A Novel Base Feed Design for High Power, High Frequency Heterojunction Bipolar Transistors

Mike Salib , Hyo-Kun Hahn , John Kositz , John Zingaro , Andris Ezis and Aditya Gupta
Northrop Grumman Corporation
P.O. Box 1521, MS 3K13
Baltimore, MD 21203

ABSTRACT **HBTs for power amplifiers are typically designed to provide high power per unit cell to minimize chip area and losses in the on-chip combiner circuitry. A high power unit cell is obtained by combining the power of several emitter fingers ("subcells"). A problem arises when the magnitude and phase of signals driving each sub-cell differ significantly from to the other. The imbalance results in reduced total power and efficiency and the problem gets worse with increasing frequency. Our experience is that at X-band the performance of the unit cell is compromised when more than four to six subcells 40um^2 each) are combined in one device using the conventional "fishbone" [1] method. This paper describes a new method of feeding signal to the sub-cells for overcoming this problem. An example is provided where the powers of the sixteen 40um^2 subcells are combined such that the output scales expected and there is minimal loss in the efficiency. The unit cell produced 29.6dBm power with a 10dB gain and PAE of 58% at 10.5 GHz. A two-stage X-Band power MMIC using this cell yielded 5W with a gain of 13 dB and 43% PAE.**

I. INTRODUCTION

Historically, when circuit designers have increased the periphery of transistors by combining several smaller devices in parallel, the performance of the larger transistor does not scale with the increase in periphery, especially at higher frequencies. This happens due to a lowering of the overall combining efficiency as a result of unequal amplitude and phase signals at the input of individual cells. This paper describes a new base feed structure for common emitter HBTs that overcomes this problem by equalizing the input drive at every cell in magnitude and phase. As a result of this technique, sixteen 40um^2 HBT subcells were combined to produce an output power of 29.6dBm with an associated gain of ~10dB and power added efficiency of ~58% at 10.5 GHz. The power and the power added efficiency of this cell scaled well with that of a quarter watt HBT where only four subcells were combined.

II. DESCRIPTION OF THE NOVEL BASE FEED TECHNIQUE

The main function of the new base feed is to drive the different HBT subcells equally in magnitude and phase. The principle of operation is most easily explained for the problem of combining only four subcells although, for X-Band and beyond, the superiority of this method is apparent only when more than four subcells are to be combined in one device. The extension of the method to sixteen subcells will be described in the full paper.

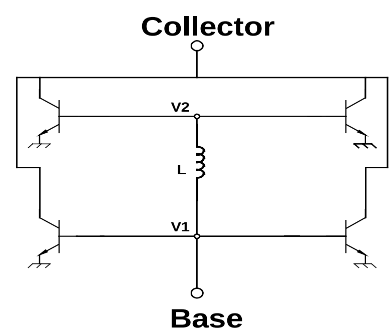

Figure –1. 4 Finger Common-Emitter with Conventional Fishbone Layout

Consider first the traditional design of a four cell "fish bone" HBT layout shown in figure-1. The inductor L connects the two HBT subcells at node-2 will be less than that that at node-1. The unequal drive causes one pair of cells to saturate before the other and that results in less output power and power added efficiency for the combined HBT. The cell to cell pitch and the width of the metal line connecting them dictates the value of the inductor ("L"). The voltage drops between the two nodes increases with frequency due to the increase in the reactance of the inductor and this limits the maximum useful frequency of operation of the transistor.

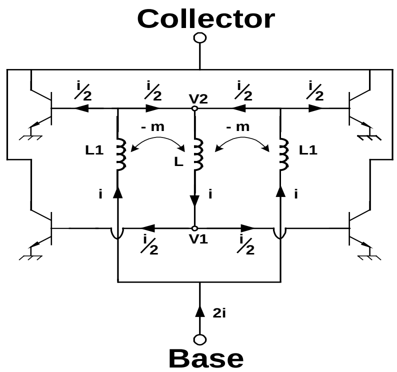

Figure 2. 4 finger Common-Emitter HBT with Novel Base Feed.

The new base feed design (Figure-2) makes effective inductance between the two nodes equal to zero and equalizes the drive to the subcells at each node. The inductance between the two nodes is canceled by bringing the signal to the back row of cells first through two inductors named in the diagram as L1 and then folding the signal back to the front row of cells through inductor L. As shown in the diagram, the direction of current flow in inductor L1 is opposite to that in the center inductor L. As a result of that, a negative mutual inductance ("-m") [2] exists between each of the two inductors L1 and the inductor L. The negative mutual inductance adds is series with the inductor L and therefore reduces its value.

If the equation

$$L - (2\,m) = 0$$

is satisfied, the inductance between node 1 and 2 becomes zero and therefore the voltage at node 1 is equal to the voltage at node 2. The inductance L1 does not cause any voltage difference between the two nodes because it is common to all the subcells..

The two nodes behave as one electrically although they are physically separated. The mutual inductance ("-m") is a function of the spacing between the two inductors and a layout can easily be designed to satisfy eqn.-1 above.

Figure 3 shows a simulation which compares the drive level at the base of each cell for the conventional design and for the novel base feed design all relative to the input drive power. The signal level at node-1 is shown by the curve marked S21 and that at node-2 is marked S31. The difference between these two curves at a given frequency is the difference in the drive level between the two nodes. The simulation shows that there is ~1.5 dB difference observed with the conventional base feed is eliminated by the new feed structure. The principle of equalizing the voltage using this new base feed technique is frequency independent because it is based on inductance cancellation and not reactance cancellation by a resonant effect which is inherently for narrow band.

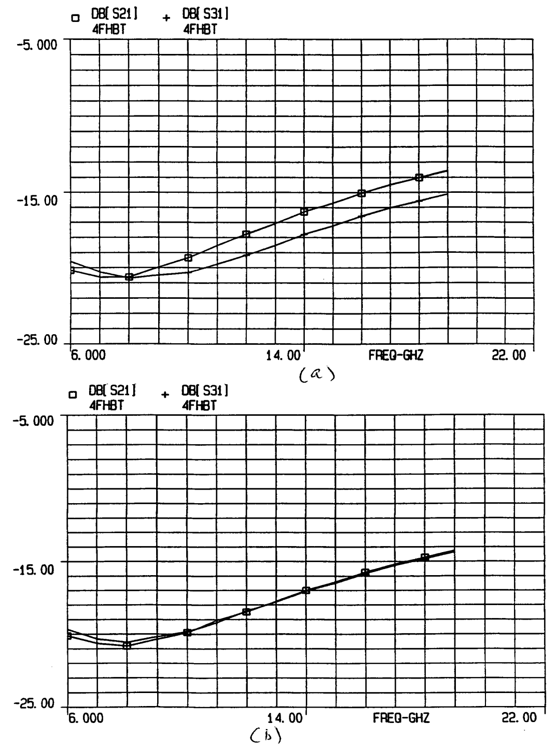

Figure 3. Difference in drive level between node 1 and 2 for conventional base feed (a) and new base feed (b)

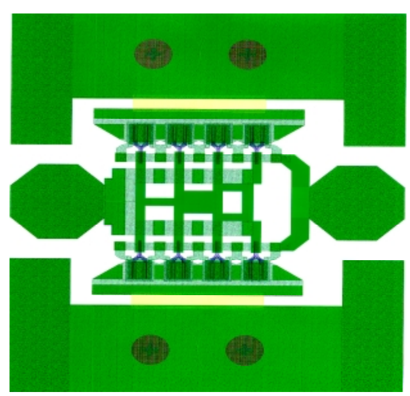

Figure 4. 16 Finger Common-Emitter HBT

The same principle was extended to the larger number of subcells. The sixteen subcells device is shown in figure 4. In this layout, the collector bus that connects all the collectors together to the output is routed next to the base feed structure. This was done to accommodate the thermal shunt and to minimize the inductance of the emitter fingers ground. An EM simulator [3] is used to calculate power at the different nodes relative to the input power (in dB) and are shown in Figure 5. It shows that the maximum difference in the drive between the various nodes is reduced from over 6dB for the straight feed to less than 1dB for the reverse feed structure.

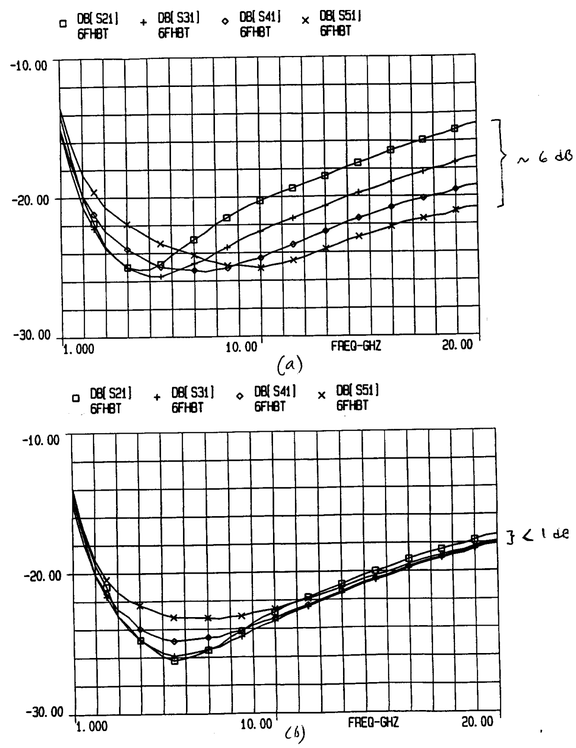

Fig.5. Base feed drive levels for the conventional (a) and the new design (b)

III. MEASURED RESULTS OF THE 16 FINGER COMMON-EMITTER WITH THE NOVEL BASE FEED

The 1W cell was load-pulled to determine the optimum load at Vc=7.5 V. A nominal collector current for a fully RF driven HBT cell was chosen to be 180 mA (=a current density of 28kA/cm^2) at which level the cell output power was 0.9W (at 1.2 dB compression) enough to satisfy the module objectives. Two of the same 1W cell are used in the first gain stage operating at Ic=140 mA each with Pout=27.5~28 dBm/cell uncompressed. Adding up all collector currents, base currents, and on-chip bias overhead current, the power added efficiency of 43% for the 5W MMIC over a desired band was predicted. The load-pull results are summarized in table 1.

TABLE I
A TYPICAL LOAD-PULL RESULT OF 1W HBT CELL WITH OPTIMUM LOADS.

	8.5 GHz		10.5 GHz	
Pin (dBm)	Pout (dBm)	PAE (%)	Pout (dBm)	PAE (%)
10	20.5	18	19.5	16
15	26	38	24.8	35.5
17	28	49.3	27	46
18	28.6	53.5	27.9	51.6
19	29.1	56.3	28.7	55.5
20	29.6	58	29.2	58
21	30	57.8	29.6	59

The following table shows the X-Band Performance for a given current density (<30kA/cm^2) of a 4,12 and 16 finger HBTs with the Novel Base Feed (reverse-feed).

IV. DESCRIPTION OF THE 5W MMIC RESULTS

The 1W HBT cell was first used to design a 2-stage 5W X-Band MMIC. The output stage combined 6 cells resulting in the total chip width of 115 mils (=2.92 mm) to the length of 180 mils. The output stage combined 6 cells and the MMIC yielded ~5Watts over 8.5 to 10.5 GHz with a power added efficiency of > 45%. The chip size was 2.92mm X 4.57mm.

The following table includes the peak current during RF pulses of 1% duty cycle and the corresponding PAE (power added efficiency) based on the averages of the measured data for MMIC's from the first lot at 8.5, 9.5 and 10.5 GHz. The HBT MMIC has an internal base bias circuit and therefore requires only one collector voltage, 7.5V. The PAE exceeds the goal of 42~44 % mainly owing to the low duty cycle (1%) used in wafer tests.

Table II
Results of MMIC Power Measurement

Frequency (GHz)	8.5	9.5	10.5
Power Out (W)	4.9	5.6	4.3
Gain(dB)	12.9	13.5	12.3
Current (Amp) during RF pulse	1.26	1.42	1.08
PAE%	48.6	49.7	49.4

Our initial goal of a 20W high efficiency X-band amplifier was achieved by combining four 5W MMICs of which the packaging is shown in Figure 6 and the power test results are shown in Figure 7.

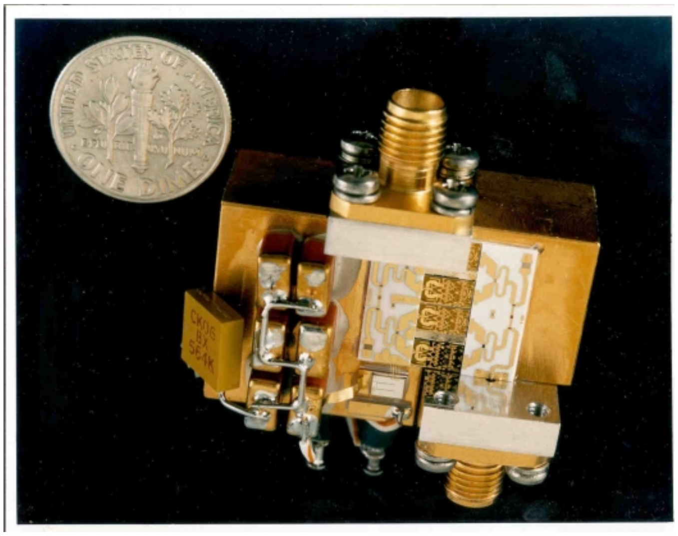

Fig.6. 20Watt amplifier package.

V. SUMMARY

A simple theory of power-combining multiple transistor fingers at X-band was developed, and applied to develop a 16-finger 1-Watt HBT cell. The combining technique equalizes drive to all fingers to achieve an excellent overall cell efficiency. The base feed uses two metal layers, one on GaAs and the other air-bridged. A 5-Watt X-band MMIC, which uses two 1-W cells in the first stage and six 1-W cells in the second stage, exhibited accordingly high efficiency in the test results. Nearly 42% power-added efficiency was realized in a 4-MMIC 20W amplifier.

REFERENCES

[1] F. Ali and A. Gupta, Eds., *HEMTs and HBTs: Devices, Fabrication and Circuits*, Artech House, 1991

[2] F. W. Grover, *Inductance Calculations*, D. Van Nostrand Co., 1946

[3] Sonnet, Sonnet Software, Inc.

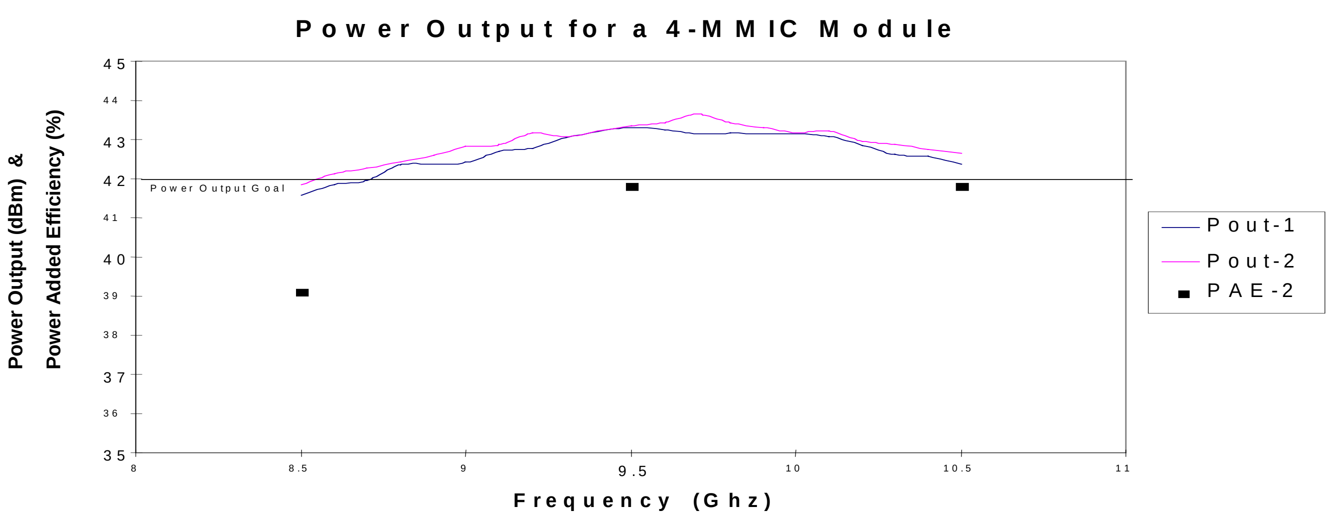

Fig.7. 20Watt amplifier pulsed power test results.