Fully Integrated HBT MMIC Series-Type Extended Doherty Amplifier for W-CDMA Handset Applications

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A highly efficient linear and compactly integrated series-type Doherty power amplifier (PA) has been developed for wideband code-division multiple access handset applications. To overcome the size limit of a typical Doherty amplifier, all circuit elements, such as matching circuits and impedance transformers, are fully integrated into a single monolithic microwave integrated circuit (MMIC). The implemented PA shows a very low idle current of 25 mA and an excellent power-added efficiency of 25.1% at an output power of 19 dBm by using an extended Doherty concept. Accordingly, its average current consumption was reduced by 51% and 41% in urban and suburban environments, respectively, when compared with a class-AB PA. By adding a simple predistorter to the PA, the PA showed an adjacent channel leakage ratio better than −42 dBc over the whole output power range.

Keywords: Doherty amplifier, extended Doherty concept, integration, MMIC, predistorter, series-type Doherty amplifier.

I. Introduction

Since the efficiency of Tx power amplifiers (PAs) in a low-power operating region is gaining considerable interest for maximizing the battery lifetime [1], many Doherty amplifier approaches have been studied for wideband code-division multiple access (W-CDMA) Tx applications due to their innate efficiency in the low- and mid-power operating regions [2]-[5]. Nevertheless, the use of two separate amplifiers and bulky circuit elements, such as the 3 dB hybrid coupler and λ/4 impedance transformers, has prevented their direct application to handsets requiring a small form-factor and low cost [2]-[4]. We recently proposed an innovative approach, in which the 3 dB hybrid coupler is removed by rearranging a peak amplifier and a carrier amplifier in a series-type connection [3]. The idea was initially demonstrated by applying it to the CDMA handset Tx PA [4]. However, the PA was implemented using off-chip elements without any consideration of size and cost.

A fully integrated series-type Doherty amplifier is proposed in this work. All circuit elements are thus implemented on a monolithic microwave integrated circuit (MMIC). Moreover, to enlarge the efficiency-enhanced power range of the PA, an extended Doherty concept is adopted based on peak and carrier amplifiers of different sizes [5]. In addition, a simple shunt predistorter is added to the PA so as to escape from the inherent AM-AM and AM-PM distortion occurring during the operation of a peak amplifier in a real world Doherty amplifier [6].

II. Design of a Fully Integrated Series-Type Extended Doherty Amplifier

Figure 1 is a circuit diagram of the series-type Doherty amplifier, where the peak and carrier amplifiers are biased as class-AB and class-C, respectively. The key feature of the series-type Doherty amplifier is that some of the output power from the carrier amplifier acts as a driver of the peak amplifier when it begins operating. For the active load-pulling operation, the impedance looking into impedance transformer 2 of path 2, Z_P, should be properly modulated according to the output power levels, and Z_C of output path 1 should be adjusted accordingly. Figure 2 shows the simulated design procedure for determining Z_P. The analysis is based on the fact that the input impedance (Z_{P1}) of the peak amplifier depends on the operating output power levels due to self-biasing of the peak amplifier

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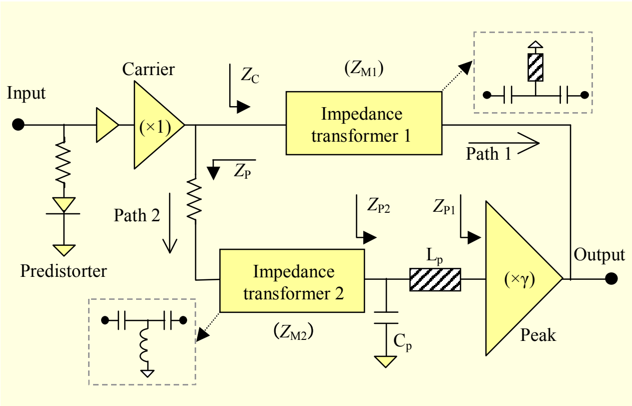

Fig. 1. Detailed schematic of the series-type Doherty amplifier without 3 dB quadrature hybrid coupler.

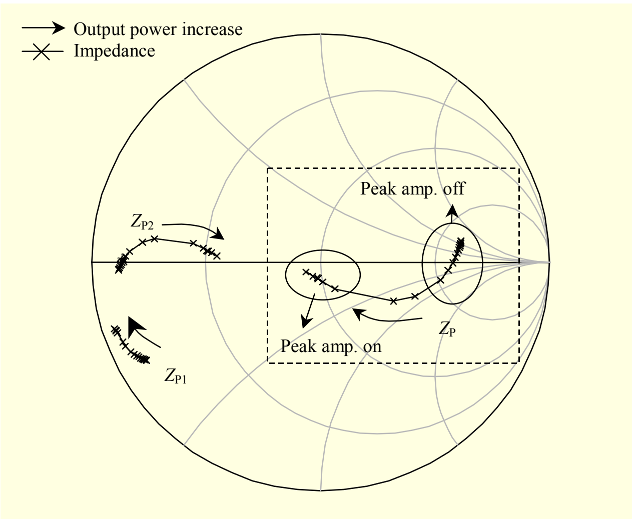

Fig. 2. Simulated design procedure for determining the input impedance (Z_P) of path 2.

by modulation in its base-emitter capacitance. As the output power increases, path 2 carries more power, and accordingly, Z_{P1} is modulated as shown in Fig. 2. The Z_{P1} is readily converted to Z_{P2} by using the simple L_p and C_p shown in Fig. 1, and Z_P finally exhibits the desired trace according to the output power levels via the λ/4 impedance transformer 2 with a characteristic impedance of Z_{M2}. The λ/4 impedance transformer 1 with a characteristic impedance of Z_{M1} shown in Fig. 1 is used to modulate Z_C for maximum voltage swing in the manner of a typical Doherty amplifier.

To fully integrate all circuit elements into an on-chip design, λ/4 impedance transformers 1 and 2 were implemented in high-pass T-networks as shown in Fig. 1. In addition, the emitter size ratio of the peak and carrier amplifiers, denoted as γ in Fig. 1, was set to two to maintain the maximum efficiency over the extended theoretical power range of $20 \cdot \log(1 + \gamma) = 9.54$ dB at the maximum output power level. It should be also noted in Fig. 1 that a simple BC diode was added to the input port of the PA as a predistorter in order to cope with the non-linearity problem occurring in the operating power region of the peak-amplifier as mentioned in section I.

III. Fabrication and Measurement

The MMIC was fabricated using a commercial 2 µm InGaP/GaAs heterojunction bipolar transistor (HBT) process with a size of 1.1 mm×1.08 mm as shown in Fig. 3. The MMIC contains a two-stage carrier amplifier and a single-stage peak amplifier with power cells of 1,120 μm^2 and 2,240 μm^2 emitter areas, respectively, thus meeting γ=2 for extension of the efficiency-enhanced power range. All matching circuits, impedance transformers, and the predistorter were fully integrated into the MMIC. The operating frequency was set in the UMTS Band-2 (Tx frequency, 1.85 GHz to 1.91 GHz).

A 3GPP uplink W-CDMA signal with a chip rate of 3.84 Mcps was used for PA characterization. On an evaluation board (a two-layered PCB, FR4 substrate, ε = 4.6), the gain, power-added efficiency (PAE), and adjacent channel leakage ratio (ACLR) at the 5 MHz offset were all measured with a 3.4 V supply voltage at the operating center frequency of 1.88 GHz as shown in Fig. 4. For the purposes of comparison, a conventional class-AB PA was also fabricated, and another series-type Doherty amplifier without the predistorter was additionally fabricated and measured to demonstrate the linearity enhancement of the proposed PA. To check the frequency dependency of the PA, the gain, PAE, and OIP3 at the maximum linear output power were measured as a function of frequency, and the overall spectrum masks were plotted under the condition of all Tx frequencies as shown in Figs. 5(a) and (b), respectively, showing no noticeable performance degradation over all frequency ranges.

As expected, the PAE-enhanced power range was extended by 9 dB at the maximum power level (from the output power (P_{out}) of 19 dBm to 28 dBm). It should be noted that in Fig. 4(a) the overall shape of the PAE curve is very similar to

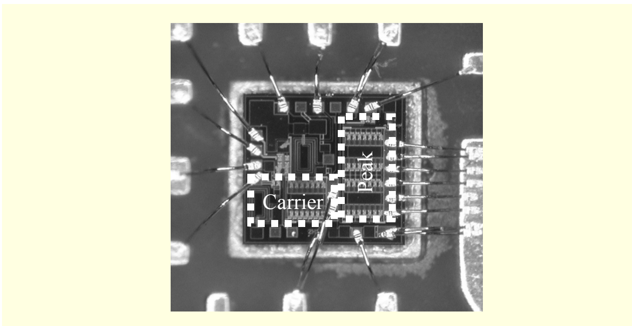

Fig. 3. Photograph of the fabricated MMIC mounted on board.

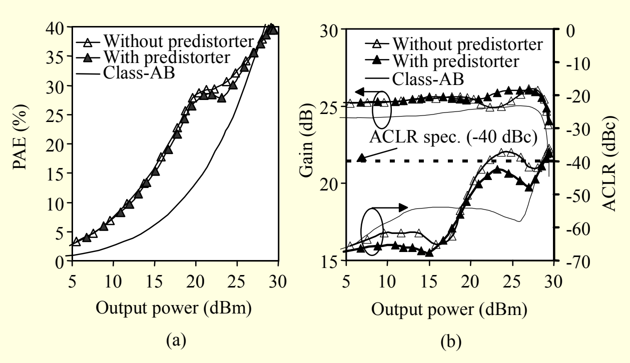

Fig. 4. Measured RF characteristics of the PAs with and without the predistorter: (a) PAE and (b) gain and ACLR.

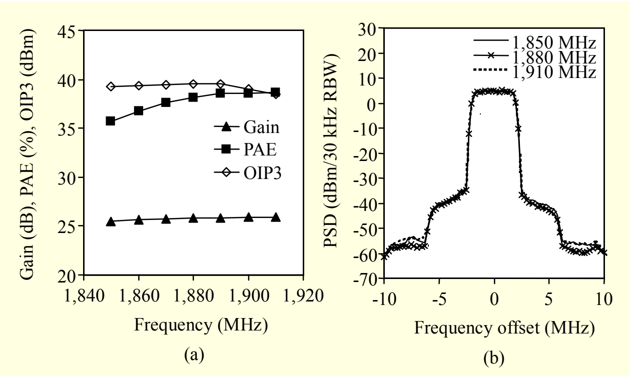

Fig. 5. Measured (a) gain, PAE, OIP3, and (b) power spectral densities at 28 dBm output power as a function of frequency.

Table 1. Comparison between the conventional class-AB and the proposed Doherty amplifier.

	Idle current (mA)	PAE (%)		Average current (mA)	
		P_{out} = 19 dBm	P_{out} = 28 dBm	Urban	Sub-urban
Proposed	25	25.1	37.5	36.6	57.4
Class-AB PA	55	11.5	38.4	74.9	96.7

that of a conventional Doherty amplifier, which validates the design approach of this work. A very low idle current of 25 mA and an excellent PAE of 25.1% at P_{out}=19 dBm were achieved. In comparison with the class-AB amplifier, the idle current, PAE, and calculated average current consumption all showed improvement, and this showed good agreement in PAE at P_{out}=28 dBm. The measured results are summarized in Table 1. By adopting a predistorter, we reduced the gain variation by 0.8 dB over the whole output power range. The ACLR was improved by 4.2 dB (from −38.3 dBc to −42.5 dBc) at P_{out}=23 dBm where the PA had showed the worst linearity before predistortion, while PAE degradation was negligible over the whole linear output power range.

IV. Conclusion

A fully integrated series-type extended Doherty amplifier was proposed in this work. To apply it to a W-CDMA handset transmitter requiring a small form-factor and low cost, all circuit elements, such as input- and interstage-matching networks, impedance transformers, a single-stage peak amplifier, and two-stage carrier amplifier, were compactly implemented on a single MMIC. By setting the emitter size ratio of the peak- and carrier-amplifier to two, the efficiency-enhanced power range of the PA was extended by 9 dB at the maximum power level. Compared with a conventional class-AB PA, the idle current was reduced from 55 mA to 25 mA, and the PAE was greatly improved over the whole output power range. In particular, the PAE at 19 dBm was increased from 11.5% to 25.1%. Accordingly, the average currents of the proposed PA were as low as 36.6 mA and 57.4 mA in urban and suburban environments, respectively, which means 51% and 41% reductions in urban and suburban environments, respectively. To improve the linearity in the operating power range of the peak amplifier, a simple shunt BC diode was added as a predistorter in the PA, and the ACLR was thus improved by 4.2 dB at P_{out} = 23 dBm of the worst linearity, resulting in an ACLR better than −42 dBc over the whole operating power range. For these reasons, the proposed series-type Doherty amplifier is a promising solution for modern multimedia handsets that require high efficiency, high linearity and compact size.

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