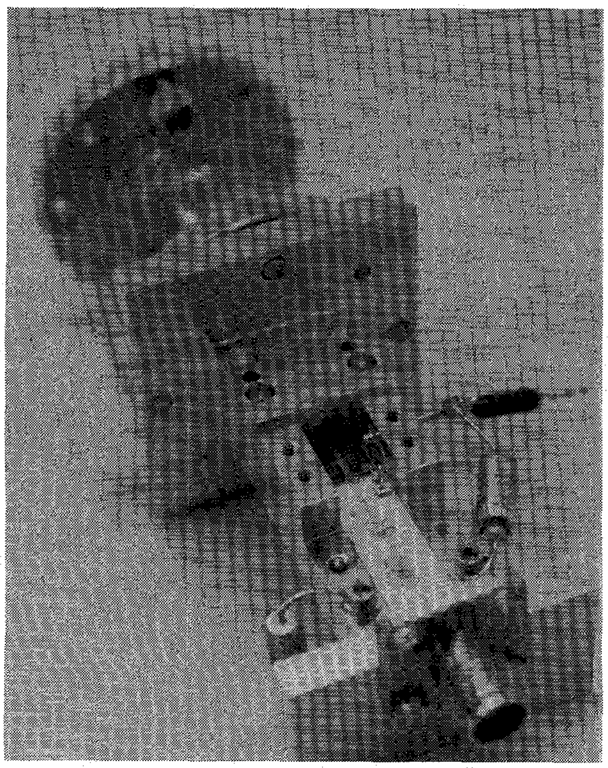

Fig. 3. 45-GHz HEMT mixer. The RF and LO are applied through a common WR-22 waveguide input.

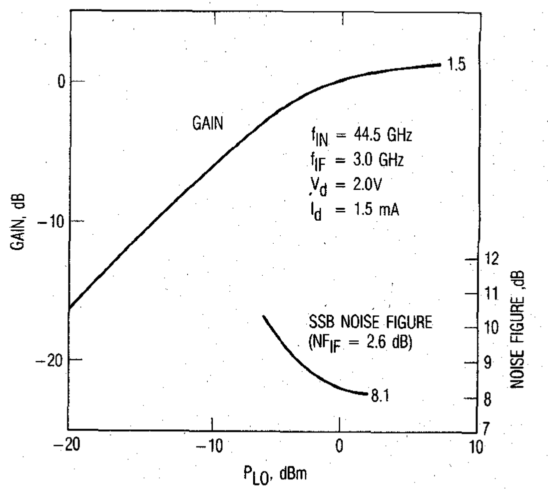

Fig. 4. Conversion gain and noise figure for the narrow-band mixer. Gate bias is varied with LO level to maintain constant drain current.

higher frequencies. Reducing gate resistance by developing a "T" gate would also improve gain significantly, and might also improve noise figure. Matching difficulties in a wide device with a highly reactive input could be overcome through the use of on-chip matching, as is sometimes done with power FET's.

The HEMT mixer circuit is shown in Fig. 2 and a photograph of the mixer is shown in Fig. 3. The input circuit is realized in microstrip on a 0.010-in-thick fused silica substrate, with an integral waveguide/microstrip transition. The substrate metalization consists of a chrome adhesion layer with a 75-μin gold layer. The input matching circuit is a simple open-circuit stub, designed using (1) and appropriate estimates for the bond-wire reactances. DC gate bias is applied through a decoupling circuit which also supplies the IF frequency short; since the input circuit has no dc connection to ground, no input dc block is needed. The output matching circuit is realized on a 0.010-in finely-polished alumina substrate to minimize the size of the IF matching elements. It consists of a filter, which supplies the required LO harmonic shorts to the drain, and a simple stub matching arrangement for the IF frequency. The filter was designed as a conventional stepped-impedance low-pass structure, and computer-optimized to achieve the desired terminations. Its IF-frequency S-parameters were then used to design the stub matching circuit to achieve the 110-Ω resistive load. DC drain bias is applied through the stub. Bond-wire reactances at the gate and drain, and especially the source, are minimized by using very short multiple connections.

The mixer is single-ended. For test purposes, the LO and RF signals must be combined by a filter diplexer or directional coupler. In a systems application, a pair of these mixers would be used in a balanced configuration, with the LO and RF combined via an input hybrid.

IV. Performance

Fig. 4 shows the conversion gain and noise figure of the mixer as a function of LO level, with the mixer tuned for narrowband (approximately 200 MHz) operation near 44.5 GHz. The IF frequency is 3.0 GHz and the LO is 41.5 GHz. Gate bias in Fig. 4 has been adjusted to maintain a constant drain current at all LO levels, but no retuning has been performed. Varying the gate bias this way, which can be done easily in practice, minimizes the variation of gain with LO level. The noise figure in Fig. 4 includes the effects of a 2.5-dB IF amplifier.

Fig. 5 shows the conversion gain and noise figure of the mixer tuned for 2-GHz bandwidth. In this figure, the IF frequency is fixed at 3.0 GHz and has a 200-MHz bandwidth. The LO and RF frequencies are varied, but the tuning, bias, and LO level are held constant. Fig. 6 shows the input return loss under the same conditions.

Fig. 7 shows the two-tone intermodulation characteristics. Under the same bias and tuning conditions as those

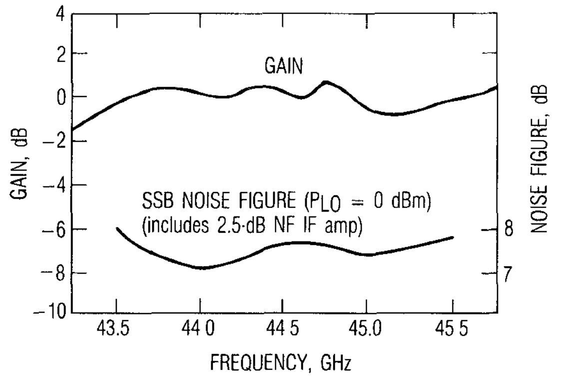

Fig. 5. Noise figure and conversion gain over a 2-GHz bandwidth. The IF is fixed at 3.0 GHz and the LO frequency is varied.

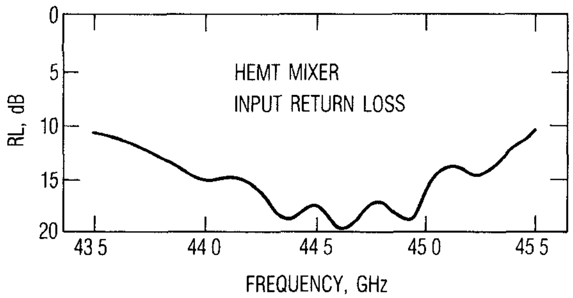

Fig. 6. HEMT mixer input return loss. IF frequency is fixed.

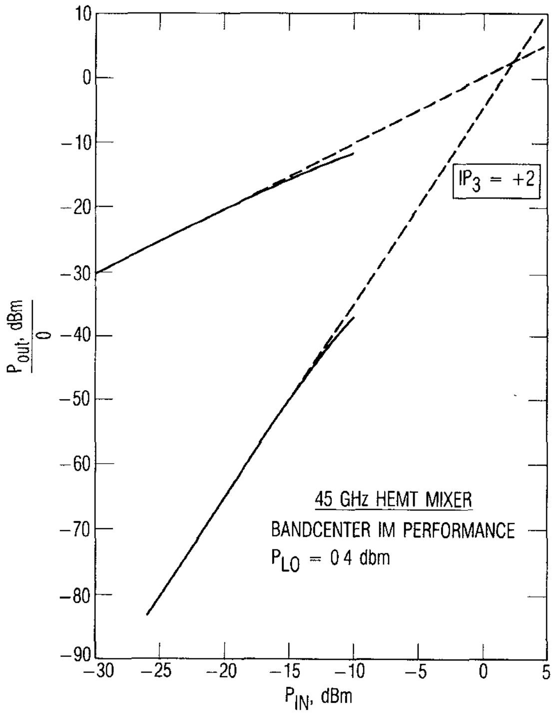

Fig. 7. Intermodulation curves for the HEMT mixer under optimum gain bias conditions. LO power is 0.4 dBm.

for Fig. 5, but at 0-dBm LO power, the output third-order intermodulation intercept is 2 dBm. This level is comparable to that of single-ended diode mixers, which are typically about 0–5 dBm, but the HEMT requires less LO power. It is difficult to compare this result to measured intermodulation levels in microwave MESFET mixers, because of differences in device size and frequency, and the paucity of published data. The transconductance/gate voltage nonlinearity of the HEMT is clearly stronger than that of most MESFET's, however, so it is to be expected that nonlinear distortion would be worse. The main cause of the mildly disappointing intermodulation level is the sharp peak in the transconductance curve, which increases the harmonic content of the transconductance waveform. It is possible to improve the intercept point to 8 dBm by biasing the mixer so that the most nonlinear part of the G_m/V_{gs} curve is avoided, but the reduced transconductance variation reduces the conversion gain by 5–6 dB. A device with a less strongly peaked transconductance characteristic would show the same gain with better linearity. It might also have better linearity in amplifier applications.

The noise figure and intermodulation performance of this mixer compares favorably to that of diode mixers at the same frequency. A very good waveguide diode mixer with whisker-contacted diodes typically would have a 4-dB conversion loss and a 4.5-dB SSB noise figure, but a 5-dB loss and a 5.5-dB noise figure is more expectable. With a 2.5-dB IF noise figure, the receiver noise figure would be 7–8 dB. Conversion loss of integrated mixers is significantly higher, in the range 6–10 dB, with resulting receiver noise figures above 10 dB [5], [6]. The noise figure of this mixer with the same IF is 7–8 dB, but it is achieved in a small, reliable, low-cost microstrip component with conversion gain, lower LO power, and better manufacturing repeatability. Furthermore, performance may improve as more suitable devices for mixer application become available. Being a FET device, it is also amenable to monolithic integration.

It is true that the noise figure of the HEMT mixer is higher than that of an amplifier using the same device. For this reason one might conclude that it would be better to use the HEMT solely in a multistage amplifier ahead of a prosaic diode mixer. This reasoning is valid if noise figure is the sole performance criterion; however in many modern space communications systems, intermodulation and spurious response susceptibility are as important as noise, and these are exacerbated by the use of high-gain, low-noise preamplifiers. The levels of third-order intermodulation products at the mixer IF, for example, increase 3 dB for each decibel of preamplifier gain. Therefore, even if a preamp must be used, a low-noise HEMT mixer affords the same noise figure with less preamplifier gain, hence better receiver dynamic range.

V. Conclusions

This paper has described the design and performance of the first active HEMT millimeter-wave mixer. Its performance compares favorably with that of diode mixers with less LO power in an inexpensive, reliable, microstrip circuit. Performance could be improved through the use of a wider device with a "T" gate, and a less strongly peaked transconductance characteristic. Since HEMT amplifiers show dramatic gain and noise figure improvements on even moderate cooling, it is likely that cooled HEMT mixers also might achieve excellent noise performance.

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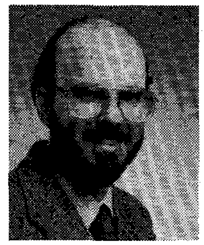

Stephen A. Maas (S'80–M'83) was born in Quincy, MA, in 1949. He received the B.S.E.E. and M.S.E.E. degrees in electrical engineering from the University of Pennsylvania in 1971 and 1972, and the Ph.D. degree in electrical engineering from the University of California, Los Angeles, in 1984.

He has been involved in the research and development of low-noise and wide dynamic-range receiving systems and components for radio astronomy and space communications at the National Radio Astronomy Observatory, Hughes Aircraft Co., and TRW. He is currently a Research Scientist at the Aerospace Corporation, with interests in FET/HEMT amplifiers, mixers, and intermodulation phenomena, and is the author of *Microwave Mixers* (Artech House, 1986).