AN MMIC LINEARIZED AMPLIFIER USING ACTIVE FEEDBACK

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Abstract

A single 2.4x2.4 mm^2 MMIC chip includes a L-band tuned MESFET Main Amplifier, and a nonlinear feedback path intended to improve its carrier-to-intermodulation margin, C/I. The circuit uses a novel concept of amplifier IMD cancelation, in which a small area MESFET based linearizer is directly applied to the terminals of the main active device. The linearizer provides a 15dB improvement on C/I, over a relative bandwidth of more than 12%.

This is, to our knowledge, the first linearized amplifier integrated in MMIC form.

I. Introduction

Generation of in-band nonlinear intermodulation distortion (IMD) has always been an effect of major concern in the design of high dynamic range (DR) communication systems. This is particularly true when many multi-level channels are simultaneously processed. The, some times, more than 70dBc C/I figures needed, in e. g. mobile radio[1], are, for the signal levels generally encountered, almost impossible to be reached, even by the best linear amplifiers.

We are convinced that the solution to those requirements must undoubtedly pass by some kind of IMD compensation scheme. That, should be, not only effective, but efficient, repeatable, low-cost and low-weight. Those characteristics are very difficult to be met by the conventional Feedforward[2] or Pre-distortion[3] implementations, because of the many drawbacks they involve. First of all they have very critical tuning, are effective only on relatively small bandwidths, and present complex circuitry with large number of adjustable components, like variable attenuators, phase shifters, etc. Although some work has recently been done to replace some of these blocks, with more compact forms, suitable for MMIC implementation[4], the proposed circuits still maintain a very high complexity level, and a really MMIC linearizer has never been published.

The aim of this paper is to present a L-band tuned amplifier, linearized by active feedback, that is believed to be the first linearized amplifier fully integrated in MMIC form.

II. Nonlinear Feedback Loop Analysis

The operation of the nonlinear feedback loop can be represented by the simplified block diagram of Fig. 1. There, the Main Device block stands for the nonlinear parts of the amplifier to be linearized, usually its active device. Similarly, the Aux Device represents the auxiliary device intended to produce the distortion signals needed to compensate the ones of the Main Device. C_1 and C_2 are simply two linear coupling networks.

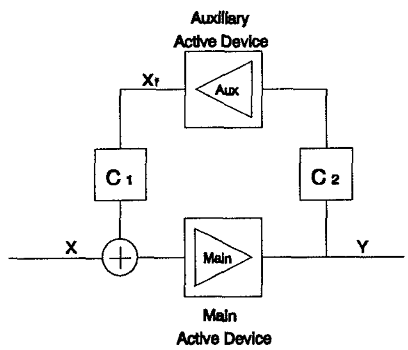

Fig. 1. Block diagram of nonlinear feedback loop.

For small-signal distortion analysis purposes, the active devices embedded in the circuit are described by their Volterra Kernels[5].

The application of an equal amplitude two-tone signal $x(t) = A.\cos(\omega_1 t) + A.\cos(\omega_2 t)$, or in phasorial form

$$x = \frac{1}{2}\cdot(x_1 + x_1^*) + \frac{1}{2}\cdot(x_2 + x_2^*) \quad (1)$$

to the system, generates responses at frequencies $n.\omega_1+m.\omega_2$. As we are only interested in the in-band distortion signals, the analysis should produce results for output frequencies at $\pm\omega_1$, $\pm\omega_2$, $2\omega_1-\omega_2$, and $2\omega_2-\omega_1$. Assuming that the narrow-bandwidth assumption applies, and that 2nd order kernels have negligible influence in the $2\omega_i-\omega_j$ nonlinear response, the Main Device's output in open loop operation, can be approximately given by :

$$Y_S = KG_S^{(1)}.x \quad (2) \qquad \text{and} \qquad Y_i = KG_i^{(3)}.x_1^2.x_2^* \quad (3)$$

93CH3316-7/93/0000-0113$01.00 © 1993 IEEE IEEE 1993 Microwave and Millimeter-Wave Monolithic Circuits Symposium

where $KG_s^{(1)}$ and $KG_i^{(3)}$ are Main's 1st and 3rd order Volterra Kernels. Since the Aux Device will be driven by the output of Main, which is designed for high gain, its IMD output deviates from the common 3dB/dB slope. So, another 5th order kernel must be included, resulting in :

$$\mathbf{X}_{fs} = KH_s^{(1)}.C_2.\mathbf{Y}_s \quad \text{and} \tag{4}$$

$$\mathbf{X}_{fi} = KH_i^{(1)}.C_2.\mathbf{Y}_i + KH_i^{(3)}.C_2.|C_2|^2.\mathbf{Y}_{s1}^2.\mathbf{Y}_{s2}^* + KH_{i1}^{(5)}.C_2.|C_2|^4.\mathbf{Y}_{s1}^2.\mathbf{Y}_{s2}^*.|\mathbf{Y}_s|^2 \tag{5}$$

where the indices identify the frequency at each kernel is evaluated: **s** for $\pm\omega_1$ or $\pm\omega_2$ (signal) and **i** for $2\omega_1$-ω_2 (IMD).

In closed loop operation the system's response will be :

$$\mathbf{Y}_s = S_s^{(1)}.\mathbf{x} \tag{6}$$

$$\mathbf{Y}_i = S_i^{(3)}.x_1^2.x_2^* + S_i^{(5)}.x_1^2.x_2^*.|\mathbf{x}|^2 \tag{7}$$

where

$$S_s^{(1)} = \frac{KG_s^{(1)}}{D} \tag{8}$$

$$S_i^{(3)} = \frac{1}{D}\cdot\left(KG_i^{(3)}\cdot\frac{1}{D}\cdot\left|\frac{1}{D}\right|^2 + C_1.C_2.|C_2|^2.KG_i^{(1)}.KH_i^{(3)}\cdot\frac{KG_s^{(1)}}{D}\cdot\left|\frac{KG_s^{(1)}}{D}\right|^2\right) \tag{9}$$

$$S_i^{(5)} = \frac{1}{D}\cdot\left(C_1.C_2.|C_2|^4.KG_i^{(1)}.KH_i^{(5)}\cdot\frac{KG_s^{(1)}}{D}\cdot\left|\frac{KG_s^{(1)}}{D}\right|^2\right) \tag{10}$$

and $$D = 1 - C_1.C_2.KG_s^{(1)}.KH_s^{(1)} \tag{11}$$

These expressions predict two modes of IMD compensation.

At very low input signal levels, IMD performance is controlled by the 3rd order kernel, $S_i^{(3)}$. Thus, the IMD generated in Aux by $KH_i^{(3)}$ can compensate the one of Main, if the product $C_1.C_2$ has the appropriate phase. In fact, if not only the phase, but also the magnitude of C_1 and C_2 are adjustable, it is possible to cancelate completely $S_i^{(3)}$. This is accomplished when :

$$C_1.C_2.|C_2|^2 = -\frac{KG_i^{(3)}}{KH_i^{(3)}}\cdot\frac{1}{KG_i^{(1)}.KG_s^{(1)}.|KG_s^{(1)}|^2} \tag{12}$$

If one accepts, as a performance evaluation criteria, the capability of the linearizer of reducing Main's IMD, without significantly degrading Main's linear gain, a very important design rule can be extracted from (11) and (12). The optimum configuration should be based on a Aux Device biased for high nonlinear distortion level, i. e., with high $KH_i^{(3)}/KHs^{(1)}$ ratio, and, for a given Aux Device, a very high C_2/C_1 ratio should be selected. Also note that if C_1 and C_2 could be arbitrarily chosen a total 3rd order IMD cancelation would be gained, without altering the linear performance of Main. This has significant consequences in system bandwidth and stability, and makes the nonlinear feedback a powerful linearization method when compared to other conventional techniques like the linear feedback[6].

Even if the above compensation condition is not perfectly met it seams possible to cancel intermodulation distortion. Expression (7) shows that if $KH_i^{(3)}$ and $KH_i^{(5)}$ have convenient values for a given Main, the distortion signals generated by $S_i^{(3)}$ and $S_i^{(5)}$ can still cancel each other at a particular input power level. Although this conclusion results from theoretical and hypothetical assumptions, it has also a great practical interest because it is supported by experimental evidences observed in this and previous published works[7]. As will be confirmed in later sections, this input power dependent IMD compensation condition, can be of great value to the overall linearizer performance. If first condition were used, where total 3rd order IMD cancelation is obtained, **Yi** would be composed of the remaining higher order contributions. In a common non saturated system, the 5th order IMD dominates. Therefore, the C/I margin would degrade by 4dB for dB of input power increase. Because this can be a severe limitation at higher drive levels, the notch imposed on the IMD characteristic, by the second IMD compensation condition can be used to extend the amplifier output power for a specified C/I margin.

III. Linearized Amplifier Description

The circuit schematic, implemented with the GEC Marconi F20 MMIC process, is represented in Fig. 2.

The main amplifier, Main Amp, is a tuned design, based on a high gain 4x150μm MESFET, T1, matched at the input and output by two high-pass networks (Cs/Ls, C_L/L_L). This block was designed for high transducer power gain and low IMD, by selecting the convenient bias-point (class-A near 50% Idss), and source and load impedances. From that quiescent point a MESFET model suitable for Volterra Series nonlinear analysis, was obtained. Its linear equivalent circuit elements were available in the foundry's data sheets, and its nonlinear elements, Cgs(Vgs) and Ids(Vgs,Vds), were modeled as Taylor Series expansions around the bias point, as explained in[8]. With that model, IMD load-pull contours were drawn for determining the optimum load impedance[8]. The source impedance was then calculated to guarantee gain and input match conditions.

Fig. 3 a) and b) represent simulated and on-wafer measured results of Main Amp linear characteristics in an open loop situation, i. e., with none of FDBout1 or FDBout2 connected to FDBin. T1 was biased through Rga/Cga, which simulate the loading imposed by the feedback circuit, when in closed loop operation.

In order to increase the bandwidth in which the linearizer can be effective, it is obvious that the loop's equivalent electric length must be reduced as much as possible. Also it is known that the only Main Amp's component that produces nonlinear distortion is the FET. This knowledge induced a novel concept in amplifier linearization, in which the linearizer is no longer applied to the whole amplifier, but directly connected across its active device terminals.

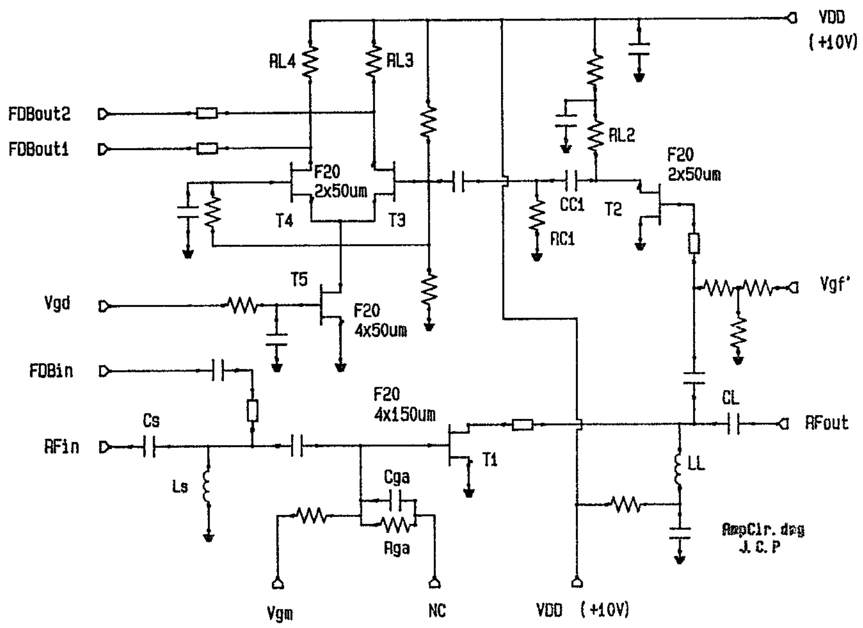

Fig. 2 - MMIC Linearized amplifier schematic.

The nonlinear feedback linearizer is composed of a single stage nonlinear auxiliary amplifier, Aux Amp, followed by a linear signal conditioner (C_1 in section II). The last includes an high-pass RC network (R_{C1}/C_{C1}) and a gain controlled differential amplifier, Dif Amp.

The heart of this linearizer is the Aux Amp. It is simply a 2x50μm FET, T_2, carefully biased for low small signal gain and high IMD. In fact, as was quantitatively shown in the previous section, to guarantee almost unchanged Main Amp linear performance and loop stability, the Aux Amp should simultaneously have very low gain, and high, input impedance and IMD. This was accomplished by, first, using the smallest area standard FET available, and second, biasing it in a zone of low and nonlinear transconductance, i. e., near cut-off.

Recent advances in MESFET IMD modeling[8] have shown that a GaAs FET can present (depending on its bias point) IMD signals that add or oppose to the ones generated in the Main Amp. In order to take advantage of that property, the loop can be closed by one of the two Dif Amp outputs. That block uses an active tailed configuration to allow amplitude control of IMD signals (C_1 magnitude control). The referred RC network provides the necessary IMD phase matching.

IV. Experimental Results

For measuring the amplifier nonlinear performance, a chip was mounted in a brass carrier and submitted to a two-tone test. Fig. 4 presents measured results of IMD cancelation versus frequency (with all voltage adjustments fixed), in the positive feedback situation (FDBout1 connected to FDBin). A 15 dB C/I improvement over a relative bandwidth of more than 12% was obtained.

To illustrate the use of the other Dif Amp output, T_2 was biased for about 20% Idss and the gain of the Dif Amp adjusted to 4 different conditions represented in Fig. 5. It was

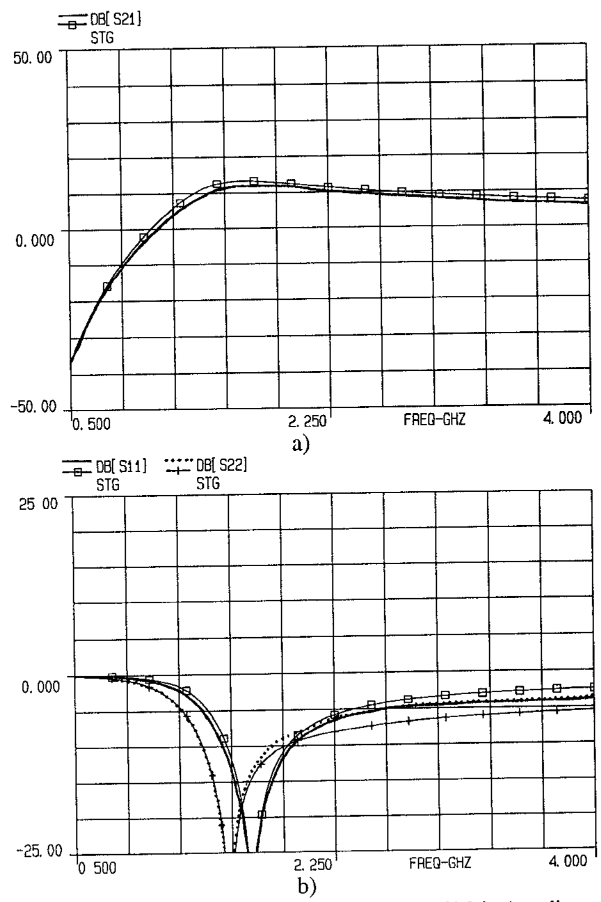

Fig. 3 - Simulated and on-wafer measured results of Main Amp linear characteristics
a) - Small signal gain : (-□-) simulated and (—) measured
b) - Input and output return loss : (-□-) / (.....) simulated / measured

observed, as predicted by nonlinear simulations, that 3rd order IMD can be completely canceled (note the 5dB/dB slope of the curve for Vgd=-1.5V), and that two different optimum IMD compensation conditions, depending on the operated input signal level, can be provided (compare graphs for Vgd=-1.5V and -1.4V).

V. Conclusions

A L-band tuned amplifier, linearized by active feedback directly applied to the Main Device's terminals, was presented. The design, implemented in MMIC form, proved the utility of the active device level linearization scheme, by presenting a 15dB C/I improvement over a relative bandwidth of more than 12%. This constitutes a remarkably good figure of merit for an active feedback linearizer.

Acknowledgement

The authors thank Dr. Pablo Dorta and D. Ignacio Alonso for their assistance in the MMIC amplifier tests.

This work has been supported by a NATO fellowship offered by Comissão Permanente Invotan, a Portuguese-Spanish cooperation program between Universidade de Aveiro and Universidad Politecnica de Madrid, and the project TIC89-0023-C02-01, National Board of Scientific and Technological Research (CICYT).

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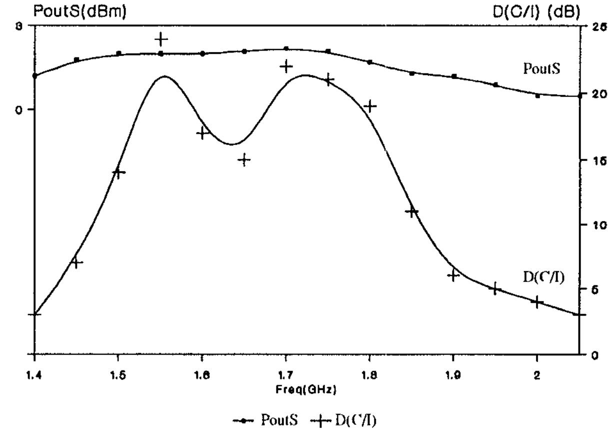

Fig. 4 - Measured results (—) of C/I improvement and output power versus frequency.

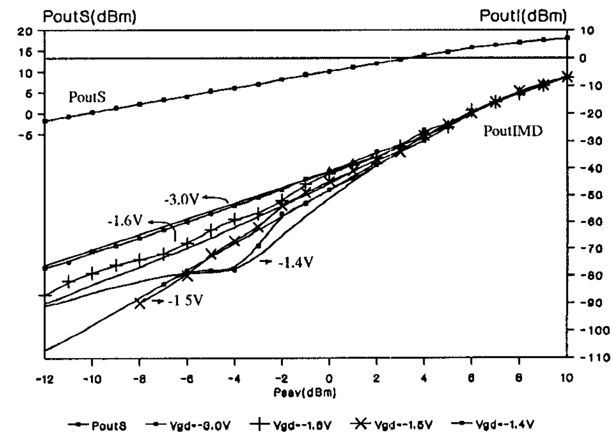

Fig. 5 - Simulated(—) and measured (≢) IMD compensation results for 4 loop gain values: Vgd=-3.0V (open loop), -1.6V, -1.5V and -1.4V ; Vgf=-3.0V.