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THIRD-ORDER NONLINEARITY OF GaAs MESFET's

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SUMMARY

Direct linearity measurements at 6 GHz show that Bell Labs GaAs MESFET's are effectively third-order in AM/PM up to output powers near saturation, and that AM/AM can be made negligible through bias adjustment. This permits the use of predistortion techniques to attain extremely high linearity power amplification.

INTRODUCTION

It is widely known that power GaAs MESFET's are in general not third-order devices.[1] The unpredictability of device nonlinearity makes it difficult to use predistortion compensation as a means of improving maximum linear power. For non-third-order devices, moreover, the third-order intercept is not meaningful. Lacking the ability to understand, predict, and control nonlinearity, it has heretofore been very difficult to design highly linear amplifiers from GaAs FET's.

In this paper, we show that, when properly biased, AT&T Bell Labs GaAs FET's act as third-order devices from low powers to output powers only 3 to 5 dB below saturation. This third-order behavior depends on the ability to reduce AM/AM (gain distortion) compared to AM/PM (phase distortion). The relevant experimental results are summarized below:

1. AM/PM is third-order up to relatively large output power.
2. AM/AM is not in general third-order. However,
3. AM/AM can be reduced to negligible levels through proper gate bias.

BRIDGE LINEARITY APPARATUS

A bridge measurement system was developed (Figure 1) capable of directly measuring variations in phase shift $\Delta\phi$ as small as 0.03° at 6 GHz. This corresponds to phase delays of only 14 femtoseconds. Both $\Delta\phi$ and Δg_v, the voltage gain (i.e. square root of power gain) variation with P_{out}, are separately measured as explained by a complex plane vector diagram (Figure 2). The 6 GHz CW signal is split in three parts: MESFET input; bridge "balance" arm; and vector network analyzer reference input. The balance arm is adjusted to exactly null the bridge output signal at low powers. The bridge output signal can be non-zero only when the device behaves nonlinearly since all other components are linear.

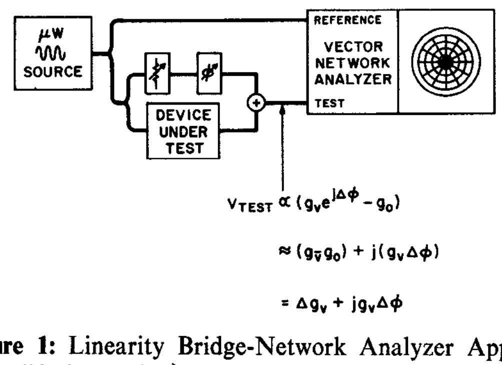

Figure 1: Linearity Bridge-Network Analyzer Apparatus (Simplified Drawing).

The network analyzer obtains two cartesian components of the bridge output signal (BOS) given by the following expressions:

$$BOS_x = g_v \cos(\Delta\phi) - g_0 \approx g - g_0 \equiv \Delta g_v$$

$$BOS_y = g \sin(\Delta\phi) \approx g_v \Delta\phi$$

where $\Delta\phi$ is in radians, g_v is voltage gain, and g_0 is the low-power value of g_v. Errors incurred by the above approximations are negligible.

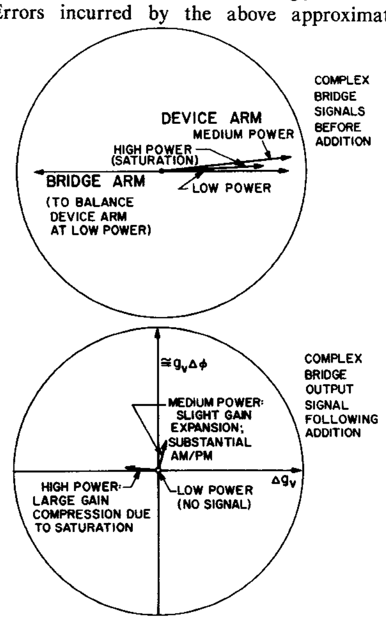

Figure 2: Linearity Apparatus Signals.

RESULTS

Figure 3 displays typical results using this measurement system at 6.4 GHz on an 8 mm gate-width power GaAs MESFET with 1.5 μm gate length and with source-via ground connections. Source-drain bias is 13 V and V_{gs} is adjusted for I_d = 800 mA, with the device tuned to maximize g_v at P_{out} = 35 dBm. For this device, which saturates at about 36.5 dBm out, g_0 = 2.7 corresponding to 8.6 dB of gain.

The most prominent feature of Figure 3 is the proportionality of $\Delta\phi$ to P_{out} up to $P_{out} \approx 2$ W. Proportionalities between $\Delta\phi$ and P_{out}, and between Δg_v and P_{out}, distinguish third-order AM/PM and AM/AM, respectively.[2]

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For IM distortion (and also for digital QAM eye-closure considerations), the relative distortion contribution of $\Delta\phi$ versus Δg_v is assessed by comparing $g_0\Delta\phi$ to Δg_v. Although not explicitly labeled, the ordinate axis scales of $\Delta\phi$ and Δg_v in Figures 3, 4, and 6 differ by a factor of g_0, so that the relative importance of AM/AM versus AM/PM can be measured directly from the linear dimensions of these Figures. Thus in Figure 3 it can be seen that Δg_v has been nearly eliminated and overall device behavior is third-order below $P_{out} = 2$ W.

Although there are instances of AM/AM nearly equal to or exceeding AM/PM in the third-order regime, behavior of the type shown in Figure 4 is by far the most common. AM/PM is third-order and dominates in the low-power regime for all reasonable values of bias, though AM/AM is not necessarily third-order as evidenced by curvature when $I_d = 600$ mA in Figure 4. Experimental evidence shows that AM/AM ($\partial g_v/\partial P_{out}$) becomes more positive with increasing I_d. For Bell Labs devices, AM/AM can typically be made negligible through adjustment of gate bias as shown in Figure 5, but this is not in general possible and depends on details of the FET transfer function.[3] The use of predistortion with the device of Figure 6 to compensate AM/PM along with gate bias adjustment to minimize AM/AM would improve M_3, the third-order IM ratio, to < -106 dB.

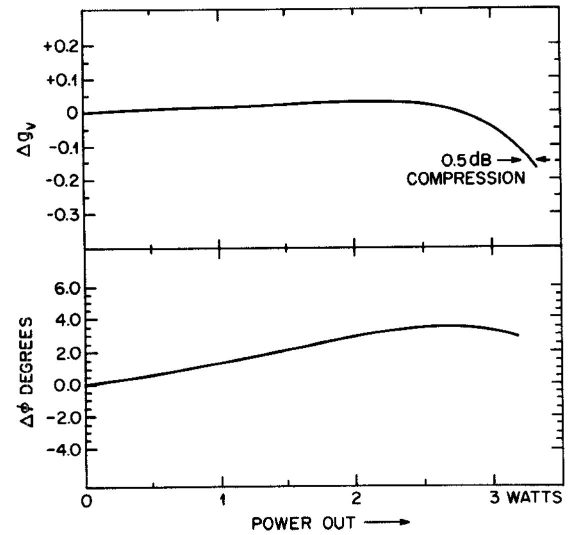

Figure 3: AM/AM (Δg_v) and AM/PM ($\Delta\phi$) distortion for the GaAs MESFET described in the text. Lack of significant curvature in AM/PM is evidence for third-order phase behavior.

VERIFICATION OF THIRD-ORDER LINEARITY

To verify third-order phase behavior $\Delta\phi$ was measured over a 20 dB range of P_{out}, using the ultimate sensitivity of the apparatus. In Figure 7 evidence is presented confirming the higher power findings.

Perhaps more relevant to other published linearity data is comparison to IM linearity measurements. For a third-order device M_3 may be calculated from low-power AM/AM and AM/PM as:

$$M_3 = 10 \log \left[(2 \times 0.001 \text{ watt})^2 \left\{ \left(\frac{\partial\phi}{\partial P_{out}} \right)^2 + \left(\frac{1}{g_0} \frac{\partial g_v}{\partial P_{out}} \right)^2 \right\} \right]$$

where ϕ is in radians. Two-tone IM measurements using unequal power tones (differing by 10 dB to facilitate comparison with the direct method) are shown as a function of P_{out} in Figure 8. Again confirming third-order behavior, the IM measurement shows that M_3 is constant to within experimental error at -91 dB for 31 dBm $\geqslant P_{out} \geqslant$ 22 dBm. Direct measurements (not shown) also revealed third-order AM/PM with negligible AM/AM below $P_{out} \approx 2.5$W. The measured slope ($\partial\phi/\partial P_{out}$) of 1.1 deg/W (= 0.019 rad/W) gives $M_3 = -88.5$ dB, in close agreement with the IM result.

DISCUSSION OF AM/PM EXPERIMENTAL RESULTS

For a given device the slope of $\Delta\phi$ is only slightly affected by operating conditions, and unlike Δg_v cannot be reduced to zero. Approximately 90% of all devices measured have normalized phase slopes of 5 to 40 deg-mm/W in the third-order regime at 6 GHz. Measurements at different frequencies show AM/PM to be proportional to frequency. Thus $\Delta\phi$ is interpreted as caused either by an increase in electron transit time with power (Figure 9) or by a nonlinear input circuit RC time constant (Figure 10).

For a saturated carrier velocity of 1.2×10^7 cm/sec, gate transit time is about 12 psec. The observed sign of AM/PM indicates electrical lengthening in proportion to P_{out}, consistent with an average lengthening of the depletion region with P_{out}. A modest 10% average lengthening of the 1.5 μm channel (for large-signals) would account for 1.2 psec additional delay or a 2.6° phase shift—roughly what is observed just below saturation. However, the RC time constant is also about 12 psec, and the effect of nonlinear input capacitance can plausibly produce the same RF nonlinearity. It is not possible to experimentally identify which of these two mechanisms is primarily responsible for the observed AM/PM.

CONCLUSIONS

To summarize, AT&T Bell Labs GaAs FET's are third-order devices up to powers 3-5 dB below saturation output power when operated so as to minimize AM/AM distortion. AM/AM can be minimized for these devices by adjusting gate bias. Through the use of predistortion in conjunction with AM/AM reduction, it is possible to reduce the third-order intermodulation coefficient M_3 to < -106 dB or less.

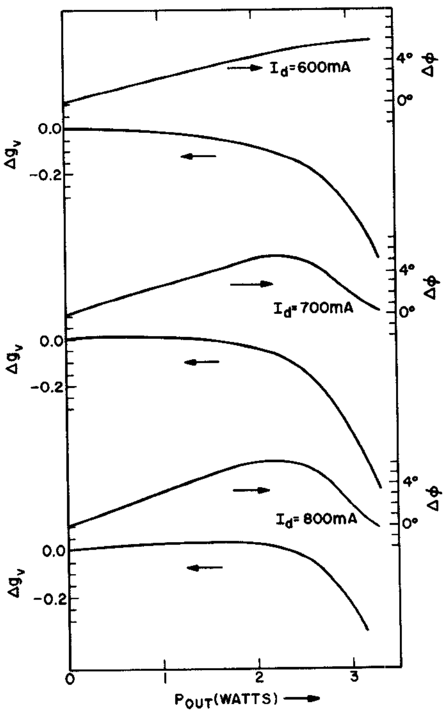

Figure 4: AM/AM and AM/PM observed as a function of gate bias resulting in several drain currents. AM/AM may show significant curvature as when I_d = 600 mA.

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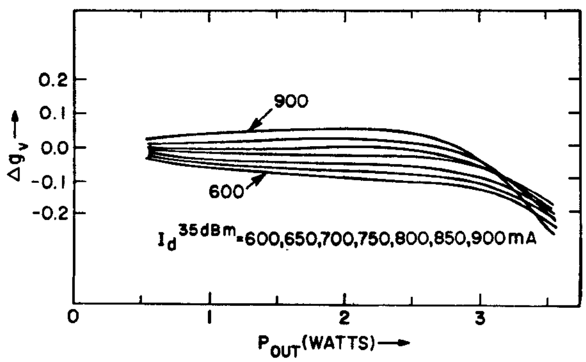

Figure 5: Experimentally observed adjustability of AM/AM as a function of gate bias, including AM/AM ≈ 0 for I_d = 800 mA.

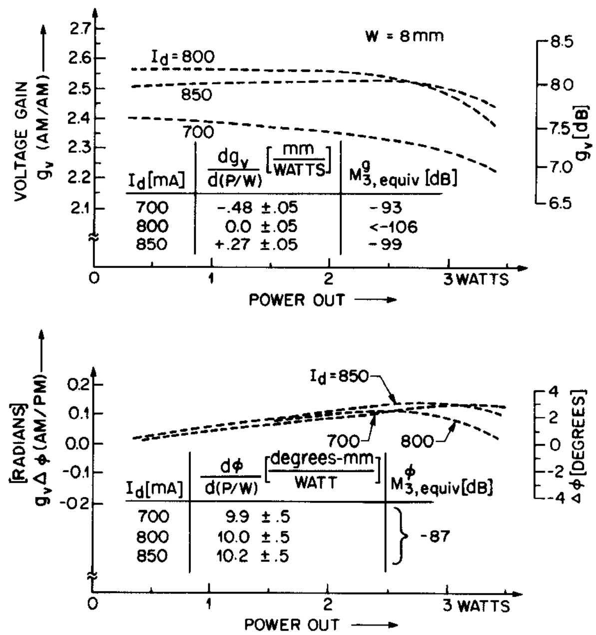

Figure 6: Reduction of M_3 to < -106 dB achievable through third-order phase predistortion and gate bias reduction of AM/AM, for a typical device.

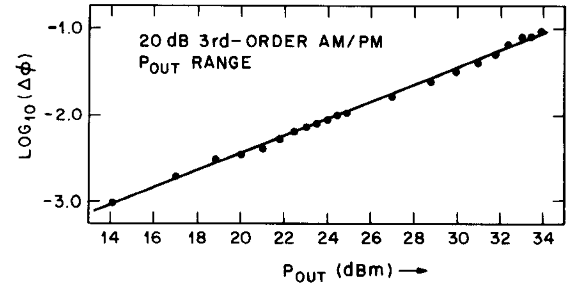

Figure 7: Third-order AM/PM nonlinearity measured for a 20 dB range of output power, down to 14 dBm out.

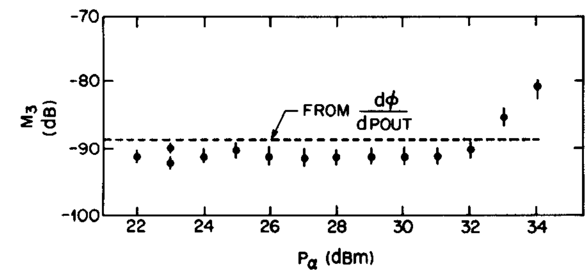

Figure 8: Two-tone IM distortion measurement showing effectively third-order behavior over a 10 dB output power range just below saturation. M_3 compares well with direct measurements.

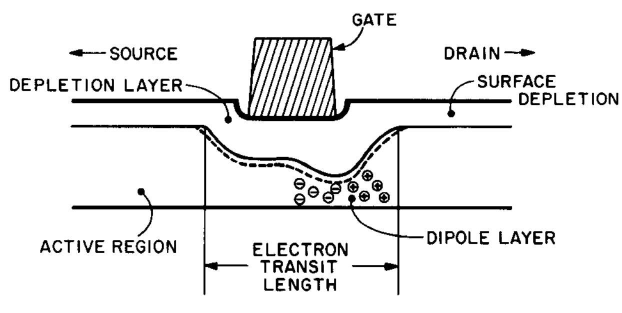

Figure 9: GaAs MESFET cross-section showing lengthening of average transit length with power.

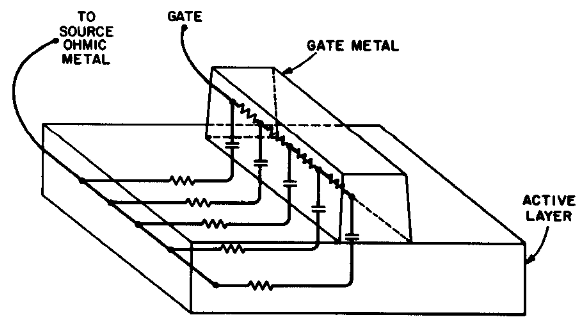

Figure 10: Simplified equivalent input circuit including nonlinear input capacitance as well as gate and source resistances.