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Design and Implementation for Hemt Based Class-E Power Amplifier for 60 GHz

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Abstract : Class E Power Amplifier for 60 GHz have been implemented based on stacking methodology in 130nm Advanced Design System. Stacking of devices in a Power Amplifier increases the achievable output voltage swing, which helps in increasing output power and efficiency. A comparison between Class E SiGe HBT Power Amplifier with Class E GaAs HEMT Power amplifier is proposed in the paper. The Power Amplifier at 60GHz operates with 0.75V supply voltage with power consumption of 8mW. The HEMT Class E Power Amplifier at 60GHz has been demonstrated with an improvement in noise figure, output power, Power Added Efficiency with respect to HBT Class E PA. The maximum power delivered of HBT Class E PA and HEMT Class E PA is 14 dBm and 16 dBm respectively. While the maximum power added efficiency of HBT Class E PA and HEMT Class E PA is 15 % and 30 % respectively.

Keywords : Heterojunction Bipolar Transistor (HBT) High-electron-mobility transistor (HEMT) millimeter wave (mm-wave) Power Amplifier (PA).

1. INTRODUCTION

The millimeter-wave spectrum offers an alternative high capacity wireless communication. Silicon (Si) based high power, high efficiency millimeter-wave power amplifier. As a result, high performance mm-wave PAs are designed in SiGe and in GaAs technology. Mm-wave wireless transceivers are capable of supporting several GHz of bandwidth. Research in SiGe and in GaAs circuits in mm-wave band, particularly in 60GHz are in active top. Operation in 60GHz band has many potential advantages compared to other frequency bands. It has wide range of applications which includes imaging for military, high resolution RADAR, commercial applications and many more [1]. 77GHz has been explored for the application of automotive RADAR while 90 GHz has been explored for imaging and remote sensing applications.

This paper focuses on mm-wave switching Class E power amplifier using HBT and HEMT transistors in stacked methodology. Section II includes the prior work of Class E PA. Section III reviews Class E design methodology. Proposed schematic approach to the design of class E power amplifier at mm-wave frequencies with emphasis on SiGe HBT and GaAs HEMT has been introduced in Section IV. Section V consists of experimental results.

The main objective of the paper is to compare the characteristics of HBT and HEMT Class E Power Amplifier. The HEMT delivers a lowest noise figure and a high gain performance as compared to that of HBT. The Class E Power Amplifier operates as a switch and shapes the voltage and current waveforms to prevent high voltage and high current in the transistor that in turn minimizes the power dissipation especially during transition.

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2. PRIOR WORK

There exists a fundamental trade-off between the breakdown voltage and the maximum frequency of operation of semiconductor devices. The majority of these mm-wave amplifiers operate in linear Classes (A, AB, B). Switching class amplifiers with a maximum theoretical efficiency of 100%, like Class-E, enable efficient power amplifiers [1]. Some of the earliest reported mm-wave medium-power amplifiers were reported using SiGe HBT processes. At the cost of lower efficiency the on- chip power can be combined to increase the overall power of silicon mm- wave amplifier [2]. The nonlinear input-output transfer function of a switching power amplifier prevents it from being used in conventional linear transmitters. However, switching amplifiers can be successfully utilized in digital transmitter architecture like digital polar transmitter, mm-wave modulator and power DACs [3]-[4].

3. CLASS-E AMPLIFIER DESIGN

Mm-wave SiGe stacked Class E architecture is mainly implemented to increase the overall voltage swing. CMOS mm-wave power amplifiers including those utilizing transistor stacking have also been reported [4]. Some of the earliest reported mm-wave medium power amplifiers were reported using SiGe HBT processes [5]. This type of switching power amplifier is not used in conventional linear transmitter as the input output transfer function is nonlinear. However, switching amplifier can be successfully used in digital transmitter architecture which includes digital polar transmitter, mm-wave modulator and power DACs. [6]-[7].

No knowledge of transistor characteristics is necessary to design a class E power amplifier when it operates at low frequencies (less than 4 MHz) [8]. But when the circuit is designed to operate at Radio Frequency or microwave frequencies, the intrinsic characteristics of the transistor play an important role in the performance of the circuit, resulting in a reduction of efficiency and other parameters. Higher collector doping is required to suppress Kirk effect as the transistor performance is pushed upward in frequency. There is a fundamental tradeoff between maximum frequency and breakdown voltage. A key challenge in the SiGe HBT PA design is obtaining a high output power due to the smaller band gap and lower breakdown of SiGe HBTs compared to many III-V HBTs. This limits the maximum collector voltage bias and dynamic output voltage swing. At higher frequencies, maintaining adequate output power has following strategies :

1. Use a higher breakdown device, with the penalty of lower gain and lower efficiency for applications at higher frequencies.
2. Increase the maximum current swing by using larger transistor area and/or more transistors wired in parallel. This comes at the expense of lower input and output impedances which can be more difficult to match while maintaining adequate frequency bandwidth [8].
3. Operate at higher collector voltage to increase the maximum voltage swing. This strategy comes cost of potentially decreased reliability.

When the HBT is driven by a high-impedance current source at its base terminal, the collector breakdown voltage is due to the inability of generated holes through avalanche multiplication to exit the base terminal. The breakdown voltage will be higher for lower base impedance termination where there is an exit path for the avalanche-generated holes. In this case, as the collector voltage increases above the collector breakdown voltage, the holes coming out of the base can cause the net base to become negative- a phenomenon known as base current reversal [9].

Stacking of transistor leads to a viable strategy to simultaneously increase the RF gain and maximum collector voltage for higher output power. An ideal class E power amplifier is shown in Fig 1, with switching model. A large input voltage swing across the transistor, in case of SiGe HBT, has a detrimental effect. It causes a heavy turn on of base-collector diode when HBT is ON, along with providing a large amount of power dissipation. When the circuit is operating at lower frequencies C1 is not realized as a device capacitance. And the size of transistor can be increased but at mm-wave, this is not possible as C1 only consists of transistor's intrinsic capacitance. The DC current consumption, Idc, the load resistance Rload, shunt capacitance C1,the peak collector voltage, VCmax, is given as follows

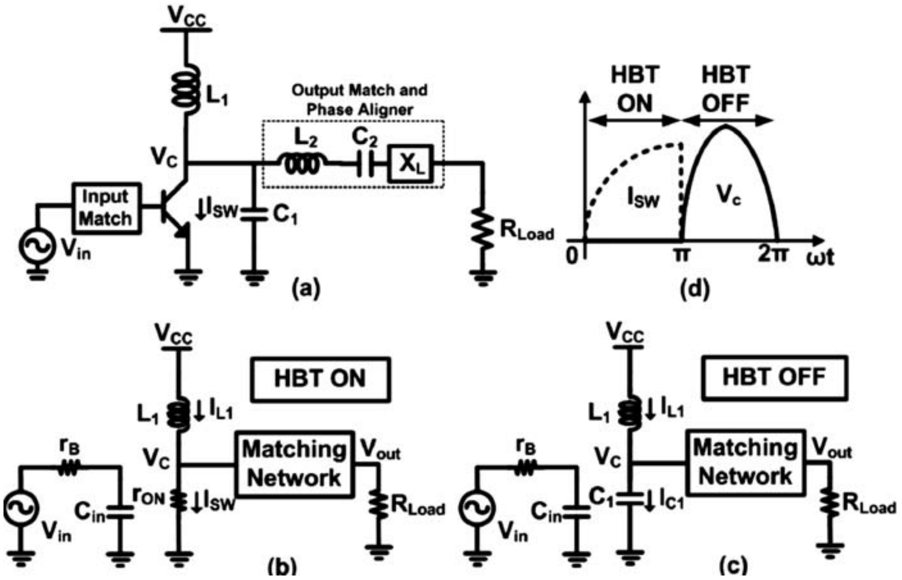


Figure 1: Class-E amplifier: (*a*) generic schematic, (*b*) simplified model during ON cycle, (*c*) simplified model during OFF cycle, (*d*) ideal transient waveforms

4. PROPOSED DESIGN

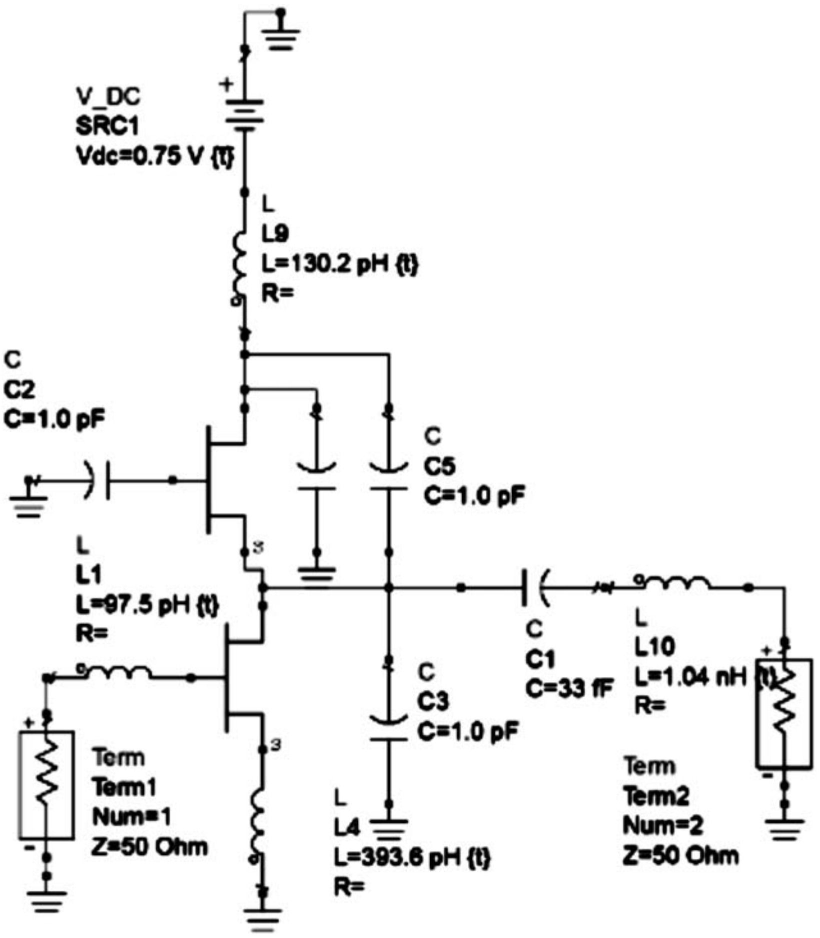


Figure 2: HEMT Class-E amplifier: (*a*) generic schematic

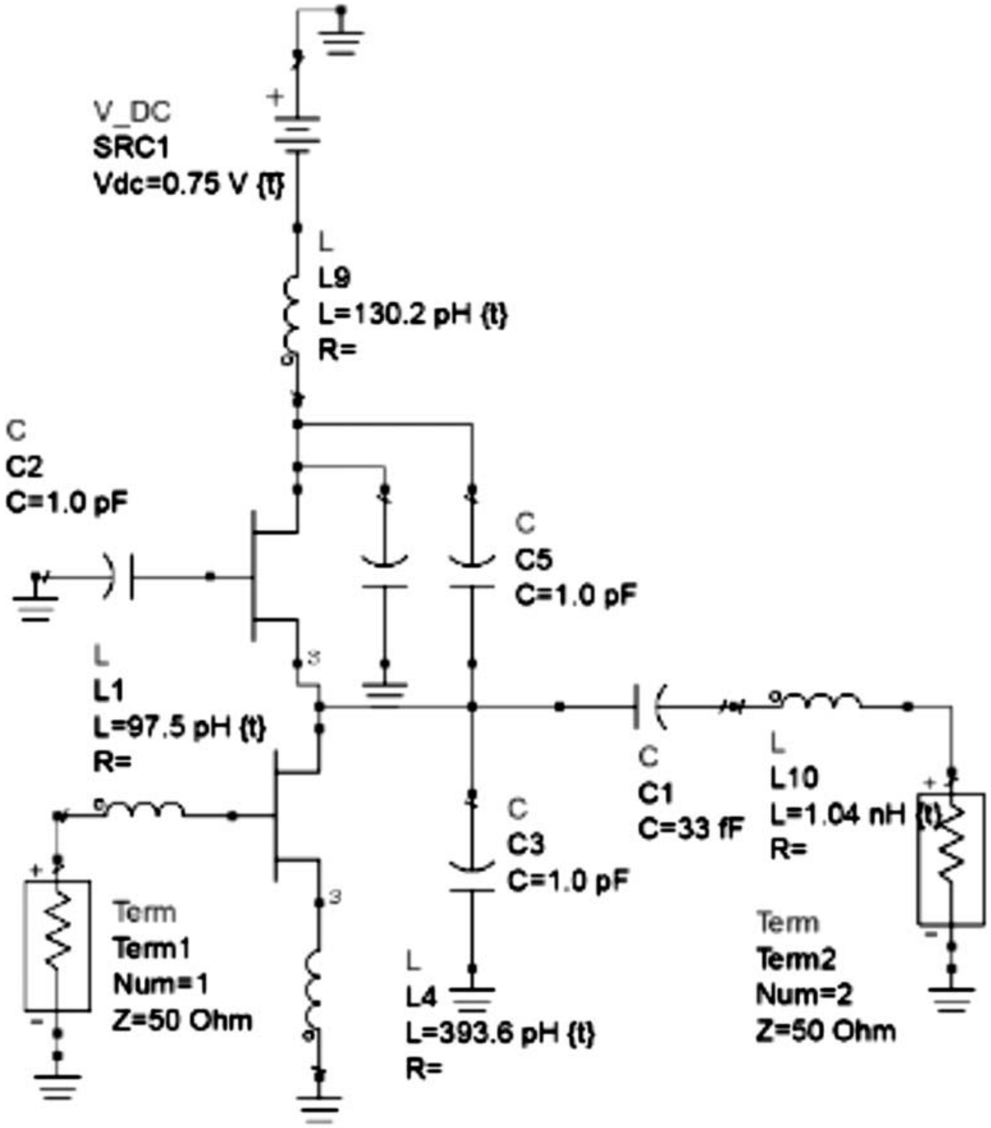


Figure 3: HEMT Class-E amplifier: (*a*) DC analysis

Series stacking of multiple devices is a potential technique that breaks the tradeoff between break down voltage and maximum frequency. The stacking also increases the voltage swing at the load, as this voltage stress can be distributed amongst various devices in the stack. Thus, for a stack of n devices, the output voltage swing can be n times higher than that of a single device. Stacking however, does not suffer from the drain-bulk and source- bulk stress of the individual stacked devices. The top most device of the stack experiences a drain- bulk swing that is equal to the n- times increased output swing of the stacked PA. To avoid stress on single HBT transistor, the dynamic voltage swing should be provided equally to amongst all series stacked transistors. Determination of voltage division across the device is done by ratio of the ON resistances, rON1/rON2.And in OFF state, a capacitance ladder network comprising of C3 and C4 has been for equal division of voltage in the intermediate node as shown in Fig (2).

The stacked configuration shown consists of series device which is of equal size. In order to preserve input power and improve power added efficiency, only the bottom device is driven by the input signal. It can be seen that for a two-stacked switching PA, the gate of the top device is connected to signal ground via a large capacitor and experiences no signal swing. However, this does not reduce a two-stacked switching PA to a regular stacking configuration because of the following reasons. The main objective of stacking is to allow operation off a higher supply voltage by distributing the overall voltage stress equally amongst the transistors. In stacked switching PAs, the nature of the voltage swings requires a constant gate bias only for the second device. PAs can operate off a higher supply voltage, as well, but a linear scaling in supply voltage cannot be achieved.

This is because the gate of the top device is usually connected to the supply voltage to maximize small-signal power gain. The transistor is driven in a way such that it spends most of its time in either completing off state or completing on state. That is nothing but there is a little overlap in the switch voltage and current waveforms. It must be noted that the stacked switching PA proposed here is different from the well known cascade Class E PA in aspects of performance and functionality metric.

The HEMT device has several advantages as compared to HBT device in higher frequencies. Fig (2) shows the implementation of HEMT Class E PA. For low-noise amplifier applications, the HEMT is generally recognized as the best choice. The main source of noise is due to thermal-diffusion, as a result there is a random variation in carrier speed in the device channel which further leads to current variations and finally leads to noise. If the circuit operates at high frequency then HEMT is the best due to its high gain, low noise and power performance.

Reliability is also an important factor intervening in the choice of device. HEMTs proves to have a good reliability characteristics and significant progress has been made in improving the reliability of HBTs. The reliability of HEMTs is considered to be acceptable for many applications but InP-based HEMTs is lacking in performance. The proposed paper proves that HEMT Class E PA has better performance as that of HBT Class E PA.

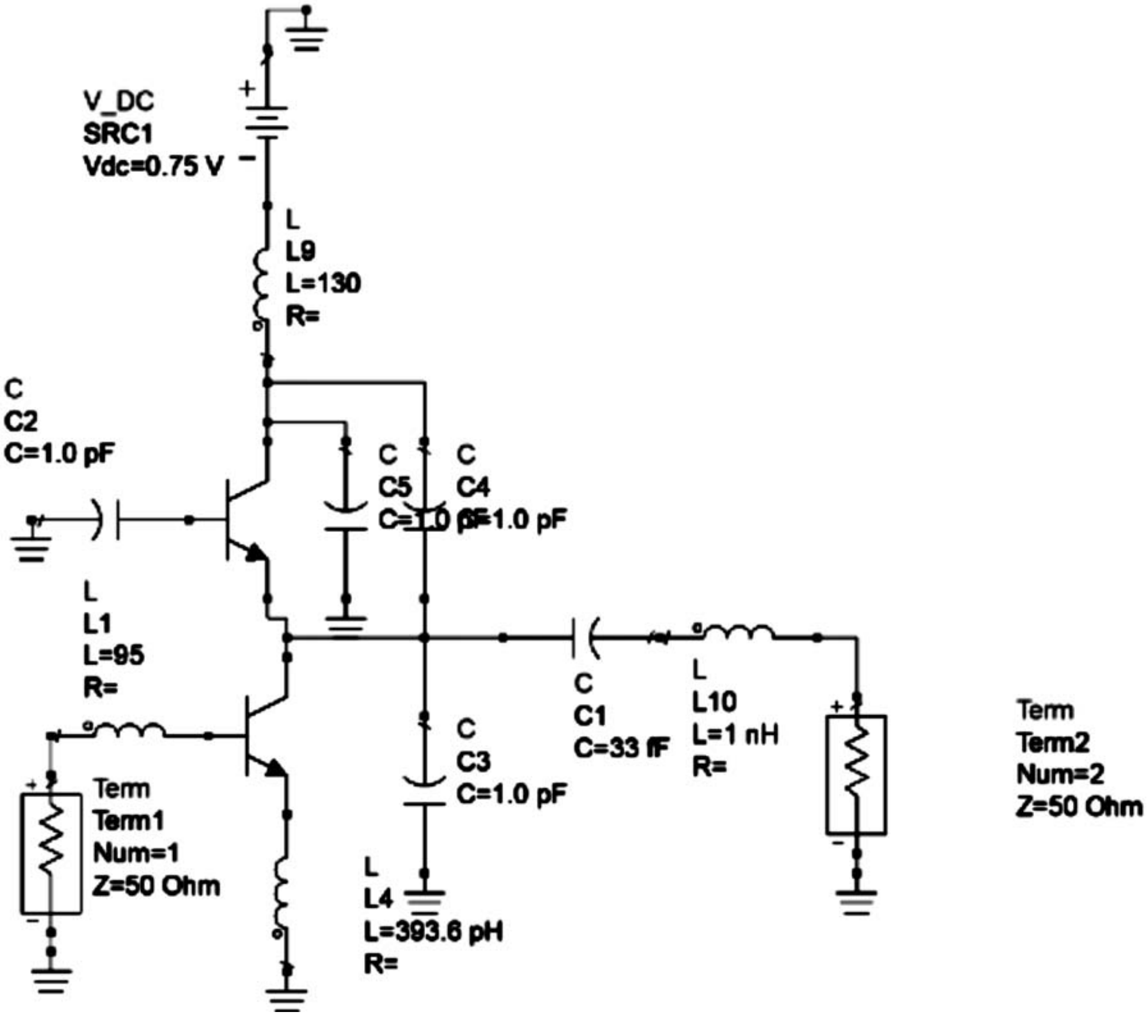


Figure 4: HBT Class-E amplifier: (*a*) generic schematic

The HEMT offer higher breakdown voltage, better threshold voltage uniformity.

5. IMPLEMENTATION RESULTS

To demonstrate the stacking methodology, a two-stage double stacked HBT and HEMT Class-E power amplifier is designed in the ADS technology. Fig (3) shows the proposed design. Both the input and output networks have been designed using minimum number of on-chip passives to reduce the effect of their loss on the overall performance. Fig (5) shows noise figure of HBT Class E PA and HEMT Class E PA, the solid line represents noise figure of HBT Class E PA while the dotted line represents noise figure of HEMT Class E PA . The output power delivered and maximum power added efficiency of HBT Class E PA is shown in Fig (6) and output power delivered and maximum power added efficiency of HEMT Class E PA is shown in Fig(7). The transient waveform of HEMT Class E PA is shown. The load current is shown Fig (8) while the drain voltage is shown in fig (9). the power consumption by the proposed design is shown in Fig (10). Fig (11) represents S-Parameters, S(1,1) is Input Reflection Coefficient while S(2,1) is Output Reflection Coefficient.

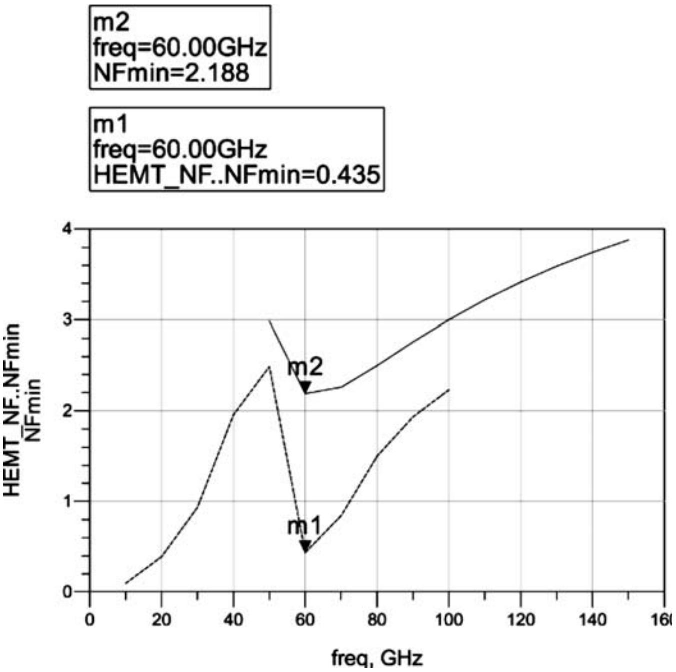


Figure 5: Noise Figure of m1 tracing HEMT Class E PA and m2 tracing HBT Class E PA

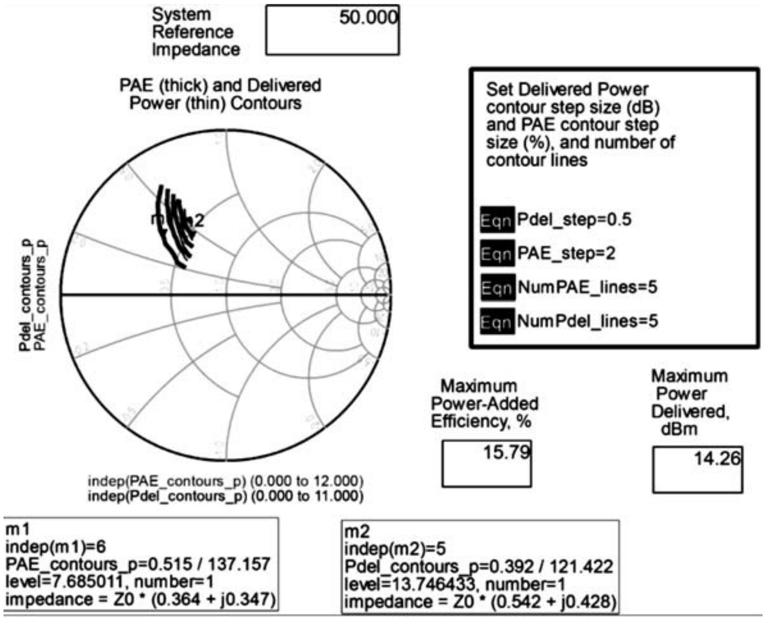


Figure 6: HBT Class-E amplifier: PAE in % with maximum power delivered in dBm

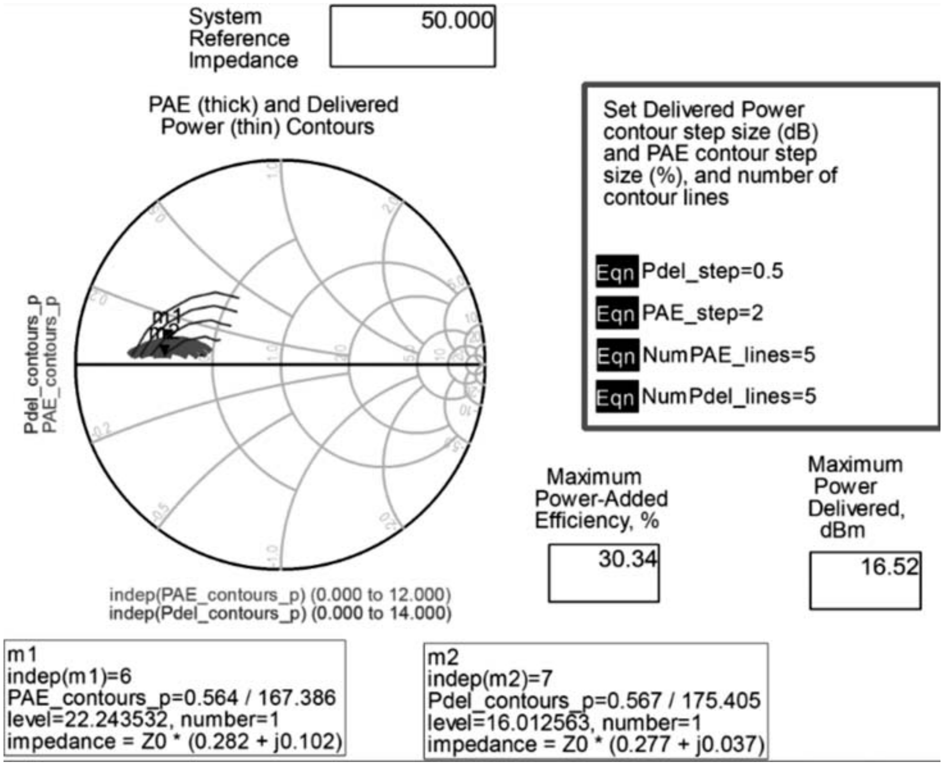


Figure 7: HEMT Class-E amplifier: PAE in % with maximum power delivered in dBm

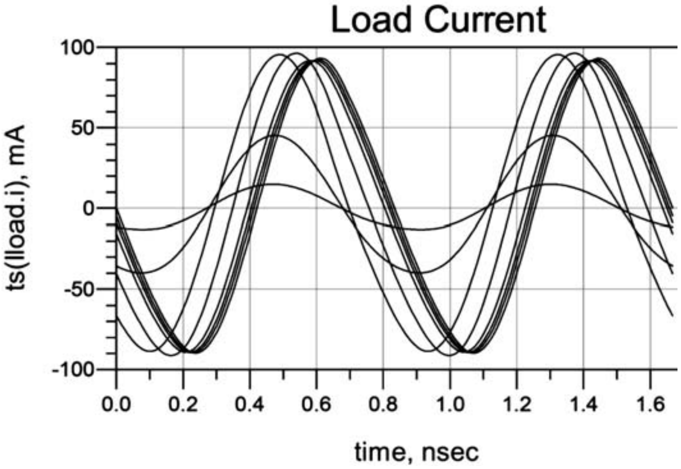


Figure 8: HEMT Class-E amplifier: Load Current

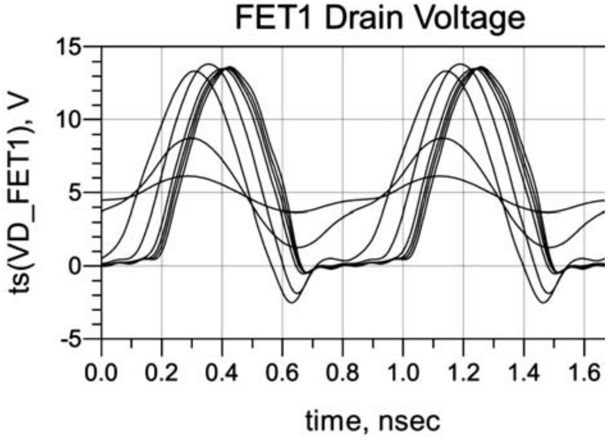
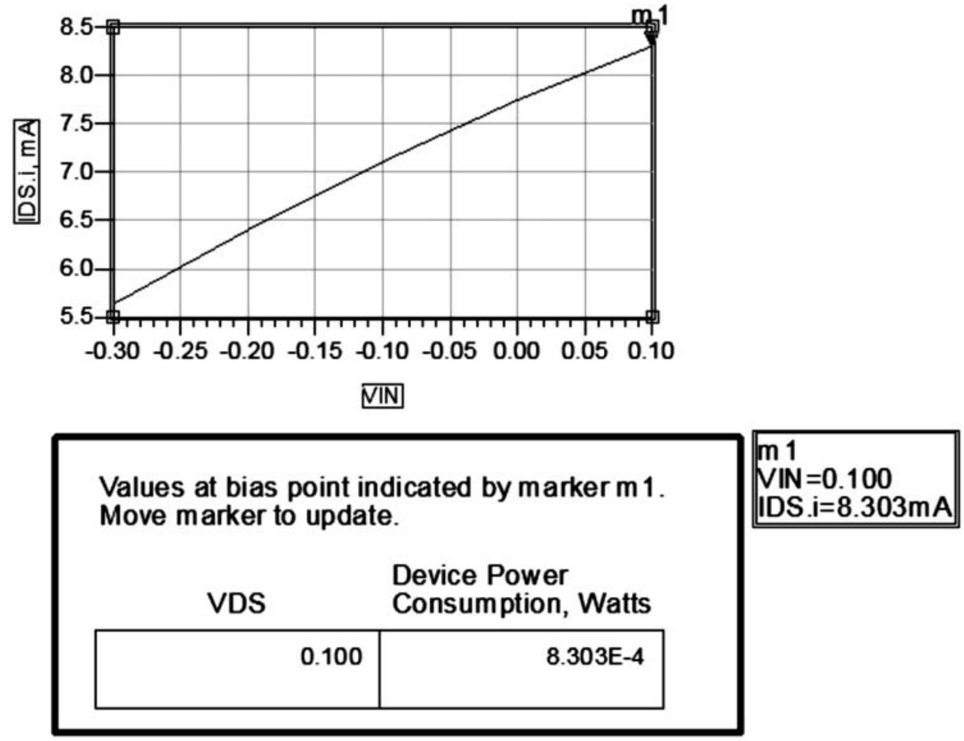


Figure 9: HEMT Class-E amplifier: Drain Voltage



Values at bias point indicated by marker m1.
Move marker to update.

VDS	Device Power Consumption, Watts
0.100	8.303E-4

Figure 10: Power consumption of HEMT Class E PA design

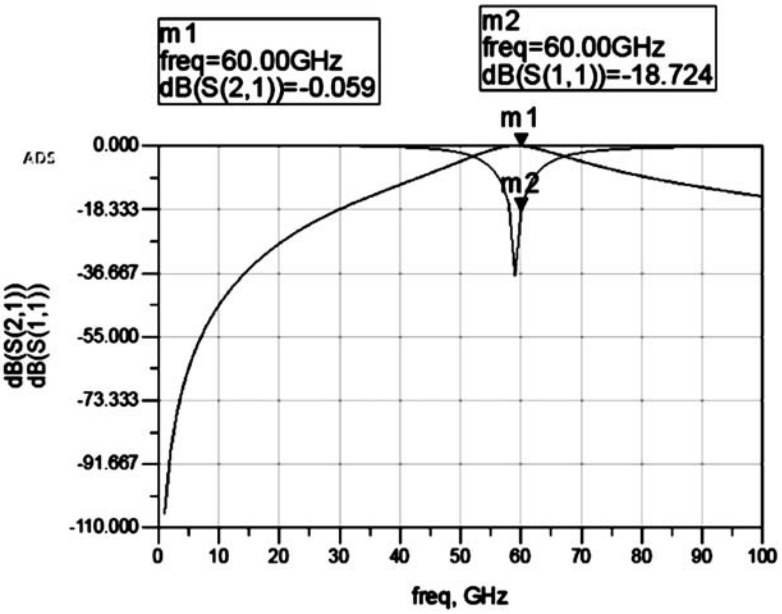


Figure 11: S-Parameters S(1,1) S(2,1) of HEMT Class E PA: S(1,1) represents Input Reflection Coefficient while S(2,1) represents Output Reflection Coefficient

6. CONCLUSION

In this paper, the operation of SiGe HBTs has been discussed in a mm-wave Class-E power amplifier design enabling the generation of larger output power high PAE. Mille-meter wave stacked Class-E architecture has been proposed, using HBT device and HEMT device where each operates in 60 GHz frequency. Thus it has been proposed that the HEMT Class E Power Amplifier has better noise figure as that of HBT Class E Power Amplifier. Noise figure of HEMT Class E Power Amplifier is 0.435 and that of HBT Class E Power Amplifier is 2.188. There is an improvement is Power Added Efficiency of HEMT

Class E Power Amplifier. It is processed with 16.52 dBm measured maximum output power delivered with 30.34 % of Power Added Efficiency. And also the HBT Class E Power Amplifier is processed with 14.26 dBm measured maximum output power delivered with 15.79 % of Power Added Efficiency. The simulation of transient waveforms at 60 GHz of HEMT Class E Power Amplifier has been shown in Fig (7). The power efficiency of the HEMT Class E Power Amplifier design proposed in Fig (2) is 50 %. The Fig (4) also shows the DC analysis. RF design application that requires a combination of low noise and very high frequency performance has been proposed in this paper.

There exists a trade-off between efficiency and linearity. Conventional PAs are most efficient and exhibit poor efficiency under back-off. Topics for future research can include Large-scale, low-loss power combining on silicon is with several challenges like harmonic-rich non overlapping voltage. HEMT devices has a wide range of RF applications including cellular telecommunications, Direct broadcast receivers - DBS, radar, radio astronomy. A further development of the HEMT is known as the PHEMT. PHEMTs, Pseudomorphic High Electron Mobility Transistors are extensively used in wireless communications and Low Noise Amplification applications.

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8. REFERENCES

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