AN INVESTIGATION OF IM3 DISTORTION IN RELATION TO BYPASS CAPACITOR OF GaAs MMIC'S

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ABSTRACT

IM3 distortion in relation to a bypass capacitor of a GaAs MMIC has been investigated. Through non-linear simulation and the measurement of a 1-stage MMIC amplifier, it was shown that only IM3 performance depended on the bypass capacitor. A new analytical model of IF amplitude modulation for the 2-tone RF carrier outputs is proposed. Based upon this model, the RF carrier outputs were distorted from the amplitude modulation by IF of the 2-tone carriers when the output matching circuit was of high impedance at the IF.

INTRODUCTION

As mobile personal communication systems such as GSM, PCN, PCS, DECT, PDC and PHS have become conspicuous, the GaAs MMIC's are indispensable from the viewpoints of its performance and advantage in size compared with hybrid integration of discrete devices. One of the important performance of a GaAs MMIC amplifier is distortion as well as gain, input/output return loss, efficiency and power dissipation. For the quantitative analysis of the MMIC distortion, third order inter modulation distortion(IM3) is generally adopted. When 2-tone carrier signals(frequencies of f1, f2 (f1<f2)) with a small frequency separation (Δf) are applied to the MMIC, the IM3 is generally defined as an output power of the distortion spectrum(dBm as unit) emerging at f1-Δf and f2+Δf or as an output power spectrum ratio(dBc as unit) between the carrier signals and the distortion (cf. Fig.8). Through non-linear simulation and the measurement of the MMIC amplifier, it was shown that only IM3 performance depended on the bypass capacitor(Cvdd in Fig.1) and the IM3 changed as much as about 15dB even at the small signal analysis while the other performance were same.[1]

In this paper, we investigate the cause of the IM3 change against Cvdd by means of the non-linear simulation and the original analysis with the measurement of the MMIC amplifier. This investigation gives an important insight for the improvement of the IM3 performance of MMIC amplifiers.

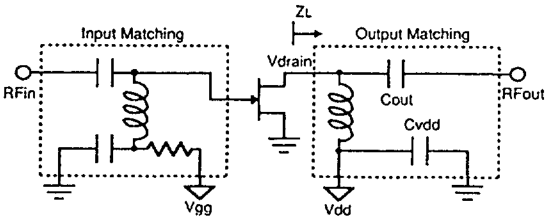

Fig.1 Schematic of 1-stage MMIC amplifier

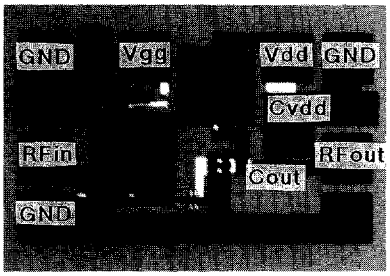

Fig.2 Microphotograph of 1-stage MMIC amplifier

INVESTIGATION AND SIMULATION RESULTS FOR AN MMIC AMPLIFIER

A 1-stage MMIC amplifier shown in Fig.1 is used as the simplest example for the investigation. The 1-stage amplifier normally consists of an input matching circuit, a FET and an output matching circuit. The input/output matching plays the roles of transforming an external input/output impedance to an optimum source/load impedance of the FET as well as biasing power supply to the FET, and normally consists of the passive elements such as inductors and capacitors. A GaAs JFET which has a p-n junction in its gate is adopted for the FET in this case. A microphotograph of the MMIC is shown in Fig.2.

Fig.3 shows the simulation results of power characteristics of the 2-tone carrier output signals and the IM3 with Cvdd as a parameter. Here, Cout

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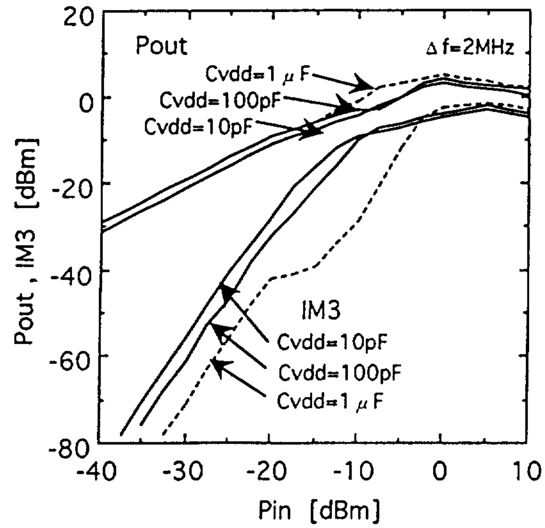

Fig.3 Pout and IM3 characteristics versus Pin and Cvdd

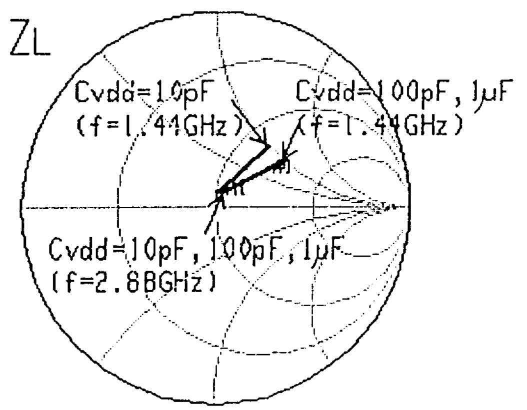

Fig.4 Load impedance of the MMIC amplifier

in Fig.1 is set at the constant value of 1.4pF. Also, Fig.4 shows the simulation results of frequency dependence of ZL which is defined as an impedance seen from the FET toward the RF output terminal(RFout) in Fig.1. In this case, ZL of carrier frequency(1.44GHz) is determined to obtain the maximum output third order intercept point (OIP3) from the load-pull measurement of the FET. In microwave IC's, Cvdd of several tenth pico-farad is usually chosen in order to obtain sufficiently low impedance of the bias terminal while being consistent with a small chip size; however, the IM3 changes as much as about 15dB even at the input power(Pin) of -30dBm as Cvdd is changed, while the carrier output power(Pout) is almost independent of Cvdd. It is commonly recognized that gain and distortion would change when ZL varies with the change of Cvdd. However, as shown in Fig.3 and 4, there is about 10dB difference in the IM3 between Cvdd of 100pF and that of 1μF, even though ZL is the same in both cases. When ZL is adopted for each Cvdd as the hypothetical load condition, assuming that ZL is given numerically in the simulation and that ZL is independent of frequency, the IM3 change such as in Fig.3 doesn't occur. Further, in the case of the load-pull measurement of the FET which uses the impedance tuners for the input/output matching, there are little changes of both Pout and IM3 when the impedance of the output tuner is slightly varied corresponding to ZL in Fig.4. Therefore, ZL variation with the change of Cvdd is not the root of the problem.

The influence of harmonics of the carrier signal might be an another cause of the problem. However, as shown in Fig.4 for the second order harmonic frequency, the impedance at the node Vdd becomes low with the increase of frequency so that Cvdd doesn't affect the ZL at harmonics. Moreover, ZL at harmonics of the hypothetical load condition is different from that of the output tuner of the load-pull measurement, since the former ZL is frequency independent and the latter ZL is different over the order of harmonics. However, the IM3 change isn't shown in both cases.

Therefore, it can be said that the difference of the ZL at harmonics isn't the dominant cause of the problem and that an another cause besides the RF load impedance should be considered.

IF AMPLITUDE MODULATION FOR RF CARRIERS AND ITS ANALYTICAL MODEL

It is generally accepted that Δf of 2-tone carriers can be voluntarily chosen and doesn't affect the IM3 when it is sufficiently small compared with the 2-tone carriers' frequencies. However, it was shown by the simulation that the IM3 was changed significantly by the variation of Δf at the condition of Cvdd=10pF as shown in Fig.5. With the change of Δf, the IM3 changed more than 10dBm, while Pout did not change significantly. This suggests that IF frequency corresponding to Δf might possibly affect the operation of the MMIC amplifier. In order to investigate this phenomenon in detail, time domain waveforms of drain voltage (Vdrain in Fig.1) with the change of Δf are simulated and the result is shown in Fig.6. These waveforms were derived from the spectra of Vdrain considered up to third order harmonics by inverted Fourier transform. It is seen clearly that Vdrain is modulated by Δf and the modulation is conspicuous at relatively small Δf. On the other hand, such phenomena shown in Fig.5 and 6 were not observed at Cvdd=1μF. Further, in the case of no Cout in Fig.1, the IM3 was independent of both Cvdd and Δf. Fig.7 shows the measured results of the 1-stage MMIC amplifier with or without Cout. In Fig.7, ΔGain and ΔIM3 are defined as the differences of measured Gain and IM3 data from those at Cvdd=10pF, respectively. The measured results support the simulation results described above.

From these results, it is confirmed that, when Cvdd is relatively small and Cout exists, the IF waveform generated from the mixing of the 2-tone carriers leads to reflection of high impedance in the output matching circuit, and consequently this reflected IF waveform expands enough to modulate Vdrain. It should be noted that, if the bias point of the FET is varied by merely changing Vdd, Pout would change in several dBm while the IM3(dBm as unit) remains almost the same. This means that the RF carrier signals are modulated in the amplitude by the IF signal, when Vdrain is fluctuated by the IF signal as shown in Fig.6.

Here, we consider the reason of no IM3 change at the condition of no Cout. When Cvdd is set at 10pF, ZL of the IF is almost equal to the characteristic impedance(Z0) and the IF waveform is absorbed into the external output terminal. On the one hand when Cvdd is set at 1µF, ZL of the IF comes close to the impedance zero and the IF voltage becomes almost zero in the output matching. Therefore, in the case of no Cout, such fluctuation of Vdrain by the IF signal doesn't occur and no IM3 change is shown.

Next, we will investigate this amplitude modulation(AM) quantitatively and propose the model. First of all, we investigate a single tone carrier. Total voltage of RFout is written as

$$\mathrm{Vout(total)} = A_0 \cos \omega_0 t \ , \quad \omega_0 = 2\pi f_0 \tag{1}$$

where A0 is amplitude of Vout(total) and f0 is a carrier frequency. Assuming that this Vout(total) is modulated in the amplitude, Vout(total) is rewritten as

$$\begin{aligned}\mathrm{Vout(total)} &= A_0(1+k\cos \omega_{IF} t)\cos \omega_0 t \ , \quad \omega_{IF} = 2\pi\Delta f \\ &= A_0 \cos \omega_0 t + \frac{A_0 k}{2}\left\{\cos(\omega_0-\omega_{IF})t+\cos(\omega_0+\omega_{IF})t\right\}\end{aligned} \tag{2}$$

where k is the coefficient used for the magnitude of AM. It is seen from (2) that the distortion spectra which are apart by Δf both sides from f0 generate. It is recognized that

$$\mathrm{Pout}(f_0) = \left(\frac{A_0}{\sqrt{2}}\right)^2 / Z_0 \ , \quad \mathrm{Pout}(f_0-\Delta f) = \left(\frac{A_0 k}{2\sqrt{2}}\right)^2 / Z_0 \tag{3}$$

are the output power of carrier and distortion, respectively.

For 2-tone carrier inputs, as shown schematically in Fig.8 which is an output spectrum at 2-tone RF inputs, the distortion spectra are generated on either side of the each carrier output. The output power of one of the carriers and the distortions are written as

$$\begin{aligned}\mathrm{Pout}(f_1) &= \mathrm{Pout}(f_0)+\mathrm{Pout}(f_0-\Delta f) \\ \mathrm{Pout}(f_1-\Delta f) &= \mathrm{Pout}(f_0-\Delta f)\end{aligned} \tag{4}$$

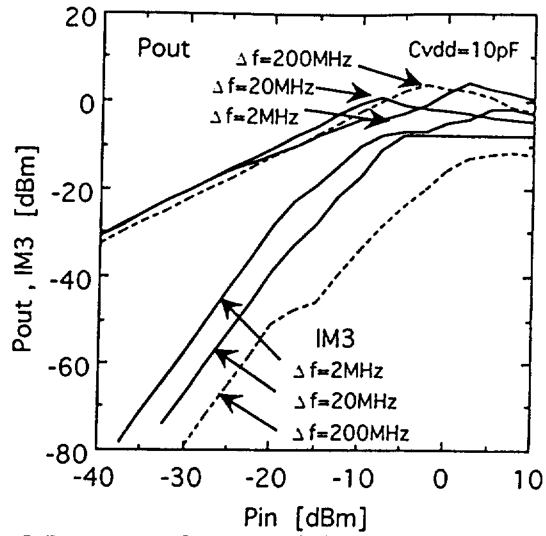

Fig.5 Pout and IM3 characteristics versus Pin and Δf

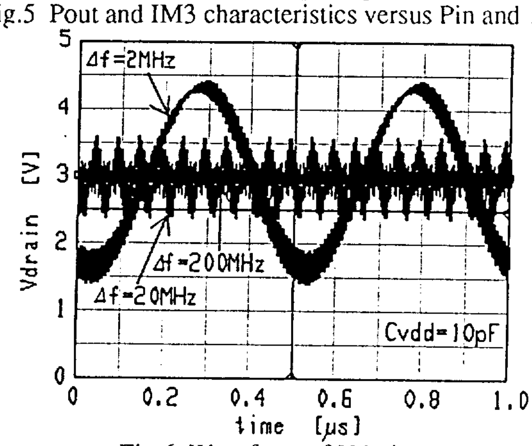

Fig.6 Waveform of Vdrain

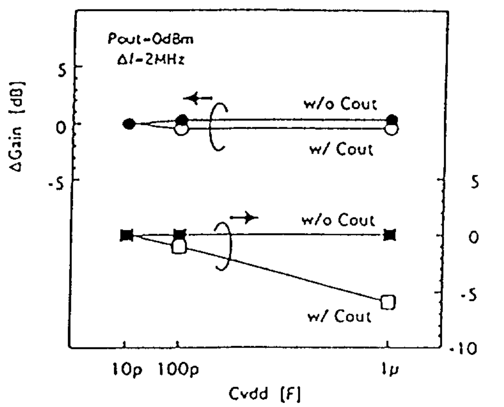

Fig.7 Measurement results of 1-stage MMIC amplifier

Therefore, from (3) and (4), the IM3 which corresponds to the ratio of the carrier and the distortion is given by

$$\mathrm{IM3[dBc]} = 10\log\frac{\mathrm{Pout}(f_1-\Delta f)}{\mathrm{Pout}(f_1)} = 10\log\frac{k^2}{4+k^2} \tag{5}$$

In order to derive k, the simulation of a single tone carrier with the variation of Vdd are invoked at the condition of Cvdd=10pF and

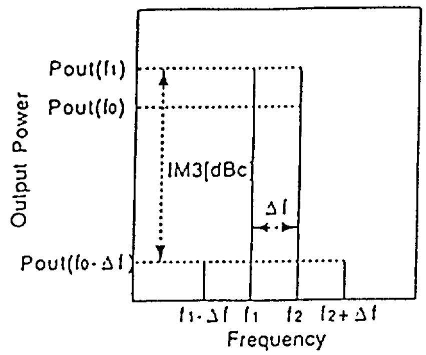

Fig.8 Output spectrum at 2-tone RF inputs

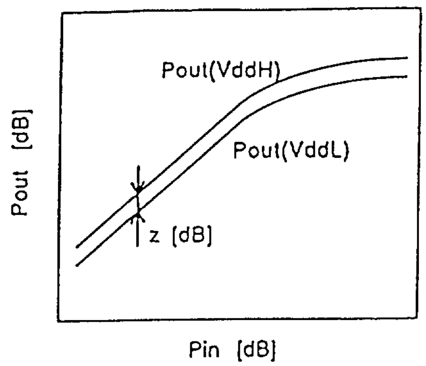

Fig.9 Power Characteristics at different Vdd

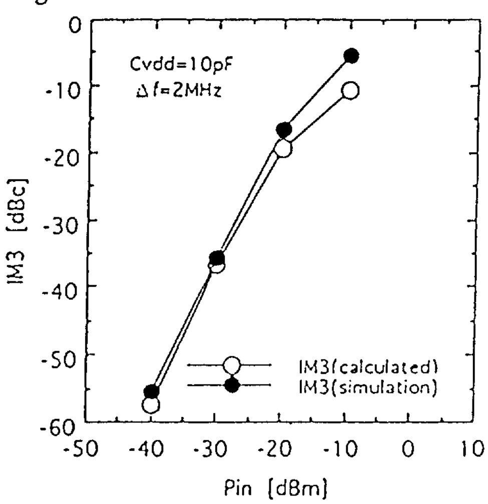

Fig.10 Comparison of calculated IM3 with simulation

Δf=2MHz. As shown in Fig.9, the ratio of each carrier output power (Pout(VddH), Pout(VddL)), corresponding respectively to the peak or the bottom value of Vdd(VddH, VddL) of the modulated Vdrain, is defined as z(dB as unit) in the form

$$z[\mathrm{dB}] = 10\log\frac{\mathrm{Pout(VddH)}}{\mathrm{Pout(VddL)}} = 20\log\frac{\mathrm{Vout(VddH)}}{\mathrm{Vout(VddL)}} \qquad (6)$$

$$\mathrm{Vout(VddH)} = A_0(1+k)/\sqrt{2}\ ,\ \ \mathrm{Vout(VddL)} = A_0(1-k)/\sqrt{2} \qquad (7)$$

and is obtained through the simulation. The IM3 can be calculated by substituting k into (5) obtained from (6) and (7).

Fig.10 shows the comparison of the power characteristics of the IM3 calculated by this model with the non-linear simulation results shown in Fig.3. It is seen that the calculated results agree well with the simulation at relatively low Pin. On the other hand, since the nonlinearity of transconductance and gate capacitance of the FET becomes dominant at relatively high Pin[2], the IM3 originated from this nonlinearity cannot be neglected compared with the distortion due to the AM. This is why the calculation results are smaller than the simulation results at high Pin in Fig.10.

CONCLUSION

IM3 in relation to a bypass capacitor of a GaAs MMIC was investigated with a new analytical model of IF amplitude modulation for 2-tone RF carrier outputs. Through non-linear simulation and the measurement of a 1-stage GaAs MMIC, it was shown that only IM3 performance changed significantly even at the low input power, as the bypass capacitor or frequency separation of the 2-tone carriers were changed. This IM3 change was shown only when the MMIC involved a small capacitor in series in the RF line of the output matching circuit. A new analytical model of IF amplitude modulation for the 2-tone RF carrier outputs is proposed. Based upon this model, the RF carrier outputs were distorted from the amplitude modulation by the IF of the 2-tone carriers when the output matching circuit was of high impedance at the IF. It is suspected that, as well as the case of the circuit configuration of Fig.1, other circuit configuration which includes a high impedance node at the IF is also possible to affect the distortion characteristics of the MMIC.

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