A 2.4 GHz High Efficiency SiGe HBT Power Amplifier with High-Q LTCC Harmonic Suppression Filter

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***Abstract* — We present a 2.4 GHz SiGe HBT power amplifier integrated with a harmonic suppression filter implemented in a high-Q multilayer low-temperature co-fired ceramic (LTCC) substrate at the output. The power amplifier delivers a power of upto 27.5 dBm with a maximum power-added efficiency (PAE) of 47%. It has a power output of 27 dBm at an input power of 0 dBm with a PAE of 45%. The second and third harmonics are –44 dBc and –49 dBc, respectively, at this operating point. The power amplifier exhibits a linear gain of 35 dB and operates at a supply voltage of 3.3 V. To the best of our knowledge, this represents the best reported performance of a SiGe HBT power amplifier at 2.4 GHz and is comparable to performance previously achieved only with GaAs-based processes. The harmonic suppression filter and output match network have been implemented completely in LTCC without the use of external discrete components.**

I. INTRODUCTION

The 2.4 GHz ISM band is very important in digital wireless communications with several applications such as Bluetooth, Home RF, DECT, wireless local loop and IEEE 802.11 wireless LAN systems. GaAs-based technologies such as AlGaAs/GaAs HBT and GaAs MESFET have traditionally dominated power amplifier design in this frequency range. However, SiGe HBT technology is now emerging as a contender for RF power amplifier applications. SiGe HBTs have many attractive features such as high substrate thermal conductivity, good f_t and f_{max} (~30 GHz and 55 GHz respectively for high breakdown devices) and low base-emitter turn-on voltage [1]. However their low breakdown (maximum BV_{ceo} of 5.5V) and Early voltages (~125V) compared to GaAs HBTs as well as the significantly higher parasitics make power amplifier design a considerable challenge. Recently SiGe HBT power amplifiers for many applications such as GSM, DECT, AMPS and CDMA have been reported [2]-[5]. A high efficiency power amplifier at 2.4 GHz in SiGe HBT technology with 0.5 W output power has not, however, been previously reported. We present a 2.4 GHz SiGe HBT power amplifier that delivers upto 27.5 dBm power output with a maximum power-added efficiency of nearly 47%. Excellent harmonic suppression is achieved by a harmonic suppression filter at the output which along with the output match has been implemented in a multilayer LTCC substrate.

The use of a filter to suppress harmonics is quite common in power amplifier design. Various types of low pass filters such as open-stub and stepped-impedance filters [6]-[7] have been reported. However all these have limitations which make it difficult to meet the requirements of modern communication systems [8]. In this paper, we present a compact filter with excellent harmonic suppression performance implemented completely in LTCC substrate. No external lumped components are used and the output match network is also implemented in the LTCC substrate.

II. DESIGN

A. Power Amplifier

The power amplifier is designed in IBM's commercial SiGe HBT process. A high breakdown device available in the process with a unit cell area of 20 um^2 is used in this design. The schematic of the designed power amplifier is shown in Fig. 1. It consists of three stages: two driver stages and a power stage; interstage, input and output match networks, and bias circuits for the three stages. The power amplifier is packaged in an 8-pin SOIC package. Package parasitics, lead and bond wire inductances are included in designing the power amplifier. The mutual inductance between bond wires and leads were found to be significant and were also estimated and included in the design. Interstage matching is compact and is achieved using only on-chip capacitors and bond wire and package lead inductances that also serve as RF chokes for the first two stages. Variations in these inductances from the estimated values due to variation in bond wire length can be compensated for using small lengths of external microstrip lines. The output match network and harmonic

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filter are off-chip and implemented in LTCC. Fig. 2 shows a picture of the designed power amplifier.

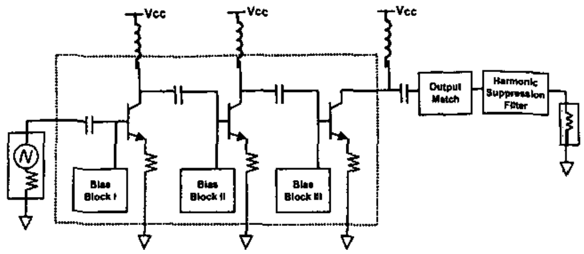

Fig. 1. Schematic of the SiGe HBT power amplifier

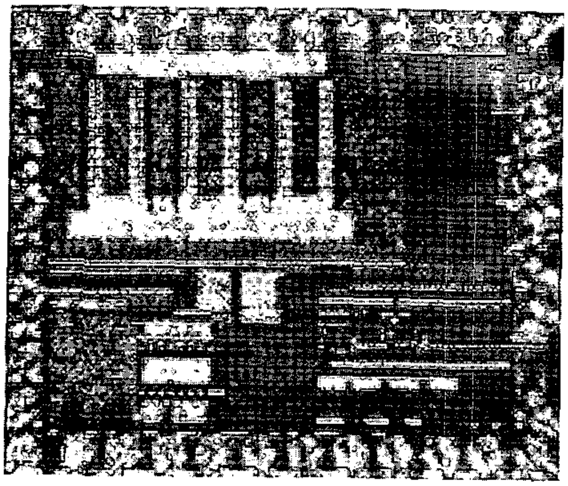

Fig. 2. Microphotograph of the SiGe HBT power amplifier

Emitter ballasting is used to prevent thermal runaway. The appropriate value of emitter ballasting resistance to be used can be calculated using the following dependence of collector current on junction temperature [9]:

$$I_c = I_{so}.\exp\left(\frac{qV_{be} - qI_c\left[\frac{r_e + R_{eb}}{\alpha} + \frac{r_b}{\beta}\right] - E_g}{kT}\right) \qquad (1)$$

where R_{eb} is the emitter ballast resistance per unit transistor cell and temperature T is given by:

$$T = T_A + R_{th} I_c V_{cc} \qquad (2)$$

where R_{th}, the thermal resistance of the device is given by [10]:

$$R_{th} = \ln(4L/W) / (\pi kL) \qquad (3)$$

where L and W are the length and width of the emitter of the device, respectively, and k, the thermal conductivity of Silicon is ~0.1 mW/μm-°C at 350 °C. From this, R_{th} is computed to be ~0.81 °C/mW. The typical highest operating ambient temperature is 85°C and from the thermal resistance of the package and the die this results in the highest value of T_A being 125 °C. Assuming a low Germanium content in the base, $E_g(T)$ can be approximated by the temperature dependence of E_g of Si [11]:

$$E_g(T) = E_{g0} - 3.6 \times 10^{-4}\, T \qquad (4)$$

where E_{g0} is 1.21 eV, and the temperature dependence of β can be represented by

$$\beta(T) = \beta(T_A)\,(T/T_A)^{XTB} \qquad (5)$$

where T_A is 298K and XTB= -0.5. The threshold for onset of thermal runaway is given by:

$$(\partial J_c / \partial V_{be})^{-1} = 0 \qquad (6)$$

Fig. 3 shows J_c as a function of V_{be} for different values of R_{eb}. It is clearly seen that if no ballasting is present (R_{eb}= 0), thermal runaway will occur. Keeping in mind the approximations involved in the above analysis, being conservative, the value of R_{eb} was chosen to be 3 Ω.

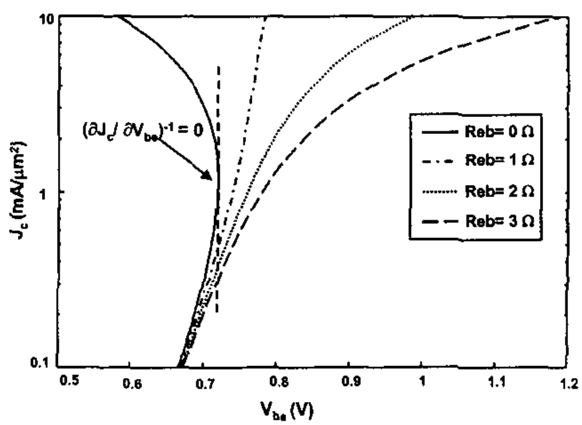

Fig. 3. Collector current density vs. base-emitter bias voltage at different emitter ballast resistance values

B. LTCC Harmonic Suppression Filter and Output Match Network

The harmonic suppression filter and output match network are designed in Kyocera's 10 metal layer LTCC process. Fig. 4 shows the designed filter and output match network. The filter consists of a transmission line in parallel with a capacitor C. The attenuation poles of this filter are the zeros of equation (8) below [8]:

$$S_{11},S_{22} = \frac{Y_0^2 - Y_c^2 + \omega C Y_c[\csc(\beta l) - \cot(\beta l)]}{\Delta Y} \quad (7)$$

$$S_{21},S_{12} = \frac{2jY_0[\omega C - Y_c \csc(\beta l)]}{\Delta Y} \quad (8)$$

$$\Delta Y = Y_0^2 + Y_c^2 + 2jY_0[\omega C - Y_c \cot(\beta l)] + \omega C Y_c[\cot(\beta l) - \csc(\beta l)] \quad (9)$$

where Y_0 is the characteristic admittance of the input and output port, Y_c is that of the transmission line, l is its length, and β its propagation constant.

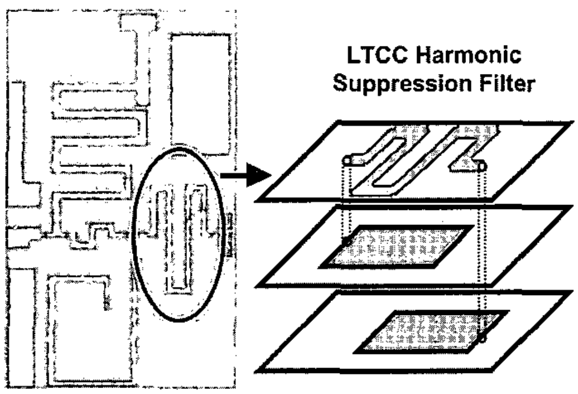

Fig. 4. LTCC harmonic suppression filter and output match network

The filter is designed to give deep suppression of the second and third harmonics. A $\lambda/4$ length RF-shorted stub is used to achieve a short at the second harmonic. The output match network, which is also implemented in LTCC using transmission lines, tuned in conjunction with the harmonic suppression filter presents nearly a short at the second harmonic and nearly an open at the third harmonic. The harmonic suppression performance of the filter is shown in Fig. 5. As can be seen, the suppression of the second and third harmonics is better than 45 dB. The filter exhibits a loss of about 1dB at the fundamental frequency (2.4 GHz).

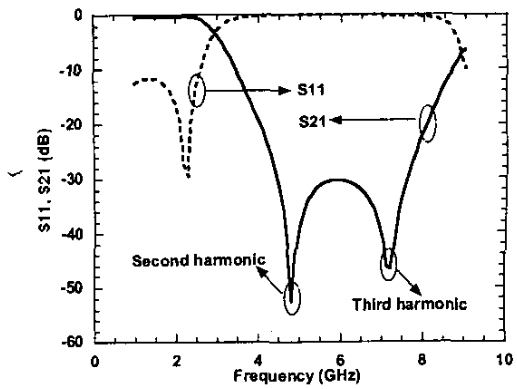

Fig. 5. Performance of the harmonic suppression filter

III. Performance

The output power and efficiency of the power amplifier with the LTCC harmonic suppression filter is shown in Fig. 6. The power amplifier achieved an output power of 27 dBm at 0 dBm input with a PAE of 45% at 2.4GHz and Vcc=3.3 V. At 5 dbm input, the output power is 27.5 dBm with a PAE of 47%. The linear gain of the power amplifier is 35dB. The second and third harmonics are –44 dBc and –49 dBc respectively at 0 dBm input. The power amplifier thus exhibits high efficiency with more than 0.5W output power. This represents the first reported high power, high efficiency power amplifier in SiGe HBT in the 2.4 GHz band with performance comparable to that seen with GaAs MESFET/HBT. Table 1 shows a comparison of this work with previous reported results.

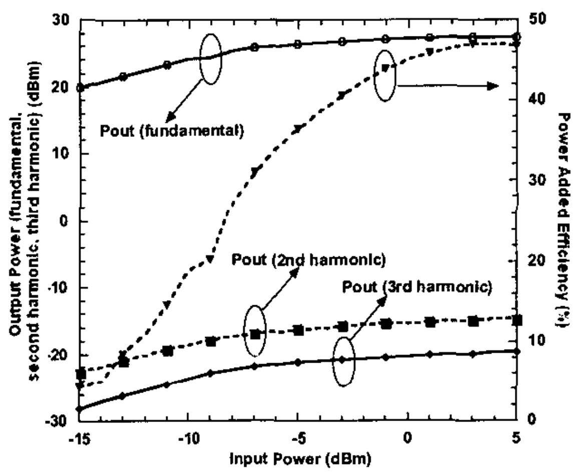

Fig. 6. Performance of the power amplifier

TABLE I
COMPARISON WITH PREVIOUS REPORTED RESULTS

Freq. (GHz)	Pout (dBm)	PAE (%)	Gain (dB)	Harm. (dBc)	Sup. V (V)	Technology	Match/ Filter	Ref.
1.9	26.6	38	33	-	3	SiGe HBT	Ext. discrete	[2]
1.9	29	43	20	-	3	SiGe HBT	Ext. discrete	[12]
1.8	32	45	30	-	3.4	SiGe HBT	Ext. discrete	[13]
2.4	26.5	51	29.5	- 40	3.3	GaAs MESFET	Ext. discrete	[14]
2.4	27	47	35	- 45	3.3	SiGe HBT	LTCC	This work

The voltage and current waveforms at the output of the power stage are shown in Fig. 7. The LTCC filter with the matching network not only suppresses the second and third harmonic giving very good harmonic performance, it also presents nearly a short at the second harmonic and nearly an open at the third, thereby shaping the current waveform towards a half sine wave and the voltage waveform towards a square wave. Since the voltage is nearly short at the second harmonic and there is little third harmonic current, very little power is dissipated at these frequencies and this Class F-like behavior helps in improving efficiency.

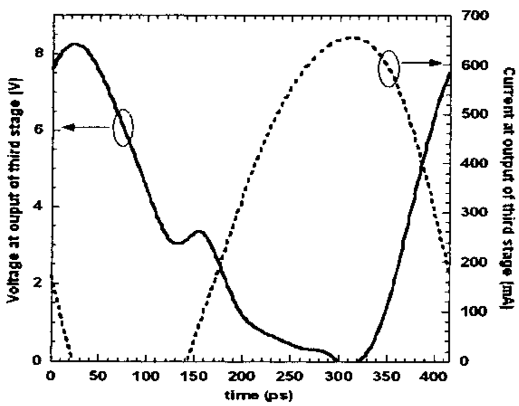

Fig. 7. Voltage, current waveforms at output of third stage

IV. CONCLUSION

A high efficiency 2.4 GHz 3.3 V SiGe HBT power amplifier has been demonstrated. The power amplifier delivers more than 0.5 W output power with a maximum PAE of 47%. A compact harmonic suppression filter at the output in combination with the output match network is implemented in a multilayer LTCC process and shows harmonic suppression of better than –44 dBc for the second harmonic and –49 dBc for the third harmonic. The power amplifier is suitable for many 2.4 GHz band wireless applications such as DECT, Bluetooth and can be backed off to achieve the linearity requirements of applications such as IEEE 802.11 wireless LANs.

ACKNOWLEDGEMENT

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