Power Amplifier Second Harmonic Manipulation: mmWave Application and Test Results

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Abstract **- The effectiveness of second harmonic manipulation for power performance improvement at millimeter-wave frequencies is experimentally demonstrated. The new power amplifier stage clearly demonstrates superior performance with respect to a standard tuned load approach, both in terms of output power and power-added efficiency. Moreover, the IM3 test showed no significant differences in the two cases.**

I. INTRODUCTION

Future K-Band commercial satellite systems are projected to use highly integrated circuit assemblies as parts of the critical antenna element array. The cost sensitivity of these commercial projects is driving the microwave industry toward on-chip integrated solutions at low cost and without a loss in performance. One key component is the power amplifier which has to provide very high efficiency and stable output power. The best candidate technology presenting such characteristics in K-Band is the power pseudomorphic HEMT (pHEMT) [1]. However to achieve high power added efficiency requested by these satellite systems proper design techniques exploiting second harmonic frequency terminations must be used. Indeed, the high efficiency performance of a Power Pseudomorphic HEMT (Power pHEMT) based MMIC power amplifier is strongly related to the circuit behavior not only at the fundamental, but also 2nd harmonic frequency. An efficient method to determine the load impedance for both frequencies is the harmonic load pull test [2]. At mmWave frequencies the load pull test for maximum efficiency is usually performed controlling the fundamental frequency only. This is essentially due to the practical difficulties in tuning harmonics which reach very high frequencies. Indeed, a 2nd harmonic tuning with a fundamental at f_0=20 GHz would require an output tuner capable of presenting very low value of impedances at 40 GHz. Passive tuners are strongly limited by the high losses between the device under test and the tuner itself which limit the reflection coefficient to values below 0.7. An active load-pull system is a good candidate for harmonic tuning at mmWave frequencies, but it requires very high power TWTA and other state-of-the-art equipments above 40 GHz which makes such systems prohibitively expensive.

On the other hand, a load pull characterization limited at the fundamental frequency only, could not explore the interesting features offered by the second harmonic manipulation [3]. In order to demonstrate this possibility, the design of a single stage amplifier at 20 GHz using a 600μm Power pHEMT device has been performed, properly loading the second harmonic both at the input and output ports.

II. DESIGN APPROACH

A single stage amplifier has been designed adopting the theory of the 2nd harmonic manipulation (amp **A**) and a second reference single stage amplifier applying a short circuit at the second harmonic at the output of the active device (amp **B**).

In the case of amp **A** (Figure 1), the pHEMT has been initially matched at 20 GHz with an output impedance $\mathbf{Z_{L1}}$ very close to the impedance value resulting from a load pull test performed at fundamental frequency only.

The second harmonic has been then matched with an inductance value $\mathbf{L_s}$, so as to resonate the output capacitive impedance ($\mathbf{C_{ds}}$) of the pHEMT at f_0=40 GHz. The large signal value of Cds was derived from the load impedance measured in an on-wafer active load pull system at fo=20GHz, Vds=6V, Ids=50%Idss, tuned for best power output condition. With $\mathbf{C_{ds}}$ tuned out at 40 GHz, the output current source of the active device results to be loaded only with the device output conductance ($\mathbf{G_{ds}}$), allowing therefore an effective swing of the second harmonic without altering the phase relationship imposed by the input terminations. In fact, the input of the device has been matched to 50 Ω and for maximum gain at fundamental frequency, and matched at f_0=40 GHz in order to guarantee the proper phase relationship between the second and fundamental components [3].

Amp **B**, based on the same 600μm pHEMT, has been realized simply short circuiting the second harmonic at the output, as shown in Figure 2. For both amp **A** and **B**, higher order harmonics can be considered effectively shorted by the predominant capacitive effect of the device output impedance. At the fundamental frequency the output characteristics of both amp **A** and amp **B** are identical, e.g., same load impedance $\mathbf{Z_{L1}}$ and same output matching loss (i.e., 0.6 dB as shown in Figure 1).

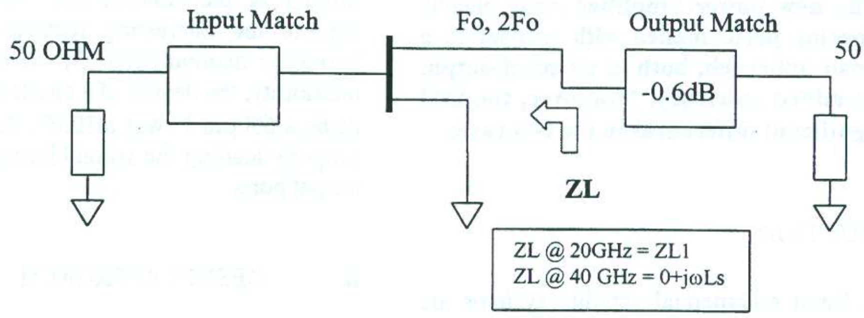

Fig. 1 – Amp **A**: 2nd harmonic manipulation stage

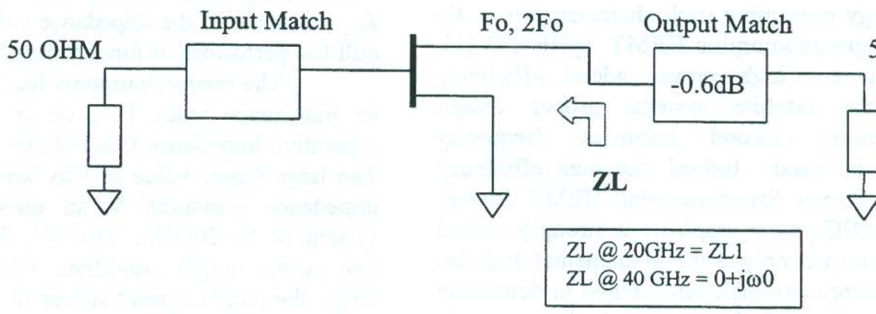

Fig. 2 – Amp **B**: Tuned load stage

The layout of Amp B is shown in Figures 3.

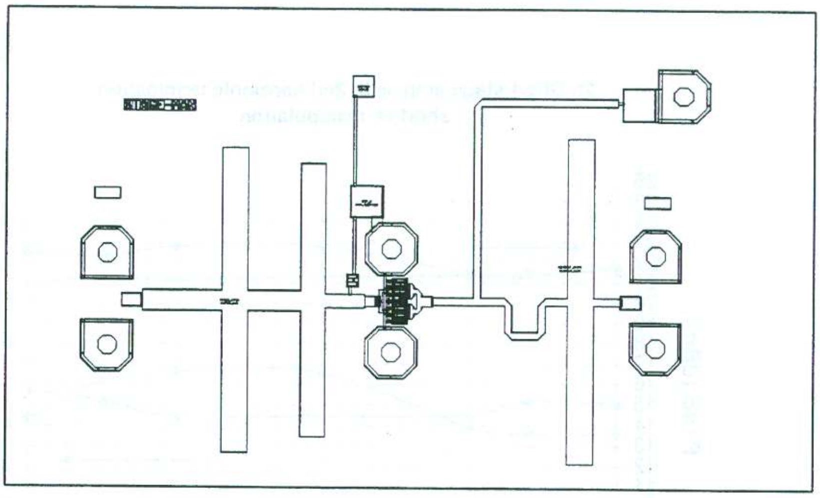

Fig. 3 – Layout of Amp **A**

III. TEST RESULTS

The two devices have been biased at $\mathbf{V_{ds}}$= 6V and $\mathbf{I_{ds}}$= 50% $\mathbf{I_{dss}}$ and the measured performances of the two amplifiers are shown in Figure 4 and 5. In Table 1 the test results and the loading conditions for the two different amplifiers are summarized.

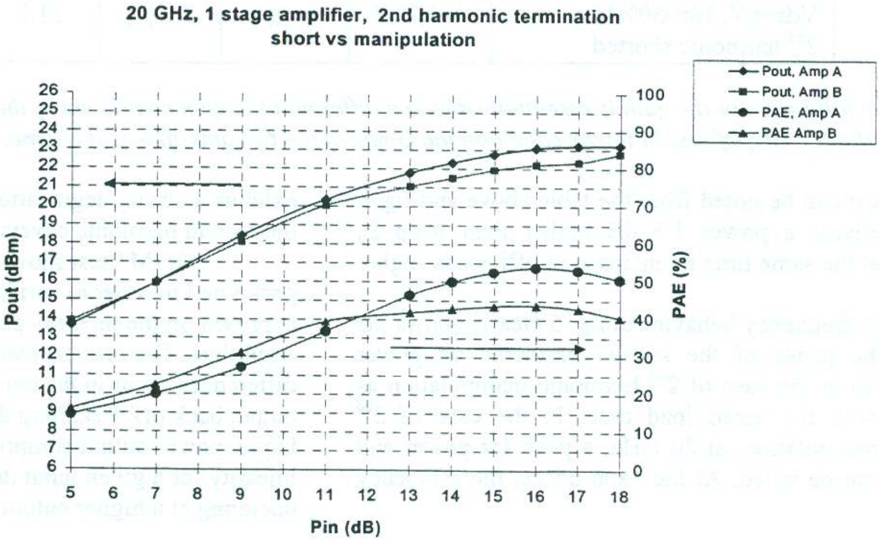

Fig. 4 – 20 GHz 1 stage amplifier test results: 2[nd] harmonic manipulation *vs* tuned load

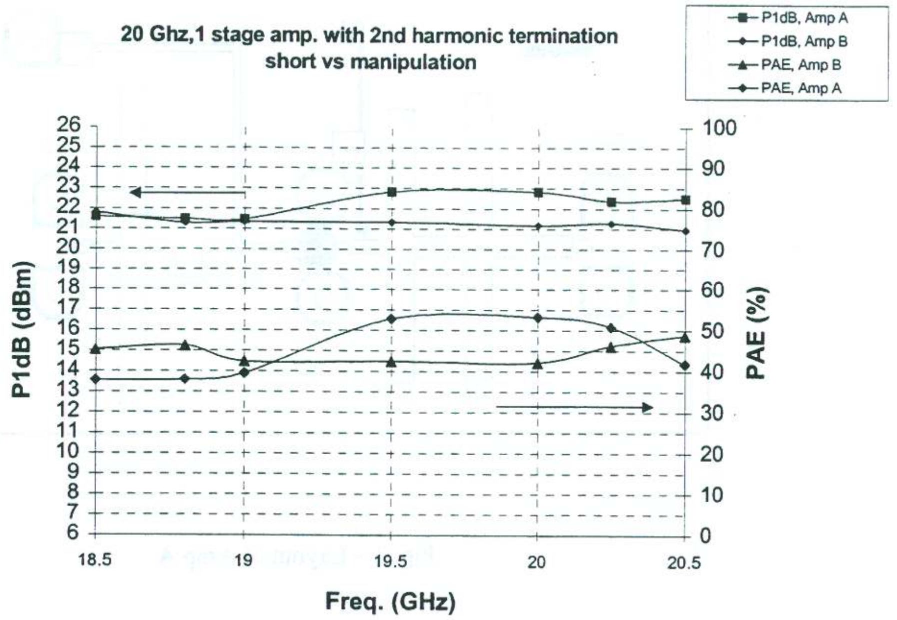

Figure 5–1 stage amplifier test results: 2nd harmonic manipulation *vs* tuned load as a function of frequency

Table 1 – 50 ohm matched Single Stage Amplifier Test Results

Freq.= 20 GHz

1 stage amplifier	$Z_Lfo=Z_{L1}$	Z_L2fo	Gain (dB)	Pout (dB)	PAE peak (%)
Amp A: 600um, Idss=70mA Vds=6V, Ids=50%Idss 2nd harmonic manipulation	11+j27.2	0+jωLs	7.8 (*)	22.8	52
Amp B: 600um, Idss=69mA Vds=6V, Ids=50%Idss 2nd harmonic shorted	11+j27.2	0+jω0	8.2 (*)	21.2	41

(*) The difference in the gain is essentially due to a different reflection coefficient of the input matching network that is different in the two amplifiers. In linear condition the Gmax of the two amplifier is the same.

As it can be noted from the table above and fig.4, Amp A delivers a power 1.5 dB higher than Amp B, exhibiting at the same time an increase of efficiency higher than 10% .

The frequency behavior in fig. 5 clearly shows the effect of the phase of the second harmonic on power performances in the case of 2nd harmonic manipulation as compared with the tuned load case. In the case of 2nd harmonic manipulation, at 20 GHz, a peak for power and efficiency can be noted. At the band edges, the efficiency exhibits a strong degradation. Still, the beneficial action of the second harmonic covers a 1 GHz span.

An IM3 test shown in Figure 6, has been also performed in order to verify the impact of such an approach on the linearity performance of the two amplifiers. The results clearly indicate that no significant differences occur in the two cases as a function of the output back off. Recalling the fact that Amp **A** has 1.5 dB higher power output compression, this translates to higher linearity for a given input drive level, as it would be operating at a higher output back-off.

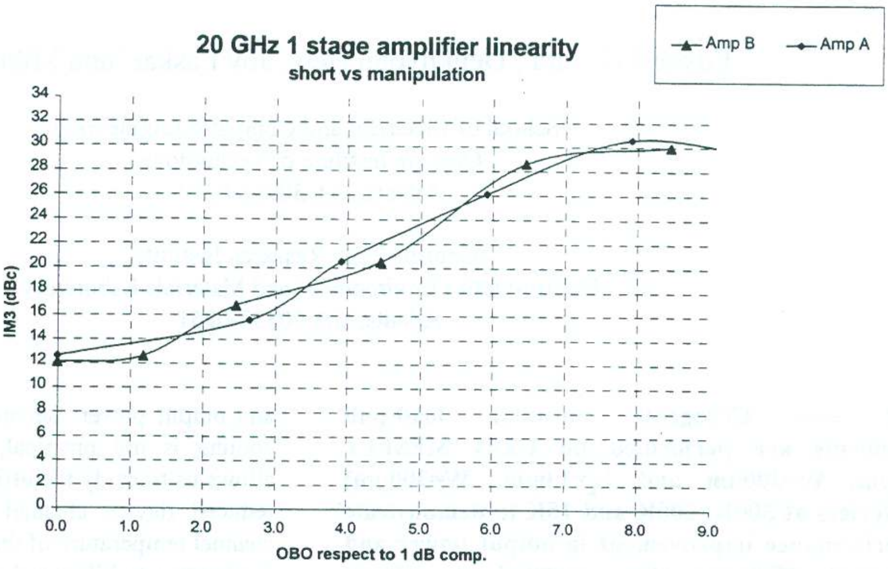

Figure 6 – 20 Ghz, IM3 test: comparison between second harmonic manipulation and Tuned Load

IV. CONCLUSIONS

We experimentally demonstrated the effectiveness of second harmonic manipulation for power performances improvement at millimeter-wave frequencies. To the authors' knowledge, these are the first remarkable results of second harmonic tuning even reported at mmWave frequencies demonstrating that the 2^{nd} harmonic manipulation approach can be successfully applied to improve the power and efficiency performances of mmWave power amplifiers. Further investigations to improve the obtainable performances by this method are in progress.

References

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