

# A Decade Bandwidth, Low Voltage, Medium Power Class B Push-Pull Si/SiGe HBT Power Amplifier Employing Through-Wafer Vias

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**Abstract** — We report a 0.5-5 GHz, 2V Class B push-pull power amplifier in a through-wafer via Si/SiGe HBT process. The amplifier utilized a small, low loss, broadband balun and a coupled spiral inductor transformer. Power added efficiencies greater than 40% from 1 GHz to 4 GHz and greater than 30% from 0.5 to 5 GHz have been achieved. Small signal gain of greater than 13dB and maximum output power of 22 dBm were realized from 0.5 GHz to 4 GHz with a 2 V supply voltage.

**Index Terms** — Baluns, MMICs, power amplifiers, silicon, broadband amplifiers.

## I. INTRODUCTION

The last decade has seen an amazing proliferation of wireless devices and standards. Standards such as GSM, WCDMA, 802.11 a/b/g/n, WiBro and WiMax are deployed or are expected to be widely adopted in the next few years. The ability to download high definition video, browse the internet, instant message in real time, and talk on the phone is quickly becoming an expectation of the average cell phone user. Manufacturers of mobile terminals are challenged with the difficult task of integrating all of these functions and standards into a single low-cost, low-power device. A software defined radio (SDR) that integrates all of this functionality onto one chip is urgently needed. One of the major impediments to building an SDR is the RF front end, specifically the nominally narrow-band power amplifier (PA). An SDR PA that operates from 0.8-6 GHz will cover all major bands in use today [1].

Cognitive Radios (CR's), often seen as an extension of SDR, have the ability to sample the frequency spectrum in its general vicinity and then transmit in the available bandwidth. The available spectrum changes with time and location, thus reconfigurable transceivers and wideband PA's are necessary for CR implementations [2]. A small, low-cost CR module requires very high integration at the chip level. A single chip that can integrate all of the digital and RF functions is the best option when low-cost and small form factor are important requirements. Integrating wideband PA's into silicon BiCMOS processes will be a major step toward implementing multi-standard radios.

## II. WIDEBAND POWER AMPLIFIER DESIGN

Class A PA's are inherently broadband due to the fact that they generally do not require band-limiting resonators. PA's of this type can achieve theoretical maximum drain efficiencies of 50%.

Class AB/B PA's can achieve maximum theoretical drain efficiencies of 78.6%. Unfortunately, the single-ended Class AB/B architecture requires a high-Q resonator that filters the output harmonics. The requirement for a resonator usually limits the bandwidth of this architecture to less than an octave.

Other classes of amplifiers (Class C, D, E, F, etc.) can achieve maximum theoretical drain efficiencies of 100%, but they require harmonic manipulation that precludes wide instantaneous bandwidths.

The Class B push-pull amplifier of Fig. 1 can achieve both the broadband performance of the Class A architecture and the theoretical efficiencies of resonant tuned single-ended Class B PA's.

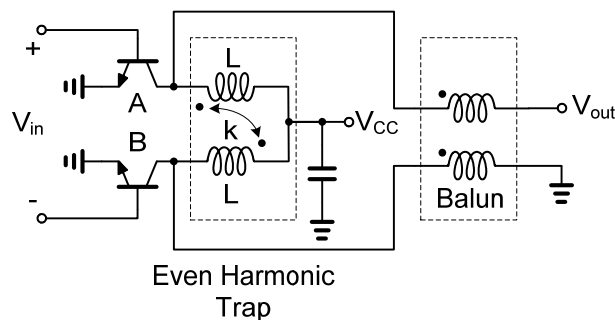


Fig.1 Simplified schematic for the Si/SiGe HBT push-pull power amplifier.

### A. Class B Push-Pull Power Amplifier Design

The Class B push-pull amplifier produces sinusoidal output swings by combining the currents of two anti-phase single-ended Class B amplifiers. If an ideal transformer is used at the output, the odd harmonics of each individual branch of the amplifier are doubled, while

the even harmonics are cancelled. Theoretically, the single-ended Class B PA does not produce any odd harmonics except for the fundamental, so the fundamental RF component is the only signal present at the output.

Push-pull amplifiers also benefit from a 4:1 impedance match advantage over parallel combining of the same devices. This advantage can bring significant relief to the design of high power amplifiers with low supply voltages [3].

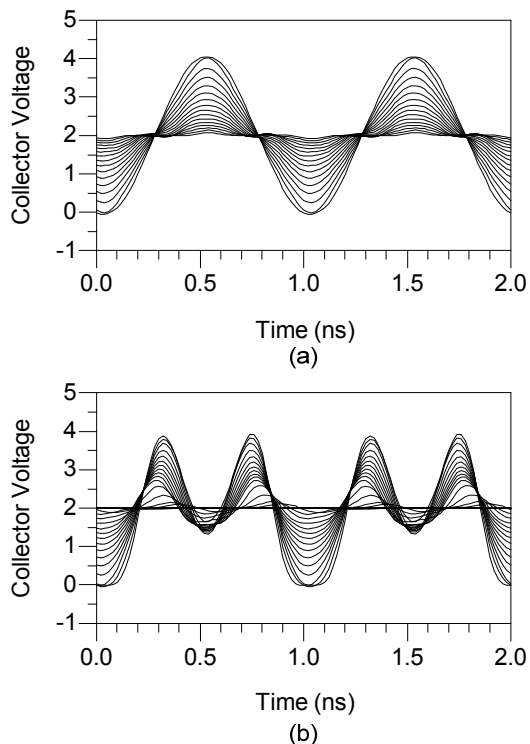


Fig. 2 Voltage waveforms at the collector terminals of a push-pull Class B power amplifier (a) with a harmonic short and (b) without a harmonic short.

If an ideal broadband balun is employed, as in Fig. 1, the voltage waveform at the output of each device will be a half-wave rectified sine wave (see Fig. 2(b)). This waveform has a lower fundamental component than a sine wave with an equivalent supply voltage as shown in Fig. 2(a). Thus, the available output power and efficiency of this architecture, without a short at the even harmonics, cannot achieve the same levels as its single-ended counterpart. Cripps [4] has derived the maximum efficiency of this architecture as 57.6% instead of the traditional 78.6%.

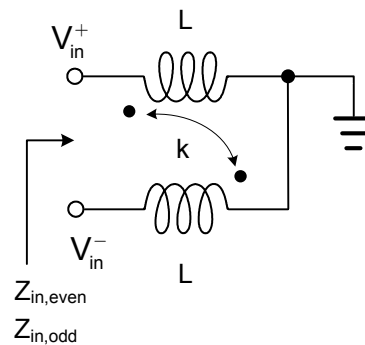


Fig. 3 Representation of coupled inductor termination for determining even and odd-mode impedances.

One way to correct the efficiency problem is to terminate the even-order harmonics with a short circuit. A short using either quarter-wave stubs or lumped elements would limit the bandwidth to less than an octave. Another way to provide an even-order harmonic short in a push-pull architecture is to connect a coupled inductor transformer from each output to ground [5].

The behavior of this circuit can be understood by determining the even and odd-mode impedances of Fig. 3. The odd-mode impedance of this network is

$$Z_{in,odd} \cong s(L - M) \quad (1)$$

and the even-mode impedance is

$$Z_{in,even} \cong s(L + M). \quad (2)$$

Assuming  $M$  is negative, and as long as  $L$  and  $M$  are large enough for the lowest frequency of interest, the odd numbered harmonics will see a high impedance while the even numbered harmonics will see a low impedance. Consequently, much higher efficiencies can be obtained over broad bandwidths.

### III. BROADBAND BUILDING BLOCKS

The system level block diagram of the amplifier is shown in Fig. 1. The input was driven with an off-chip differential source. Although the Class B push-pull architecture is inherently broadband, the balun, coupled inductor transformer, and differential amplifier were all designed to operate from 0.5 – 5 GHz.

#### A. Wideband Balun

Push-pull PA's necessitate a balun that exhibits low loss, good phase balance and good amplitude balance over large bandwidths.

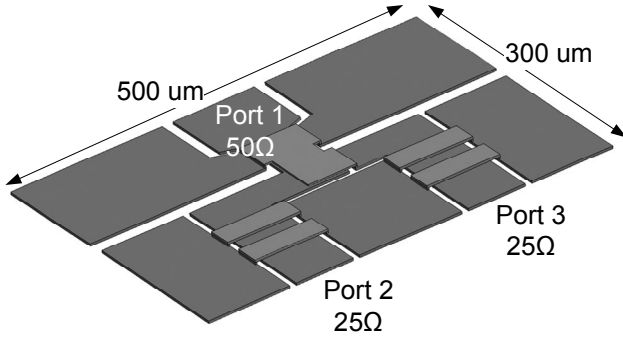


Fig. 4 3D layout of the wideband output balun.

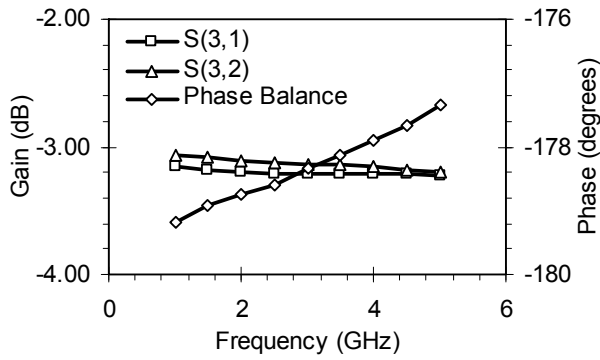


Fig. 5 Simulated performance of wideband balun.

The balun used here (Fig. 4) operated from 1 – 92.5 GHz when implemented on a quartz substrate [6]. Unfortunately, the low substrate resistivity of silicon decreases its bandwidth. Sonnet™ simulation results of the balun used in this work are shown in Fig. 5.

#### B. Coupled Inductor Transformer

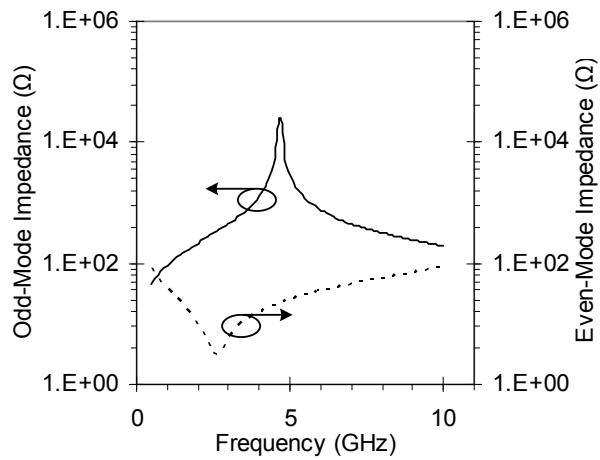


Fig. 6 Simulated performance of coupled inductor transformer.

The even-mode short circuit must act as an open to the odd-order frequencies from 0.5 – 5 GHz and as a short to the even-order frequencies from 1 GHz to at least 10 GHz in order to be effective. A capacitor could be used to provide a short circuit above 5 GHz, in which case the even-mode termination would need to provide a short circuit below 5 GHz.

An EM model was generated in Sonnet™. Each branch of the transformer had a simulated inductance of 7 nH and a series resistance of 3 Ω. The mutual inductance,  $M$ , of the transformer was found to be 6.16 nH.

#### C. Capacitive Cross-Coupled, Resistive-Feedback PA

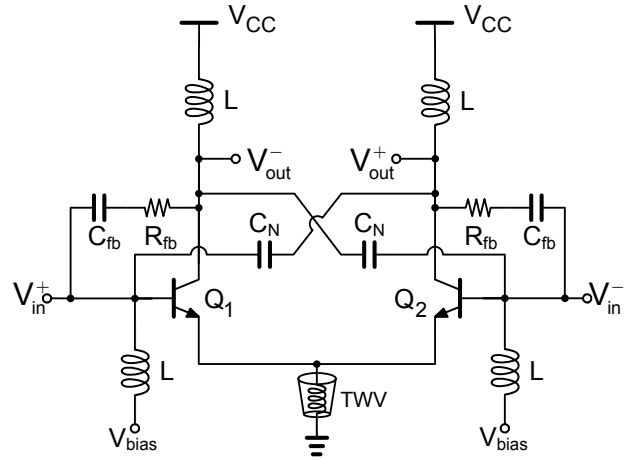


Fig. 7 Broadband resistive-feedback amplifier.

A differential, resistive-feedback amplifier with capacitively cross-coupled neutralization was employed. The schematic of this amplifier is shown in Fig. 7. If the current that flows through the neutralization capacitor,  $C_N$ , is equal and opposite to the current that flows through  $C_{bc}$ , then there is no net feedback from the collector to the base of the transistor and large gain-bandwidth improvements can be achieved. It was found that the gain-bandwidth product of this amplifier was maximized when  $C_N$  was chosen to be equal to  $C_{bc}$ .  $R_{fb}$  was chosen to provide both high gain and good output match.  $C_{fb}$  is a DC blocking capacitor. The design equations for resistive-feedback amplifiers can be found in [7].

#### IV. DEVICE TECHNOLOGY

A Class B push-pull amplifier was realized in an IBM BiCMOS Si/SiGe 5PAe HBT technology. This technology features an NPN transistor with peak  $f_T$  of 35 GHz and  $BV_{CEO}$  of 5.5 V. Also, this technology has many features that are useful for the implementation of MMIC PA's. It employs two thick metal layers, through-wafer

vias, and  $50\Omega$ -cm substrate resistivity. The through wafer via technology is especially useful for high power amplifier applications.

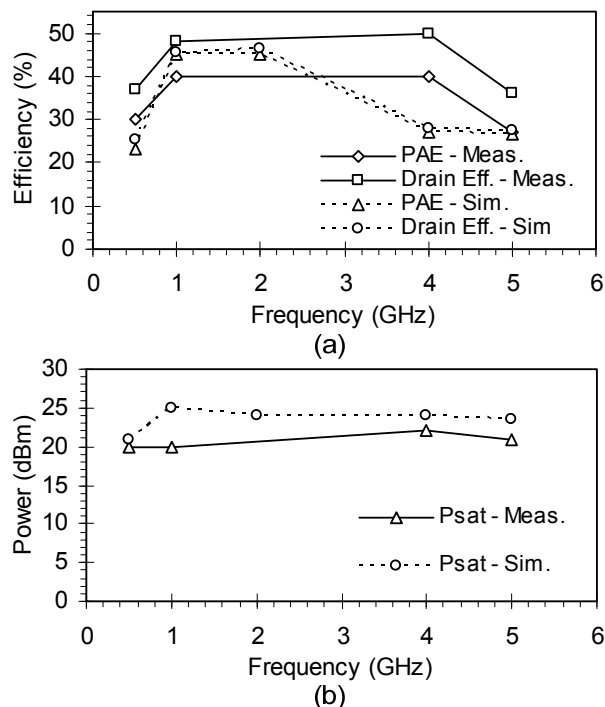


Fig. 8 Performance of the push-pull power amplifier.  $V_{CC} = 2V$ . (a) Simulated and measured drain efficiency and PAE. (b) Simulated and measured saturated output power.

## V. EXPERIMENTAL RESULTS

Measured and simulated values for maximum drain efficiency, PAE, and  $P_{sat}$  for an unmodulated input can be found in Fig. 8. The maximum measured drain efficiency, PAE and  $P_{sat}$  was found to be 50%, 40%, and 22 dBm, respectively. Each transistor used an emitter area of  $176 \mu m^2$ .

## VI. CONCLUSION

Details of an ultra-wideband Class B push-pull power amplifier have been described. This amplifier is fully integrated and achieves high efficiency operation over a wide bandwidth at a very low power supply voltage. Detailed design techniques were described to achieve near ideal Class B operation over a wide bandwidth.

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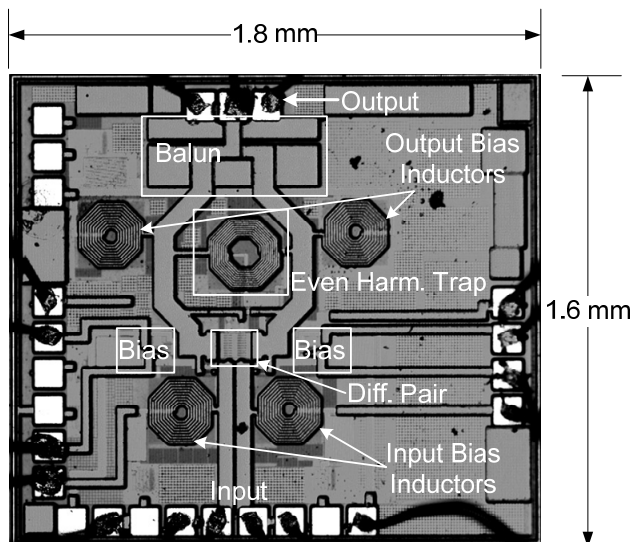


Fig. 9 Microphotograph of push-pull amplifier.

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