Ultra-small Form-Factor Helix on Pad-Type Stage-Bypass WCDMA Tx Power Amplifier Using a Chip-Stacking Technique and a Multilayer Substrate

Changhyun Yoo and Junghyun Kim

A fully integrated small form-factor HBT power amplifier (PA) was developed for UMTS Tx applications. For practical use, the PA was implemented with a well configured bottom dimension, and a CMOS control IC was added to enable/disable the HBT PA. By using helix-on-pad integrated passive device output matching, a chip-stacking technique in the assembly of the CMOS IC, and embedding of the bulky inductive lines in a multilayer substrate, the module size was greatly reduced to 2 mm × 2.2 mm. A stage-bypass technique was used to enhance the efficiency of the PA. The PA showed a low idle current of about 20 mA and a PAE of about15% at an output power of 16 dBm, while showing good linearity over the entire operating power range.

Keywords: Chip-stacking, efficiency, HoP-iPD, multilayer substrate, small form-factor, stage-bypass PA.

I. Introduction

As mobile phones become smaller and lighter, the single-band Tx power amplifier (PA) module has been miniaturized to 3 mm × 3 mm by using advanced assembly techniques such as chip-embedding [1]. However, bulky matching networks have hampered further reductions in module size. Moreover, to ensure control logic compatibility between the baseband chipset and the PA, the use of an additional control IC has been necessary to implement the PA module, which has been another obstacle to reducing the size of the PA module.

To reduce the area of the output matching network (OMN), which occupies the largest area inside a PA module, we recently proposed a new type of OMN [2], [3]. It consists of a helix-on-pad (HoP) and an integrated passive device (iPD). These replace bulky transmission lines and lumped surface mountable chip elements, respectively, in a conventional OMN as shown in Fig. 1. However, because the work in [2] and [3] was focused on introducing the idea of a HoP-iPD OMN, there was no consideration for practical use, such as a control IC and the commercial bottom dimension.

In this study, fully integrated 2 mm × 2.2 mm PA modules using the HoP-iPD OMN are proposed for UMTS applications. For practical use, the PAs included control ICs implemented using a chip-stacking technique with well-configured bottom pads. In addition, the bulky inductive lines were mostly integrated into a multilayer substrate. To increase the battery

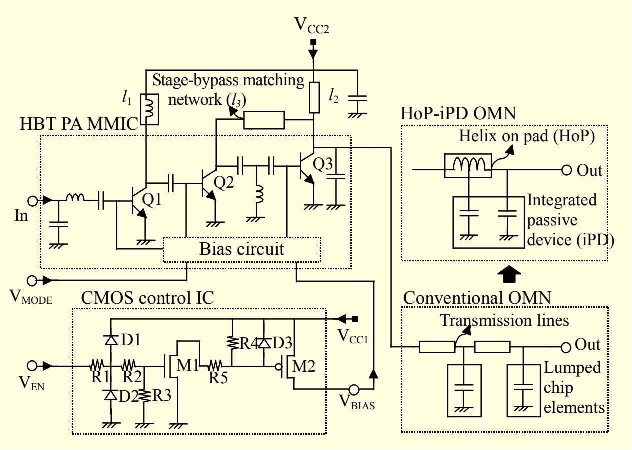

Fig. 1. Circuit diagram of the proposed 2 mm × 2.2 mm PA module.

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life [4], [5], our stage-bypass technique was used to implement the PAs [5]. A diagram of the entire circuit is shown in Fig. 1.

II. Circuit Description and Fabrication

The HBT PA MMIC shown in Fig. 1 is composed of 3-stage amplifiers. The main stage (Q3) is bypassed via a stage-bypass matching network during low-power operation in order to minimize the average current consumption [5]. It was fabricated using a 2 μm InGaP/GaAs HBT process with a size of 1.09 mm × 1.1 mm, in which the emitter areas of the driver (Q2) and Q3 are 1,440 μm^2 and 5,760 μm^2, respectively.

The HoP in the OMN consists of solenoid-type wires with a height of 1.5 mm and a diameter of about 30 μm (1.2 mil) on a substrate. The measured results show that it incurred almost the same loss as a typical transmission line over the whole band-5 frequency range (less than 0.07 dB difference) [3]. The on-chip iPD was fabricated using a low-loss Si_3N_4 dielectric (ε_r of about 6.8 and $\tan\delta = 0.001$) on the same GaAs process with the HBT PA MMIC to replace the capacitors in the OMN. In addition, by using a 5-layer substrate (ε_r of about 4.7, $\tan\delta = 0.018$, and dielectric thickness = 310 μm), bulky inductive lines (l_1, l_2, and l_3) for the bias feeding and the stage-bypass network were fully integrated into the inner layers of the substrates for further reduction of the module size.

The CMOS control IC was designed to be compatible with a logic signal (V_{EN}) of a baseband chipset which plays a role in enabling (or disabling) the HBT PA MMIC. It was fabricated using a 0.5 μm CMOS process with a size of 0.45 mm × 0.54 mm. As V_{EN} is high (above 1.3 V), M1 and M2 are both activated, and the feeding voltage (V_{BIAS}) can thus enable the PA. When V_{EN} is low (0.5 V and lower), the opposite is true. Diodes, D1 to D3, and resistors, R1 to R5, are used for ESD protection and voltage distribution, respectively. Photographs of the fabricated HBT PA MMIC and CMOS control IC are shown in Fig. 2.

Figure 3 shows the PA module scope. Note that in Fig. 3(a), the CMOS control IC was stacked on the HBT PA MMIC using a commercial non-conducting epoxy (Ablestik 2025Dsi) without any extra area occupation. Since the CMOS control IC was back-ground to 150 μm, the module was able to be implemented with a height of 0.62 mm except for the bonding wire loop and mold cavity. In addition, the bottom of the module was well configured with typical dimensions of 350 μm pad size and 550 μm pitch for commercial use as shown in Fig. 3(b). Note that in Fig. 3(b), a module length of 2.2 mm is the minimum requirement when taking eight pins of the PA (RF_{IN}, RF_{OUT}, V_{CC1}, V_{CC2}, V_{EN}, V_{MODE}, and two GNDs) into consideration.

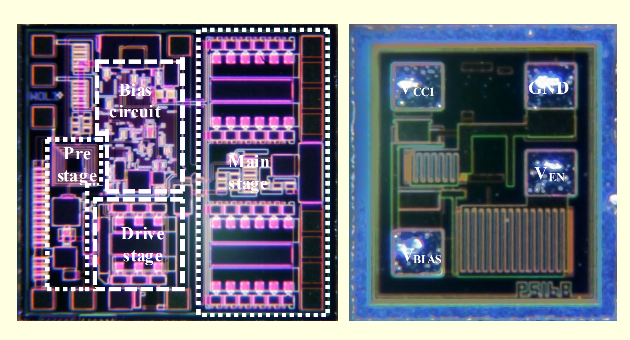

Fig. 2. Photographs of (a) HBT PA MMIC and (b) CMOS control IC.

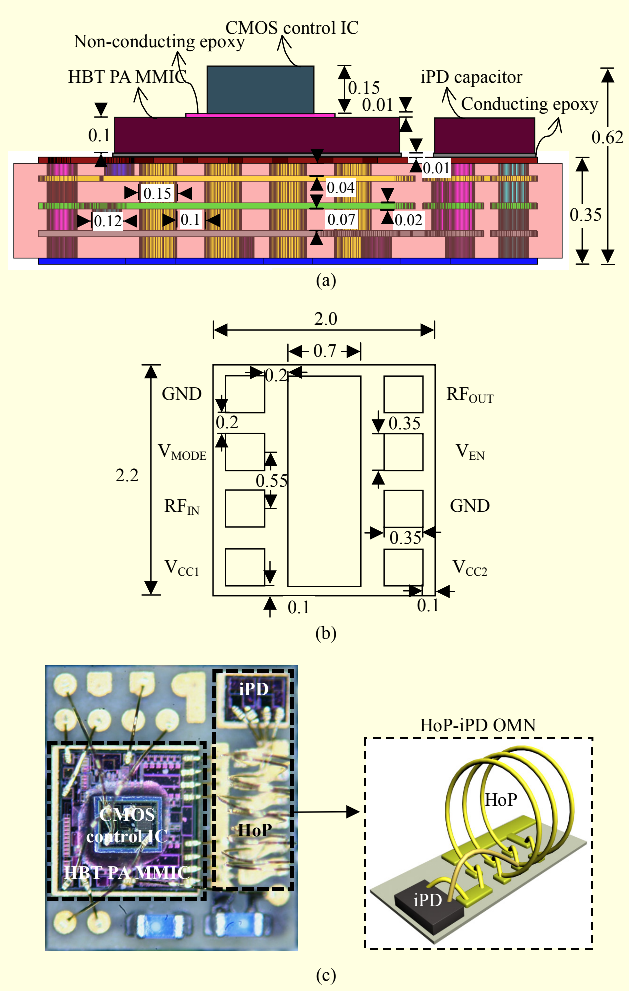

Fig. 3. Fabricated PA module: (a) side view, (b) bottom dimension, and (c) top view.

III. Measurement

A 2 mm × 2.2 mm UMTS band-5 stage-bypass PA was developed to demonstrate the validity of the proposed circuit. The top view of the fabricated module is shown in Fig. 3(c).

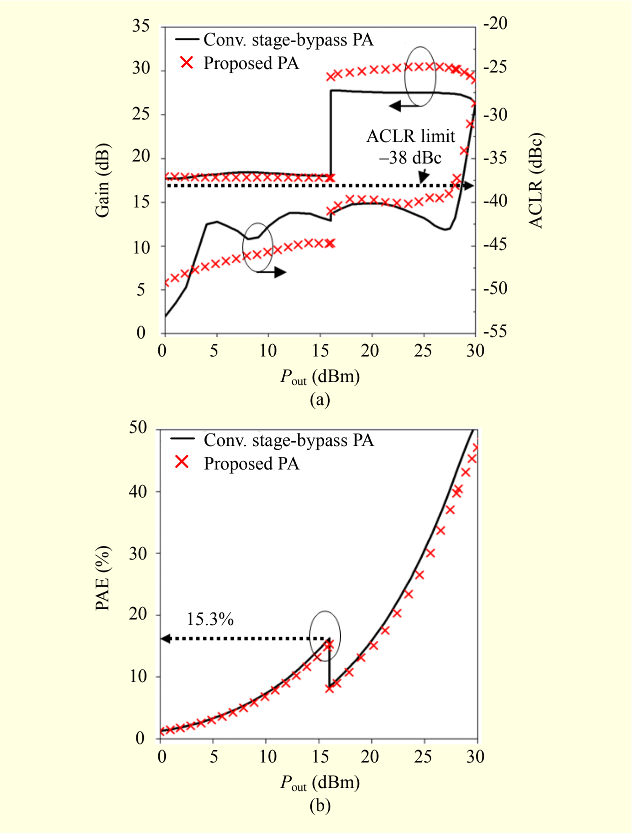

Fig. 4. Measured results of the proposed 2 mm × 2.2 mm band-5 PA: (a) gain, ACLR, and (b) PAE.

Table 1. Measured results of the proposed 2 mm×2.2 mm PAs and the conventional stage-bypass PAs at UMTS high bands (band-1 and band-2).

	Proposed PAs (2 mm × 2.2 mm)				Conventional PAs (3 mm × 3 mm)			
	band-1*		band-2*		band-1*		band-2*	
P_{out} (dBm)	16	28	16	28.5	16	28	16	28.5
Gain (dB)	19.9	28.1	19.9	28.1	18.8	28.1	18.8	29.2
PAE (%)	15.2	39.4	16.1	40.5	17.3	40.7	19.1	41.6
ACLR (dBc)	−50.9	−38.1	−52	−38.7	−53.3	−38.3	−54.3	−41.1

* PAs were measured at their center frequencies.

For comparison, a 3 mm × 3 mm conventional stage-bypass PA was additionally fabricated for band-5 application. For the measurement, a 3GPP uplink WCDMA signal was used with a 3.5 V supply voltage at the Tx center frequency (836.5 MHz). Figure 4 shows the measured gain, power-added efficiency (PAE), and adjacent channel leakage ratio (ACLR) at the 5 MHz offset. Linear gains of 18 dB and 28 dB were achieved at low- and high-power operation, respectively. The use of the stage-bypass technique allowed a very low idle current of 22 mA and an excellent PAE of 15.3% at an output power (P_{out}) of 16 dBm. At the maximum P_{out} of 28 dBm, a PAE of 40% was achieved. ACLR was better than −38 dBc over the whole power range. Thus, the RF characteristics of the proposed PA are very close to those of the conventional PA as seen in Fig. 4.

To demonstrate the general usefulness of the proposed PA, band-1 (Tx frequency: 1,920 MHz to 1,980 MHz) and band-2 (Tx frequency: 1,850 MHz to 1,910 MHz) UMTS PA modules were additionally fabricated, which were also compared with 3 mm × 3 mm conventional ones. The measured results are summarized in Table 1, and the proposed PA results show excellent agreement with those of the conventional ones, thus validating the general usefulness of the proposed design.

IV. Conclusion

Fully integrated stage-bypass UMTS PA modules of 2 mm × 2.2 mm size were developed for band-1, 2, and 5 Tx applications. To minimize the module size, the OMN was implemented using HoP-iPD, and the bulky inductive lines were mostly embedded in a multilayer substrate. For practical use, a CMOS control IC was added to the PA module and was implemented using the chip-stacking technique to eliminate additional area occupation. The bottom of the PA module was well configured to be compatible with the commercial pin-pad dimensions. As a result of the stage-bypass technique, the PAs showed low idle currents of about 20 mA and PAEs of about 15% at P_{out}=16 dBm, while achieving an ACLR of better than −38 dBc over the entire output power range. The proposed approach can also be applied to other types of wireless applications requiring compact size and high efficiency.

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