Control of Circuit Distortion by the Derivative Superposition Method

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Abstract— **The derivative structure of the characteristics of GaAs FET's naturally gives rise to changes in magnitude and reversals of phase of intermodulation distortion components. An MMIC design method that exploits the phase reversal to achieve control of distortion in an amplifier is presented. An example circuit is designed and its measured performance is compared with that of a conventional amplifier.**

I. Introduction

Nonlinearity in a FET may be characterized by considering its gain-surface (S_{21} plotted against V_{gs} and V_{ds}) and by its second- and third-order derivative surfaces. These are easily obtained from low-signal, second- and third-order intermodulation measurements. An example set of such surface characteristics for an NE33284 HEMT is given in Figs. 1–3. This behavior has been observed for MESFET's and HEMT's at 2.5 GHz [1].

Note that the surface depicted in Fig. 3 shows two loci of notches, or "rivers," and that of Fig. 2 shows one. There is a phase reversal in the intermodulation component as such a river is crossed. This is predicted by more advanced nonlinear FET models [1]–[3]. It is now obvious that it should be possible to scale and bias two devices appropriately so as to have either the even or odd intermodulation component cancel in their summed output when they are operated in parallel [4]. In fact, more subtle and useful possibilities can be realized with more than two devices [5]. For instance, simultaneous even and odd cancellation is possible, or maximization of even with minimization of odd components for a mixer, etc. In this paper we use the derivative superposition design method to produce a gain element with greatly improved third-order intermodulation (IM3) performance.

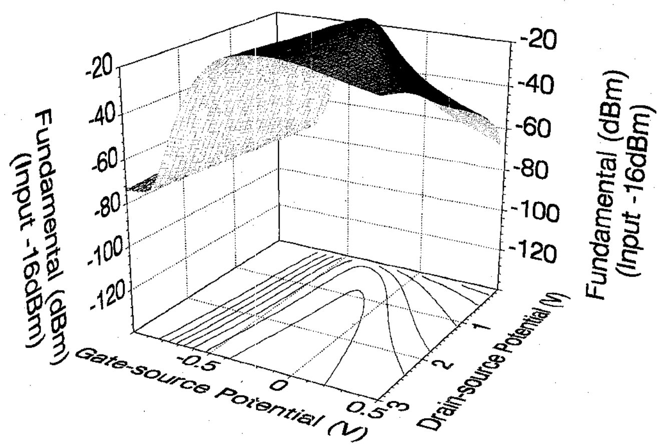

Fig. 1. Gain surface of an NE33284 HEMT with 50-Ω load. A contour plot of the surface is projected onto the XY-plane for clarity.

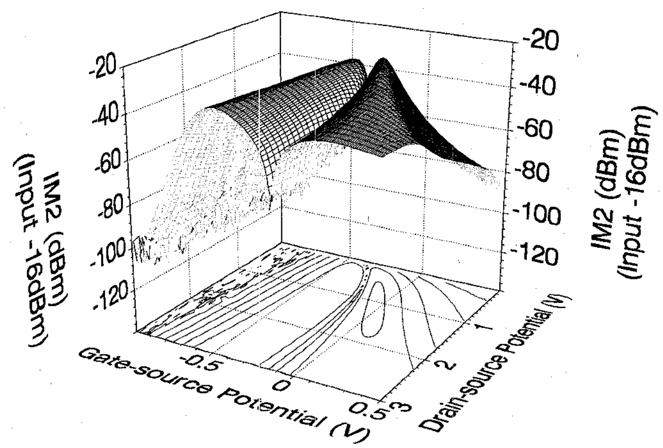

Fig. 2. Second-order intermodulation (IM2) surface for the same transistor and conditions as Fig. 1.

II. Design

The first three curves in Fig. 4, identified with open symbols, show a slice through the three surfaces for a single HEMT, with $V_{ds} = 2.6$ V. Such curves are directly obtained with instruments such as an HP4195A. A circuit of the form shown in Fig. 5 may be used to produce summed output of several devices of different gate widths and with differing gate bias. The problem of design is then to select the bias voltages and device widths to produce the desired characteristic.

The most rapid method of determining the desired widths and biases is numerical. The measured variation of the derivatives of a typical device with gate-source voltage, for a given drain-source voltage, are expanded into signed linear form in a suitable mathematical package. Scaled and bias-shifted copies of the characteristics are summed together to predict the output of a multidevice circuit. The magnitudes and shifts are varied so as to minimize the undesirable part of this predicted output.

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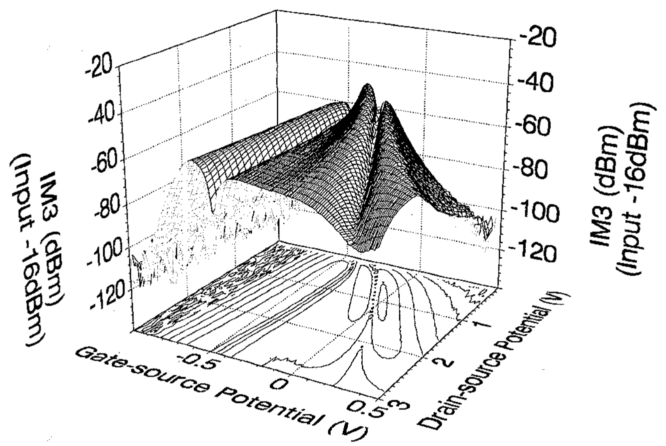

Fig. 3. Third-order intermodulation (IM3) surface for the same transistor and conditions as Fig. 1.

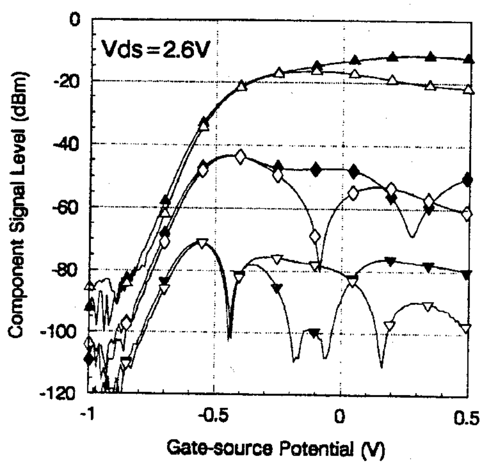

Fig. 4. Fundamental (△), even-order (◇), and odd-order (▽) intermodulation components plotted against gate-source potential for a single device (open symbols) and an amplifier designed by the new method of superposition of derivatives (solid symbols).

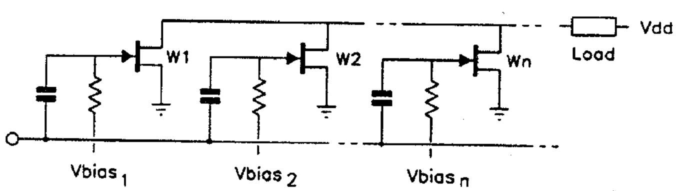

Fig. 5. A circuit suitable for realising a gain stage with desired distortion characteristics fixed by the derivative superposition method.

The relative magnitudes then define device widths and the relative shifts are the bias offsets.

A combination of device widths and offsets may be determined manually. This approach can yield a solution that is close enough to optimal and, carried out in a number of stages, serves to make the method clear. Initially, one secondary device is added to the first, or main, device. Its relative bias is chosen such that its positive (first) IM3 peak is added to the high negative IM3 peak of the main device. The position of this peak determines the left-hand margin of the resultant IM3 null. The width of this secondary device is then chosen such that the magnitude of its positive IM3 peak gives a deep null in the resultant IM3, at the position of the secondary device's positive IM3 peak. Next, a third device is added, such that its positive IM3 peak occurs at a higher bias than that of that of the first secondary device, and it produces a second deep null adjacent to the first. If the offset voltage between the two secondary devices is too high, a double null will occur. This relative offset is reduced until the two nulls form a canyon, the peak between nulls at the bottom of the canyon becoming sufficiently small. Further devices may then be added, extending the resultant canyon (possibly requiring minor adjustments to all the secondary device widths and offset voltages). Experimentation shows that trying to place the resultant IM3 canyon too close to the original IM3 minimum of the main device can lead to larger secondary devices and can lead to using more devices for a given result.

In order to demonstrate the method, we designed a four-device, broadband amplifier circuit. It has the topology of a solid-state travelling-wave amplifier, found in wideband MMIC's. It is optimized to produce low third-order intermodulation across a relatively wide input voltage variation. The aim of this is to extend the dynamic range of the improvement. (In the absence of frequency dispersion, input signal can be visualized as movement around a fixed operating point on the X axis of Fig. 4. Thus, one might expect a wide region of low IM3 to preserve the low level of IM3 for higher input signal levels.)

For the devices we used and the chosen drain bias voltage, the design requires width ratios of $W2/W1 = 0.4, W3/W1 = 0.4$, and $W4/W1 = 0.7$; The main bias is intended to be $V_{gs_1} \approx -0.15$, with gate bias offsets of $V_{gs_1} - V_{gs_2} = 0.37$ V, $V_{gs_1} - V_{gs_3} = 0.45$ V, and $V_{gs_1} - V_{gs_4} = 0.58$ V. Since the devices used were discrete, the width scaling factors were realized by means of π-section attenuators at the drains. Because secondary devices are more pinched off and narrower, power consumption is virtually unaltered from the case of the main device at the same operating point. The total gate width is increased by a factor of 2.5, but power consumption increases by less than 4%.

III. MEASUREMENTS

The second group of three curves in Fig. 4, identified with solid symbols, show a slice taken through the three surfaces, but for the parallel-connection of four devices in the new amplifier. The wide region of low IM3 is clearly visible about $V_{gs} = -0.15$. The shape and position of this characteristic is relatively invariant with V_{ds}.

Fig. 6 is a plot of output power against input power for the combined four-device amplifier and for a single-device amplifier scaled to deliver comparable power. For this comparison, the single device has been biassed at the IM3 minimum at $V_{gs} = -0.43$ V, the most advantageous point for a single-device amplifier. In the region below the onset of gain compression, the third-order intermodulation performance is visibly improved over a wide spread of power levels. The measurements show 20–30 dB improvement over a substantial range.

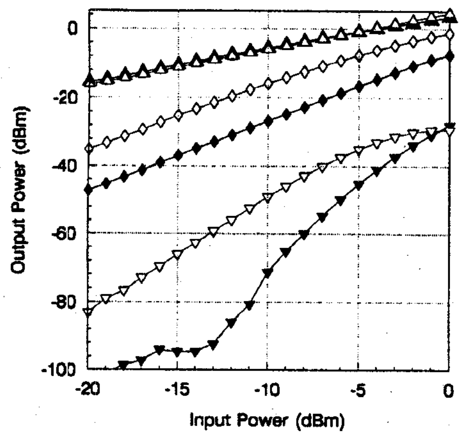

Fig. 6. Fundamental (△), even-order (◇) and odd-order (▽) intermodulation component power plotted against input power for a single device (open symbols) and an amplifier designed by the new method of superposition of derivatives (solid symbols).

The IM2 is lower than the case of a single device biased for minimum IM3 and delivering the same power. However, it is higher than would be the case with a single device biassed at the same point as the main device of the new amplifier, and of the same size. Nevertheless, with such bias on a single device, the IM3 is much worse and the gain is still not as high.

IV. Conclusion

We have described the derivative superposition method for designing gain stages with control of the intermodulation products. We have demonstrated the effectiveness of the method with a design using four HEMT's to achieve low IM3 with maximum gain over a wide range of input powers. The technique is especially applicable to broadband MMIC design. The method is anticipated to have application in multichannel communication systems where intercarrier interference is of concern.

References

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