A GaAs MESFET Mixer with Very Low Intermodulation

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Abstract —This paper describes the design and performance of a new type of resistive mixer, which uses the channel resistance of a GaAs MESFET to achieve frequency mixing. Because this resistance is highly linear, very low intermodulation results. The mixer can be analyzed via existing mixer theory, with good agreement with measured performance. At 10 dBm LO power, the X-band mixer achieves 6.5 dB conversion loss, 6.6 dB noise figure, 21.5 dBm output third-order intermodulation intercept point, and 9.1 dBm 1-dB compression point.

I. INTRODUCTION

THE INTERMODULATION (IM) performance of a receiver front end is often limited by that of the mixer. This is because the mixer performance is usually worse than that of the other stages, and the mixer must handle the largest signal levels. Consequently, in most low-noise microwave receivers, improving the mixer's large-signal capability can do much to improve dynamic range.

The most commonly used mixers in microwave systems employ Schottky-barrier diodes as the mixing elements. These are usually used in balanced structures to separate the RF and local oscillator (LO) signals, to improve large-signal capability, and to reject certain even-order spurious responses and intermodulation products. Because the Schottky diode is very strongly nonlinear, diode mixers have at best mediocre intermodulation susceptibility.

Methods of improving the intermodulation performance of diode mixers have been proposed periodically. Beane [1] and Tou and Chang [2] relate the experimentally observed nulling in a diode mixer's intermodulation output to the nulling of certain terms in a polynomial expansion of the diode I/V characteristic. Lepoff and Cowley [3] show that, by slight unbalancing of a balanced mixer, it is possible to achieve cancellation of odd-order intermodulation currents in the IF. Markard *et al.* [4] and Ernst *et al.* [5] show that similar techniques can be applied to reactive mixers. These approaches have not been widely adopted, possibly because they compromise sensitivity, or are difficult to maintain over bandwidth, variations in LO power and frequency, environmental temperature, and source/load mismatch. In conventionally designed diode mixers, the second- and third-order intermodulation intercept points generally increase with applied LO power. Accordingly, the main technique for reducing diode mixer intermodulation is to increase LO power. However, increasing LO power beyond the level which gives optimum conversion loss usually increases noise figure.

This paper describes a new type of resistive mixer, which uses the channel resistance of a GaAs MESFET to realize a time-varying resistance. Because of the very weak nonlinearity of this resistance, the mixer generates very low intermodulation and is capable of high output power at moderate LO levels. This mixer represents a fundamental improvement over existing mixers, and is not unduly sensitive to operating or system parameters. Unlike a diode mixer, its noise is entirely thermal, so it is not subject to shot-noise enhancement. As a result, its noise temperature is generally lower than that of a diode mixer of the same conversion loss.

II. OPERATING PRINCIPLE

Mixers are conventionally realized by applying a large LO signal and a small RF signal to a nonlinear device, usually a Schottky-barrier diode. The LO modulates the junction conductance at the LO frequency, allowing frequency conversion. In principle, this conductance could be realized via a time-varying linear conductance, rather than a nonlinear one, resulting in a mixer without intermodulation. A simple example of such a time-varying linear element, which is capable of intermodulation-free mixing, is an ideal switch, operated at the LO frequency, in series with a small resistor.

The channel resistance of an unbiased GaAs MESFET is only very weakly nonlinear. The unbiased channel operates as a simple resistor whose resistance can be varied by changing the gate voltage; this portion of the FET's I/V curve is commonly called the *linear*, or *voltage-controlled resistor*, region. Fig. 1 shows the I/V characteristic in this region of an Avantek AT10650-5 MESFET, indicating a total channel resistance (i.e., including the source and drain resistances) between 14 Ω and an open circuit for gate/source voltages of -0.9 V to $+0.4$ V. This range of resistances is entirely adequate to realize a resistive mixer with good conversion efficiency.

Fig. 2 shows the equivalent circuit of the MESFET without drain bias voltage. R_g is the gate resistance, and R_d and R_s are the drain and source ohmic contact resistances, respectively. The gate/channel capacitance is dis-

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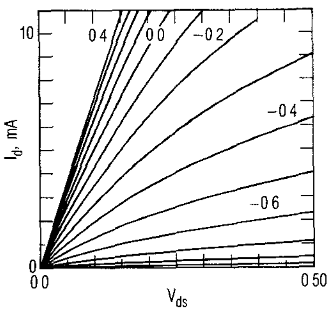

Fig. 1. I/V characteristic of an Avantek AT10650-5 GaAs MESFET in its linear region.

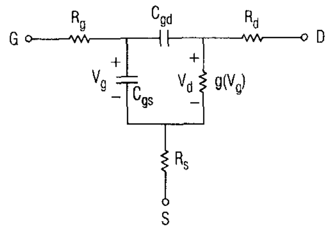

Fig. 2. Equivalent circuit of a GaAs MESFET operated at zero dc drain voltage.

tributed along the channel, but for simplicity is modeled as two lumped capacitances, C_{gs} and C_{gd}. $C_{gd} \ll C_{gs}$ if the FET is biased into its saturation region, but if $V_{ds}=0$, $C_{gs} \cong C_{gd}$, and each is half the gate/channel capacitance. The channel conductance is $g(V_g)$.

To realize a mixer, the MESFET is operated in a common-source configuration, the LO is applied to the gate, with negative dc bias, and the RF is applied to the drain. The IF is filtered from the drain. The relatively large value of C_{gd} would couple the RF and LO circuits to an unacceptable degree, so for a single-device mixer, RF and LO filters must be used. It is important that the LO voltage not be coupled to the drain terminal; if it is, the drain voltage will traverse the more strongly nonlinear portion of the I/V curve, increasing the IM level. The RF filter should therefore be designed to short-circuit the drain at the LO frequency. The design goal for the LO filter is not so clear. If RF voltage is coupled to the gate, it is conceivable that intermodulation could be increased because of the nonlinearities in $g(V_g)$. If the gate is shorted at the RF frequency, no RF voltage appears on the gate, so there is no possibility of IM generation in this way. However, open-circuiting the gate effectively halves the capacitance in parallel with the channel resistance, so conversion loss should be lower. In the mixer described here, the LO filter was designed to short-circuit the RF at the gate.

When these conditions are met, the mixer LO and small-signal equivalent circuits can be approximated as shown in (a) and (b), respectively, of Fig. 3. In Fig. 3(a), it is assumed that $R_s \cong R_d$, so there is no LO voltage across $g(V_g)$. R_g and C_{gs} can be eliminated in Fig. 3(b) because the reactances of C_{gd} and C_{gs} are much greater than the resistances of R_g and R_s. The resulting small-signal circuit is identical to that of a diode, and can be analyzed in precisely the same way. First, the large-signal conductance and capacitance waveforms are determined, then a small-signal analysis is performed using conversion matrices.

If the gate is not driven into conduction, the drain is shorted at the LO frequency, and the capacitance nonlinearity is weak, one can assume that $V_g(t)$, the LO voltage across C_{gs}, is sinusoidal. In this case the channel conductance can be determined from Shockley theory [6]. For very low drain voltages, the drain current is

$$I(V_g, V_d) = I_1\{3[u^2(V_g, V_d) - u^2(V_g, 0)] - 2[u^3(V_g, V_d) - u^3(V_g, 0)]\} \quad (1)$$

where $u(V_g, V_d)$ is the normalized depletion width:

$$u(V_g, V_d) = \sqrt{(V_d + V_g + \varphi)/V_p} \quad (2)$$

V_p is the pinchoff voltage, φ is the gate built-in potential, and I_1 is a constant with dimensions of current. The channel conductance $g(V_g)$ is found by differentiating (1) and setting $V_d = 0$:

$$g(V_g) = 3I_1(1 - u(V_g, 0))/V_p. \quad (3)$$

The capacitance C_{gd} is modeled as an ideal Schottky-barrier capacitance, with uniform epitaxial doping:

$$C_{gd}(V_g) = C_{gd0}(1 - V_g/\varphi)^{-0.5}. \quad (4)$$

To analyze the mixer, the parameters of (1) and (2) were determined from Fig. 1, and the gate/channel capacitance was determined from measured S-parameters. The large-signal analysis was performed by first assuming $V_g(t) = V_b + V_{\mathrm{LO}}\cos(\omega_p t)$, where V_b is the gate bias voltage and V_{LO} is the LO voltage magnitude. A straightforward analysis of Fig. 3(a) gives an expression for the minimum required LO power:

$$P_{\mathrm{LO}} = 0.5 V_{\mathrm{LO}}^2 \omega^2 (C_{gs0} + C_{gd0})^2 \left(\frac{R_s R_d}{R_s + R_d} + R_g \right). \quad (5)$$

It is assumed in (5) that the gate/channel capacitance can be approximated by its zero-voltage value, $C_{gs0} + C_{gd0}$.

The small-signal portion of the program DIODEMX [7], [8] was used to calculate the input/output impedances and conversion loss of the mixer. The LO frequency was 8.8 GHz, and the IF was 1.5 GHz. The small-signal embedding impedances were assumed to be short circuits at all mixing frequencies except the RF and IF. With -2.2 V gate bias and 10 dBm LO power, DIODEMX predicted conjugate match input and output impedances of $63 - j53$ Ω and $170 - j19$ Ω, with a conversion loss of 3.9 dB. For 50-Ω source and load impedances, the predicted conversion loss was 6.2 dB, with input and output VSWR's below 2.1. These impedances and conversion losses are relatively easy to match, and are similar to those of a well-designed diode mixer at the same LO levels.

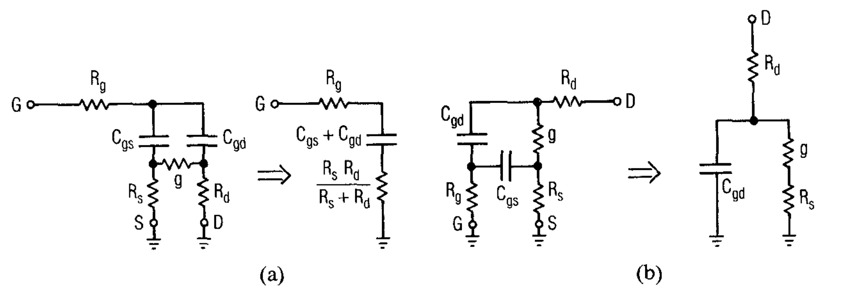

Fig. 3. (a) LO equivalent circuit and (b) approximate small-signal equivalent circuit of the MESFET.

III. Design and Performance

A schematic diagram of the mixer is shown in Fig. 4. Its LO frequency is 8.8 GHz, the IF is 1.5 GHz, and the upper-sideband RF is 10.3 GHz. It was designed primarily to verify its conversion loss and two-tone intermodulation properties, and not to achieve any specific bandwidth; it did, however, exhibit approximately 300 MHz 1-dB bandwidth at a fixed LO frequency, and its IM performance was uniform over at least 400 MHz. The mixer consists of little more than three filters and a packaged AT10650-5 FET. The RF filter is a conventional two-section coupled-line filter, with a 600-MHz bandwidth and a 0.9-to-1.1-dB insertion loss in a 50-Ω system. Its measured rejection at 8.8 GHz is 16 dB. The LO filter is a simple two-stub design, and the IF filter is a three-section low-pass structure. The filter types were chosen primarily for the desired combination of passband characteristics and out-of-band terminations. The rest of the circuit consists of a dc gate bias coupling structure and LO dc block.

The mixer was realized on a copper-clad 0.032-in fiberglass-filled Teflon substrate (RT Duroid 5880) with a dielectric constant of 2.4. The filters were tested individually before the mixer was assembled. The LO port was tuned for minimum VSWR, and the RF port was tuned for minimum conversion loss at center frequency (10.3 GHz). Because of the low frequency and the small size of the IF filter, IF tuning was not practical; the IF load impedance was 50 Ω. The resulting IF VSWR of 3.4 certainly increased the conversion loss over the conjugate match value, but probably did not affect the ratio of IM level to that of the desired signal. Gate bias was adjusted for minimum conversion loss, usually 0.1–0.2 V more negative than the minimum value which allowed LO rectification by the gate/channel junction. RF port tuning and bias values which gave minimum conversion loss also produced optimum IM performance, although a slight IM level improvement (2–4 dB) could be achieved by fine adjustment of the gate bias within the relatively broad (0.1–0.2 V) conversion loss optimum. Adjustment of the mixer was straightforward; no heroic efforts were required to optimize either the conversion loss or the IM performance.

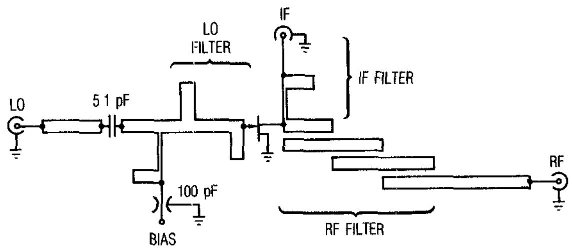

Fig. 4. Schematic diagram of the mixer.

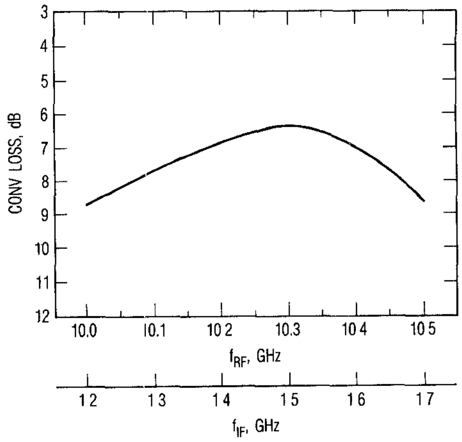

Fig. 5. FET mixer passband. $P_{LO} = 10$ dBm, $V_b = -2.1$ V.

Fig. 5 shows the mixer's passband at 10 dBm LO power and −2.1-V gate bias. Minimum measured conversion loss is 6.3 dB. Including the measured 1-dB RF filter loss and the mismatch loss in the untuned IF, the calculated conversion loss is 6.5 dB. With an untuned input (i.e., with a 50-Ω source impedance), the conversion loss was approximately 7 dB, in good agreement with the predicted 7.2 dB (including 1-dB filter loss). The bandwidth is limited primarily by the RF filter and single-frequency input tuning. Fig. 6 shows the measured and calculated bandcenter conversion loss as a function of bias and LO level. Conversion loss is more sensitive to LO power at higher reverse biases, but IM performance is better. As long as the bias is adjusted properly, good conversion loss and IM performance can be achieved at very low LO levels.

Figs. 7 and 8 show the measured second- and third-order IM output levels at bandcenter as a function of LO power and dc bias voltage for a fixed RF input power level of −7 dBm per tone. For third-order IM, the minimum for each bias level is broader and occurs at lower LO levels at the lower bias voltages, but the minimum IM level is lower at higher bias voltages and LO levels. The rise in IM with LO

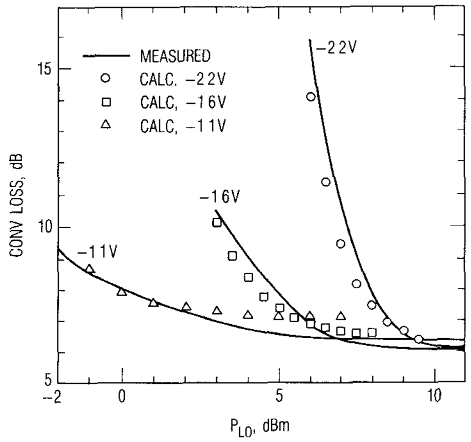

Fig. 6. Measured and calculated bandcenter conversion loss as a function of LO level and gate bias voltage. The calculated results are corrected for 1-dB loss in the LO and RF circuits.

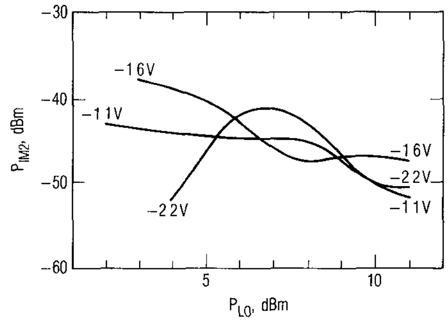

Fig. 7. Measured second-order IM output level as a function of gate bias and LO level for a fixed input power of −7 dBm per tone. The IM component is the difference frequency of the input tones.

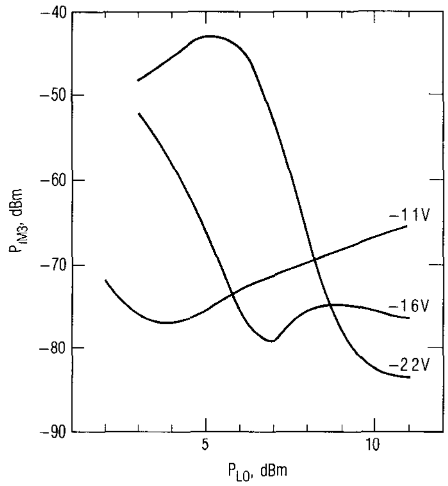

Fig. 8. Measured third-order IM output level as a function of gate bias voltage and LO level for a fixed input level of −7 dBm per tone.

level occurs as the FET begins to draw gate current on the positive LO voltage peaks. In all cases, IM performance became worse if the gate was driven hard enough to rectify the LO, but conversion loss did not become noticeably worse for gate currents below approximately 1 mA. The second-order IM product shown in Fig. 7 occurs at the difference frequency between the two input tones, approximately 20 MHz. In this mixer, it is outside the IF

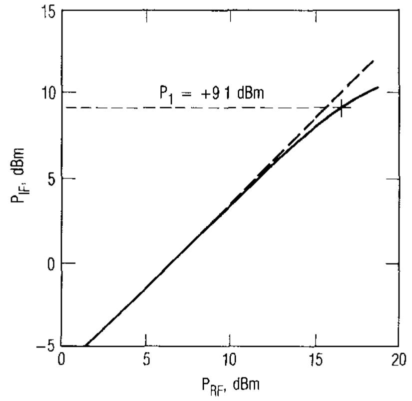

Fig. 9. Input/output characteristics at bandcenter showing a 1-dB compression point of 9.1 dBm at 10 dBm LO level.

TABLE I
MIXER COMPARISON

Mixer Type	Conversion Loss/Gain (dB)	IP2 (dBm)	IP3 (dBm)	P(-1 dB) (dBm)	NF (dB)
Diode	-7.2	9.5	10.5	0	7.7
Resistive MESFET	-6.5	23.6	21.5	9.1	6.6
Active MESFET	+6.0	--	16.0	5.0	5.0

$P_{LO}=10$ dBm; $f_{RF}=10$ GHz.

All intercept points are referenced to the output.

passband, so it would normally be of no concern. However, in many mixers, especially those with broad bandwidths and low IF frequencies, this product is of great concern. The second-order IM product is not as strongly dependent upon bias and LO level as the third-order, but higher LO power is still beneficial in reducing it. The IM performance was checked across the band and found to be equal to or better than that at bandcenter.

Fig. 9 shows the saturation characteristics of the mixer at 10 dBm LO power and −2.0 V gate bias. It is most remarkable to note that the 1-dB compression point of this mixer occurs at 9.1 dBm, only 1 dB lower than the LO level. This situation is in sharp contrast to diode mixers, where the compression point is usually around 0 dBm at the same LO level.

The noise figure of the mixer was measured at an LO level of 10 dBm. Under conditions which gave 6.5 dB conversion loss, the measured SSB noise figure was 6.6 dB. This is consistent with the expectation that the noise is entirely thermal in origin. The noise figure is lower by approximately 0.5 dB than that of a diode mixer of the same conversion loss. It also implies that very low noise temperatures may be obtainable with this type of mixer if it is cooled to very low temperatures.

Table I summarizes the FET mixer IM performance and compares it to that of a 10-GHz single-diode mixer. For comparable conversion loss, the FET mixer second- and third-order IM intercept points are 14 dB and 11 dB greater, respectively. The FET mixer's IM performance cannot be achieved at X-band with a single-diode mixer, and its third-order output intercept point is greater than that of most commercial doubly balanced mixers. Equal performance probably could be achieved with a balanced diode mixer if its design were optimized for large-signal performance. However, such a mixer would likely have greater conversion loss, and would require much greater LO power, at least 20 dBm. Its IM improvement would come primarily from the "brute force" approach of power-combining devices, a technique which is also applicable to the FET mixer. Achieving this performance level with a single-device mixer has many advantages. The most obvious is economy, but it also allows image enhancement, which is much easier to obtain, especially over broad bandwidths, with simple single-device circuits. Even better performance should be obtainable, including even-order IM rejection, with two-device balanced circuits.

A disadvantage of a FET resistive mixer compared to a diode mixer is that the minimum channel resistance of the FET is higher than the minimum resistance of a diode. Therefore, the minimum achievable conversion loss of a diode mixer is, in theory, lower than that of the FET. It remains to be seen whether this theoretical disadvantage is manifest in practice, because very few diode mixers achieve their minimum theoretical conversion loss, and most prosaic diode mixers have conversion losses higher than that of this mixer. Even if diode mixer loss is lower, the noise and IM advantages of the FET should offset any conversion loss advantage. It may also be possible to design MESFET's which are optimized for resistive mixers, and have both theoretical and practical conversion losses equal to that of a diode, and even better IM performance.

This mixer also compares favorably with active MESFET mixers. The best reported third-order output IM intercept points for active MESFET mixers are 16–17 dBm for a single device, although without uniformly good noise figures [9]–[12]. When used in an active mixer, the Avantek AT10650-5 has achieved a 13-dBm intercept point at X-band with a 4.5-dB noise figure. The intermodulation intercept point by itself is not a valid figure of merit for mixers with widely different conversion efficiencies, because the superiority of one mixer over another depends strongly upon receiver requirements and architecture. The resistive FET mixer would probably be preferred to the active mixer in receivers where substantial low-noise preamplification is necessary. In receivers where the active mixer noise figure is lower than that of the resistive FET mixer and is adequate without preamplifier stages, it would probably be preferred.

IV. Conclusions

This paper has shown that mixers based on the resistance of a GaAs MESFET channel have significant advantages in noise, intermodulation, and power output capability over those based on a pumped Schottky-barrier diode junction. Such mixers are easy to design and adjust, and have characteristics which make them entirely practical for use in low-noise receivers.

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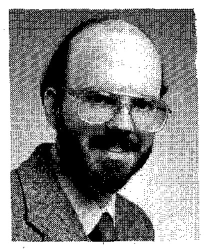

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