Proceedings of Asia-Pacific Microwave Conference 2006

Differential Power Combining Technique for General Power Amplifiers Using Lumped Component Network

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***Abstract* — A differential power combining method for general power amplifiers (PAs) with combining and matching network using lumped components is proposed for the first time. The proposed power combining technique greatly reduces board area at 1.95 GHz as compared to the traditional in-phase power combining method using transmission line, such as Wilkinson power combiners. The output matching is achieved with smaller impedance transformation ratio and the matching loss is reduced. The proposed SiGe PA with power combining technique achieves 28 dBm output power, 14 dB gain and 22.6% power-added efficiency (PAE) at 1.95 GHz with 1dB output power enhancement as compared to the single PA.**

***Index Terms* — differential power combining, impedance transformation ratio, lumped component network, matching loss, power amplifiers**

I. INTRODUCTION

As future communications trends demand higher data rates and broader coverage, power amplifiers (PAs) in the radio-frequency (RF) front-end circuits have to produce larger output power to satisfy the link requirement. Using more unit cells in parallel to produce higher output power is one of the possible solutions. But the smaller optimal output impedance by paralleling more transistors leads to the problem of higher impedance transformation ratio and thus higher matching loss [1].

To mitigate this issue, power combining techniques are applied. With fewer transistors in each power amplifying path, the optimal output impedance for the PA is larger, and impedance transformation ratio and matching loss are both reduced. Also, when more unit cells are used, more bonding pads are needed to provide lower parasitic inductance caused by the bondwires.

Power combining techniques are classified and discussed comprehensively in the literature [2]. Among them, Wilkinson power combiners are often applied in monolithic microwave integrated circuit (MMIC) because they can perform in-phase power combining with low loss and good isolation [3]–[5]. At very high frequency, the $\lambda/4$ transmission lines are quite compact and suitable for integration. But at lower RF frequency, they are quite large as compared to the size of integrated circuits (ICs) [4]. On the other hand, lumped components can achieve the same performance with smaller chip or board area at lower RF frequency [6]. Differential power combining using lumped component network has been proposed for class-E PAs [7]. However, the switching-mode PAs, such as class-E PAs, do not have the output impedance and thus without impedance matching concerns. In this paper, linear PAs with finite output impedance are considered. The differential power combining technique with a simple combining and matching network using lumped components at lower RF frequency is proposed for the first time.

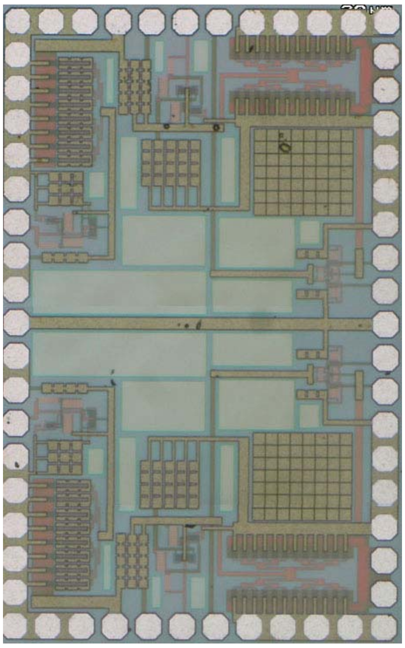

Fig. 1. Die photo (1.88 mm × 1.18 mm) of SiGe PAs.

II. DIFFERENTIAL POWER COMBINING TECHNIQUE

Fig. 1 shows the die photo (1.88 mm × 1.18 mm) of the dual PAs in the SiGe technology with 0.9 μm emitter width. The PAs each have two stages operating in class AB mode. For the purpose of power combining, they are located in the same chip with layout symmetry.

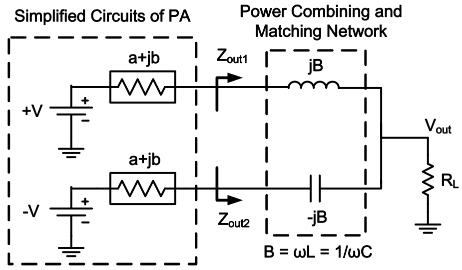

Fig. 2. Schematic of differential power combining technique.

Fig. 2 shows the schematic of the differential power combining technique. Two identical PAs with output impedance $a + jb$ are fed with differential inputs. The PA can be viewed as a Thevenin's voltage source with output impedance $a + jb$. Following the PAs, a simple resonant LC network with their reactances related by $B = \omega L = 1/\omega C$ plays the role of both power combining and impedance transformation to the load R_L. Through the LC network, the phases of +V and –V are led and lagged by 90° respectively, so the power at the output is in-phase and combine. The amplitude modulation/phase modulation (AM/PM) effects of the PAs are assumed to be negligible. By superposition, Z_{out1}, Z_{out2}, and V_{out} can be calculated, and because $R_L >> a$, equations can be simplified as shown in (1) - (3). From (3), it is shown that the output voltage V_{out} is directly related to the input voltages ±V by the output impedance of the PAs and the B value of the LC network. In other words, the output power is combined, and can be controlled by the designed PA parameters.

$$Z_{out1} = \frac{(2aR_L - b^2 + B^2) + j2bR_L}{2R_L + j(b - B)} - (a + jb) \qquad (1)$$

$$Z_{out2} = \frac{(2aR_L - b^2 + B^2) + j2bR_L}{2R_L + j(b + B)} - (a + jb) \qquad (2)$$

$$V_{out} = \frac{2BR_L}{-2bR_L + j(2aR_L - b^2 + B^2)} V \qquad (3)$$

Notice that in (1) and (2), the real parts of Z_{out1} and Z_{out2} are not the same, and this will cause asymmetric phase change of the signals in each path. Therefore, for the purpose of power combining, two additional capacitors C_b are added to each path to eliminate b, the imaginary part of the output impedance of the PAs. This is significantly important in the underlying concept of the proposed differential power combining technique. After C_b, $Z_{out} = \mathrm{Re}[Z_{out1}]|_{b=0} = \mathrm{Re}[Z_{out2}]|_{b=0}$, and for conjugate matching, we let $Z_{out} = a$, the real part of output impedance of the PAs. With $R_L = 50\ \Omega$, the value of B can be derived, and the values of L and C can thus be determined at a specified frequency. Notice that in the lower path, C_b can be combined with the capacitor in the power combining network to further reduce the board area.

$$Z_{out} = \frac{2B^2 R_L}{4R_L^{\ 2} + B^2} = a \qquad (4)$$

$$B = \sqrt{\frac{4aR_L^{\ 2}}{2R_L - a}} \cong \sqrt{2aR_L} \qquad (5)$$

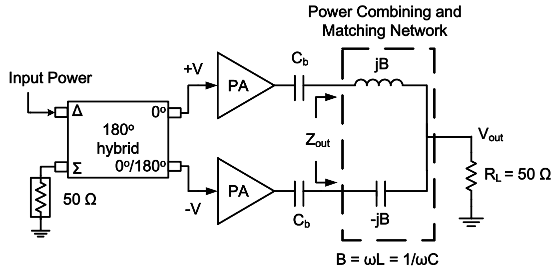

Fig. 3. Schematic of differential power combining measurement setup. C_b is added to eliminate b, the imaginary part of the output impedance of the PAs.

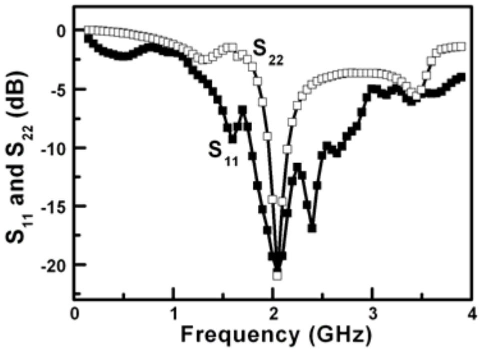

Fig. 4. The S_{11} and S_{22} of the PA with differential power combining.

III. MEASUREMENT RESULTS

The output matching and power combining network are achieved using lumped components on the printed circuit board to reduce board area. A 3-dB 180° hybrid is used to generate differential input signals for measurement.

A. Performance of Differential Power Combining

The power combining network design is based on (4), and Fig. 4 shows the S_{11} and S_{22} of the PA. The very low reflection loss indicates that the matching is well achieved. The frequency is shifted a little bit from the designated frequency because of the limited choices of discrete values of lumped components.

The DC supply voltage and the quiescent current of each PA are 3.3 V and 100 mA, respectively. The loss of 3-dB 180° hybrid and the cable has been measured and de-embedded in the performance evaluation.

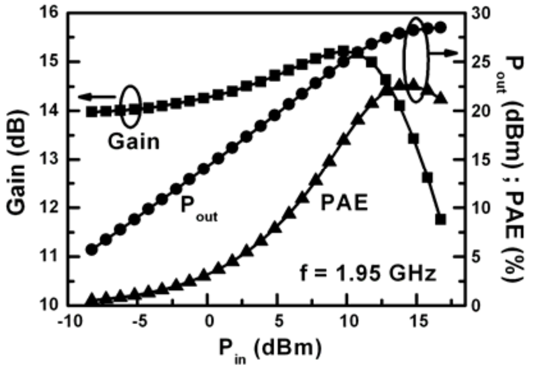

Fig. 5. The power gain, P_{out}, and PAE of the PA with differential power combining.

Fig. 5 shows the power gain, P_{out} and power-added efficiency (PAE) of the PA with differential power combining. The linear gain, P_{1dB}, and PAE at P_{1dB} are 14 dB, 27.9 dBm, and 22.6%, respectively.

B. Performance Compared with In-Phase Power Combining

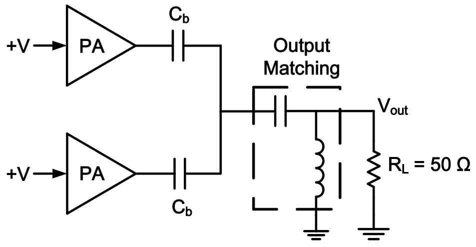

Fig. 6. Measurement setup of in-phase power combining for comparison.

To compare the proposed differential power combining with the traditional in-phase power combining, we connect the input power to the Σ port of the 3-dB 180° hybrid to generate two in-phase output signals for measurement, as shown in Fig. 6. The power combining and matching network is discarded and replaced by traditional output matching network. Notice that the compensation capacitors C_b remain unchanged for the purpose of comparison.

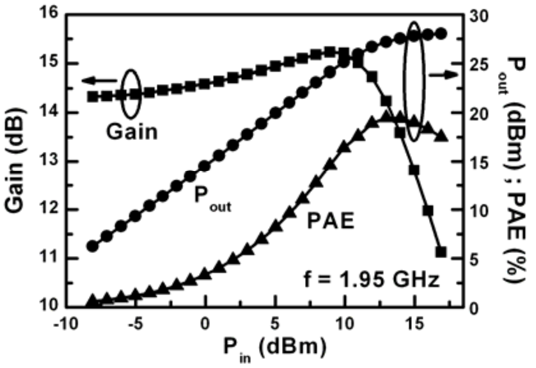

Fig. 7. The power gain, P_{out}, and PAE of the PA with in-phase power combining.

Fig. 7 shows the power gain, P_{out}, and PAE of the PA with in-phase power combining. The linear gain is 14.3 dB, while P_{1dB} is 27.6 dBm and PAE at P_{1dB} is 19.3%. By Fig. 5 and Fig. 7, it is found that the differential power combining can achieve almost the same performance as the traditional in-phase power combining with reduced number of components of the output matching network. The power combining and matching network can be further fully-integrated into chip. The PAE of the in-phase power combining is poorer than the differential case because of additional matching loss.

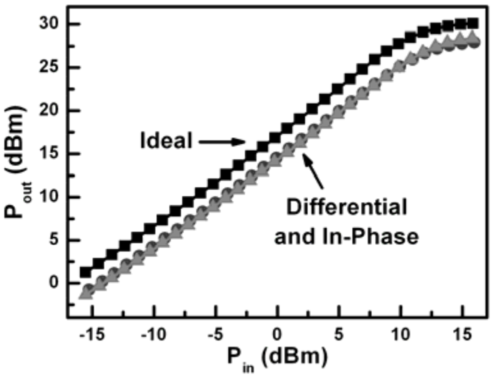

Fig. 8. Comparison of differential and in-phase power combining with ideal power combining.

In terms of combining efficiency, the power characteristics of the two PAs are measured independently. The output power of the two PAs are added directly to be the ideal combining curve shown in Fig. 8.

The summary of their performances are listed in Table I. The proposed differential power combining technique in this paper demonstrates 1 dB output power enhancement with reduced output matching network. Notice that the power combining equations are derived in conjugate matching sense. If power matching is done, the performance might be enhanced a little bit more.

TABLE I

POWER COMBINING PERFORMANCE SUMMARY

	Ideal	Differential	In-Phase
Frequency (GHz)	1.95		
P_{1dB} (dBm)	29.9	27.9	27.6
Linear Gain (dB)	16.6	14	14.3
S_{11} (dB)	--	-17.1	-19
S_{12} (dB)	--	-44.2	-31
S_{22} (dB)	--	-8.1	-9
PAE @ P_{1dB} (%)	27.8	22.6	19.3

IV. CONCLUSION

The proposed differential power combining method can achieve the same performance as the traditional in-phase power combining method without the need of additional output matching network. Using lumped components instead of transmission lines can greatly reduce the board area at 1.95 GHz.

ACKNOWLEDGEMENT

The authors would like to acknowledge the technical support provided by National Chip Implementation Center (CIC) and the foundry service of Taiwan Semiconductor Manufacturing Company (TSMC).

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