0.5W X-Band SiGe PA With Integrated Double-Tuned Transformers

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Abstract — Power amplifier (PA) for a next generation X band T/R-modules in active array antennas is realized using low cost, high yield and high integration 0.18µm SiGe-HBT Technology. A single stage class AB cascode PA using only high-speed HBTs and double tuned transformers at the input and output matching networks with excellent performances has been designed. The PA achieve peak output power of 27dBm and maximum 36 % power added efficiency (PAE). The core RF size is 0.85mm x 0.56mm without pads and low frequency decoupling capacitors exhibiting an output power density of 1.0 W/mm^2. To our knowledge, those values are the highest in SiGe-HBT power amplifiers.

Index Terms — Cascode, heterojunction bipolar transistor (HBT), power amplifier (PA), silicon germanium (SiGe).

I. INTRODUCTION

The field of phased array for radar systems is growing every year. The opportunity of using phased array radar is great due to the application advantage of fast tracking and low weight. A phased- array antenna consists of a few to several thousands of T/R modules. This large amount of T/R modules requires the use of cheap highly integrated components to make the realization of phased-array antennas economically feasible.

BiCMOS and SiGe-HBT are good candidates for such systems due to their low cost, high level of integration, and high maturity and yield compared with III-V technology.

The proposed future T/R module, as shown in Figure 1, is a two chip solution composed of a SiGe multi function chip such as [1] and a GaN driving front-end chip [2] with output power of ~39dBm. Increasing the output power of the SiGe PA driver reduces the required number of stages in the GaN HPA that enables a significant lower cost without performance compromise.

One of the challenges in the design of microwave PAs in SiGe technologies is to cope with a decrease in the breakdown voltage (BV) as scaling down of the transistor dimensions continue. Previous research work at X-band includes single ended two stage cascode design to overcome the low breakdown [3]. Matching networks that were previously used were implemented with lumped inductors, capacitors and with transmission lines. A two stage cascode design [4] in push pull configuration used output matching that consists of LC-Balun with additional inductor for biasing. Another approach to increasing the voltage swing is to use a common base design [5].

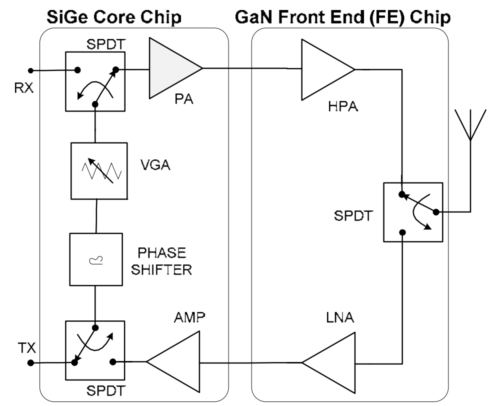

Fig.1. Proposed next generation X- Band T/R module.

In this work, we use several techniques to increase the output power and efficiency of an X-band PA using SiGe HBT. A cascode stage is used to increase the voltage swing while using high speed HBTs with significant gain at X-band. A differential configuration is used to increase the output current swing without further increase in device size. Transformers are used for input and output matching to allow a compact matching while providing baluns for the single-ended GSG pads and biasing through the center taps. These techniques allow the achievement of a peak output power of 27 dBm and maximum power added efficiency (PAE) of 36 %. Such record values at X-band will open new opportunity to design low cost T/R modules by reducing area of high cost GaN and still targeting high performance.

II. CIRCUIT TOPOLOGY

The schematic view of the PA designed in this work is shown in Fig.2. In this design a differential topology is preferred to a single-ended one. The virtual ground in the differential topology helps minimize the ground path in the circuit which improves the small signal gain by reducing emitter degeneration. Another advantage is improving the voltage headroom, thus increasing the output voltage swing. The differential configuration has another advantage that concerns power amplifiers. In order to increase the output power, devices with larger periphery are needed to provide more current. Connecting more transistors in parallel to increase the total periphery results in low output impedance that is difficult to match over a wide frequency range with low

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loss. The output impedance of differential topology is 4 times higher compared to single ended topology. This impedance boost helps to increase the amount of devices in parallel to produce higher power with lower impedance transformation compared to single ended topology.

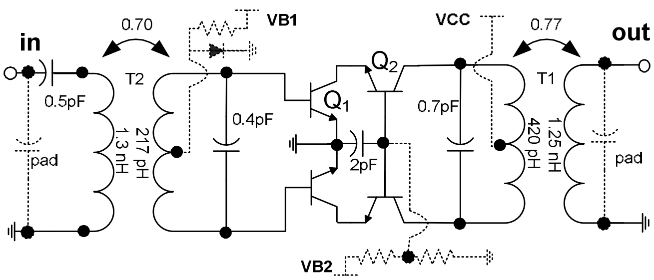

Fig.2. Schematic view of the X-band power Amplifier.

The cascode configuration can operate with twice the supply voltage compared to common emitter configuration. This allows the circuit to work with half of the bias current and results in an optimum load resistance that is larger than the common emitter topology.

The available voltage swing at the output of Q_2 can be significantly increased [7] depending on the load conditions and $Q_{2\text{-base}}$ DC Biasing. Moreover, biasing Q_1 with a voltage source (low impedance) rather than a current source (high impedance) circuit can tolerate collector-emitter voltages greater than BV_{CEO} without causing the device to break down.

The cascode configuration also offers superior bandwidth compared to common emitter due to the reduced Miller effect. The cascode configuration is almost unilateral easing the matching of the input and output independently, unlike common emitter which requires iterations to achieve simultaneous conjugate matching due to the collector-base feedback capacitance.

Another consideration is stability. In order to achieve the same output power in a common emitter or common base configuration, the transistor has to handle twice the current, requiring more cells in parallel compared with cascode transistors. In order to keep the circuit stable with increased transistor size additional resistors and special RF choking are needed, which require more area.

Considering all the issues above a differential cascode configuration is chosen for implementing the PA in this work.

III. POWER AMPLIFIER DESIGN

The X-Band power amplifier is designed in a commercial 0.18µm SiGe-HBT technology. The process has 5 metal layers. High speed (HS) devices have a cutoff frequency ≈170GHz and fmax ≈ 250 GHz. The breakdown voltages are BVCEO ≈ 1.7V and BVCES ≈ 6.5V.

Allowing voltage swing of 1.8V at each cascode cell and targeting 0.55 W output power the estimated current swing is 0.3A. Thus, the total device should handle up to ~ 0.6A. The unit cell of the common emitter – Q_1 and the common base – Q_2, is composed of 16 parallel CEBEC configurations with emitter width and length of 0.18 µm and 9.87 µm, respectively. The total of unit cell emitter area is 56.8 µm^2. The PA operates in deep class AB to reach both high power and high PAE.

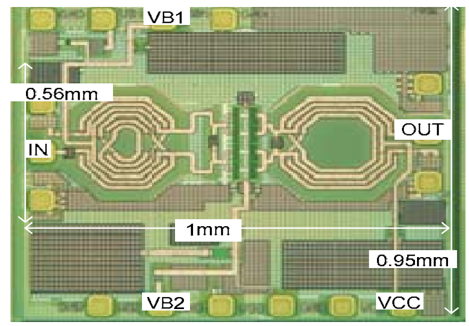

Fig.3. Photograph of the fabricated X-band power amplifier.

An output equivalent model (Parallel- RC) is derived from load pull simulation over the frequency range. The model values are C_{out}=0.3 pF and R_{out}=21 Ω. This equivalent circuit is set as a load and the optimum input impedance is determined under large signal. The model values for the input equivalent model are C_{in}=1 pF and R_{in}=13 Ω.

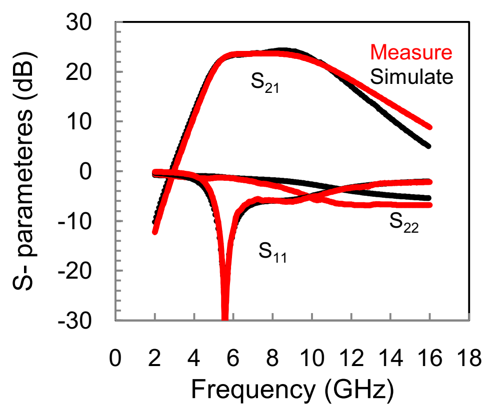

Fig.4. Simulated and measured S_{11}, S_{22}, and S_{21} versus frequency for the power amplifier.

In order to match input and output impedances to 50 Ω, a 2.5:1 transformer is needed at the output and a 4:1 transformer is needed at the input. The analytical values of the both double tuned transformers T_1 and T_2 are derived using [7]. Both transformers utilize series-parallel interleaved structure which offers excellent coupling and a non-unity turn-to-turn ratio. The output transformer is built with two parallel inductors structure and two turn series inductor. The input transformer is built with three parallel inductors and three turn series inductor. Electro-migration and high ohmic loss considerations set the trace width to 15µm. The conductor spacing is set to the minimal 2.5µm to enhance the coupling

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factor. The transformer performance is validated in Momentum™ simulation. The final values are shown in Fig. 2. The transformer acts as a matching network, balun and RF-choking through the center taps. Using double tuned transformers, the device input and output capacitors are easily absorbed with the tuning capacitors, which also act as built-in harmonic tuning for both input and output, shorting the second harmonic to enhance efficiency. Moreover, they alleviate the electro-static discharge requirements.

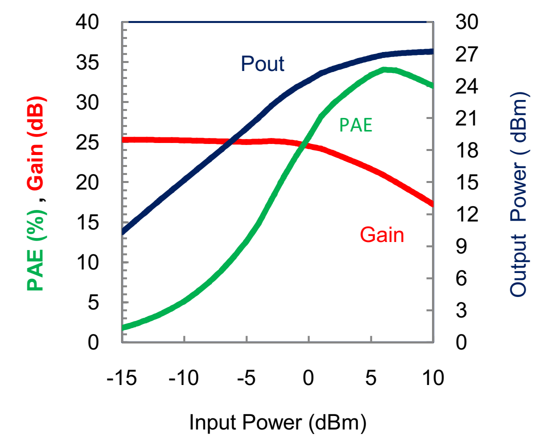

Fig.5. Measured output power, gain and PAE versus input power at 8.25GHz.

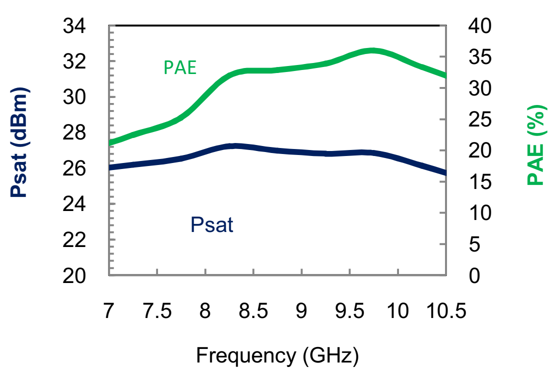

Fig.6. Measured saturated output power and PAE versus frequency.

IV. Measured Results

The fabricated X-band PA is shown in Fig. 3. Its size is 1mm x 0.95mm (0.85mm X 0.56mm core) including pads and low frequency decoupling capacitors to stabilize the PA at low frequencies.

The PA was measured on wafer under a V_{cc} of 3.5 V with a quiescent current of 165 mA. Fig 4 compares the simulated and measured small signal gain and I/O return loss. A gain of 22-24.5dB is achieved across a bandwidth of 4 GHz. The simulated and measurements are in good agreement. The output power, power gain and PAE versus input power at 8.25 GHz are depicted at Fig 5. An output P1dB of 25.2 dBm and Psat of 27 dBm are reached. The PAE at P1dB is 28 % and reaches a maximum of 34 %. The output power and PAE versus frequency are depicted at Fig 6. Over a frequency range of 7.25GHz to 10.25 GHz the output power is 26.2-27.2 dBm and the PAE is 22.5-36%. Table I provides a comparison of our work with state-of-the-art PAs in SiGe-HBT technology at X band frequency.

TABLE I
COMPARISON OF X-BAND SIGE POWER AMPLIFIERS

Frequency [GHz]	Peak Pout [dBm]	Peak PAE [%]	Gain [dB]	Size [mm²]	Ref.
8.5-10.5	21.4	26	41	1.32	[3]
7-12	25.5	35	20	2	[4]
8.5	25	16	8.7	0.75	[5]
7.25-10.25	27	36	21	0.95	This Work

V. Conclusion

A single stage class AB differential cascode PA using only high-speed HBTs and double tuned transformers at the input and output matching networks has been developed using an advanced 0.18μm SiGe-HBT technology. Some new design techniques were applied to optimize the PA performance. The PA achieves maximum output power of 27dBm and maximum 36 % PAE. The RF core size is 0.85mm x 0.56mm exhibiting output power density of 1.0 W/mm^2. To our knowledge, those values are the highest among SiGe-HBT power amplifiers.

References

[1] Mark Hauhe, and Glenn Sakamoto, "SiGe System on a Chip for radar applications" *2012 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1-3, June 2012.

[2] Masuda Satoshi, *et al*,"GaN single-chip transceiver frontend MMIC for X-band applications" *2012 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1-3, June 2012.

[3] J.Andrews, J.D. Cressler and M. Mitchell, "A High-Gain, Two-Stage,X-Band SiGe Power Amplifier " *2007 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 817-820, June 2007.

[4] J.Walling, and D. Allstot, "A 25 dBm 35% PAE, 7-12 GHz Power Amplifier Utilizing Techniques to Increase Optimal Load Impedance" *2006 IEEE Topical Workshop on Power Amplifiers for Wireless Communications*, Jan. 2006.

[5] Z.Ma, *et al*,"An X-Band High-Power Amplifier Using SiGe/Si HBT and Lumped Passive Components." *IEEE Microwave and Wireless Components letters*, vol. 11, no. 7, pp. 287-289, July 2001.

[6] C.M.Grens, *et al*,"An Investigation of the Large-Signal RF Safe-Operating-Area on Aggressively-Biased Cascode SiGe HBTs for Power Amplifier Applications," *,2009 Proc. IEEE Topical Meeting on Silicon Monolithic Integrated Circuits in RF Systems*, pp. 1-4,Jan. 2009.

[7] C .J .Galbraith, *et al*,"A Low-Loss Double-Tuned Transformer" *2007 IEEE Microwave and Wireless Components letters*, vol. 17, no. 11, pp. 772-774, November 2007.

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