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A 0.9-3.0 GHz Fully Integrated Tunable CMOS Power Amplifier for Multi-Band Transmitters

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Abstract—**A tunable power amplifier (PA) from 0.9 GHz to 3.0 GHz is presented. This paper proposes an output impedance tuning method by using resistive feedback and a parallel resonance consisting of an inductor and a tunable capacitor array. The proposed multi-band PA can adjust the output impedance to 50 Ω over a wide frequency range, so external isolators following PAs can be eliminated. The PA is implemented by using a 0.18 μm CMOS process, and the supply voltage is 3.3 V. Over all of the frequency range, the PA realizes output return loss S_{22} of smaller than -10 dB, power gain of larger than 16 dB, output 1-dB compression point of larger than 17 dBm, and power added efficiency (PAE) at 1-dB compression point of larger than 10 %.**

I. Introduction

Recently, CMOS PAs have been gathering attention due to its low cost and high integration capability. A single-chip transceiver integrating all functional blocks for wireless communication is expected, especially for cellular applications. An integrated CMOS PA is also required for such transceivers. In addition, an integrated multi-standard RF front-end is also required to realize a small competitive mobile terminal covering GSM, UMTS, LTE, WiMax, WLAN, Bluetooth, GPS, DTV, *etc*.

Fig. 1(a) shows an example of a conventional multi-standard transceiver, consisting of multiple antennas, duplexers, isolators, and PAs for each frequency band. In general, the output impedance of PAs is not matched to 50 Ω to derive maximum output power and obtain maximum efficiency. Isolators are often employed to stabilize operating condition of PAs due to the impedance variation caused by the antenna reflection. The isolators also contribute to make a filter and an antenna work as expected. However, the isolator is a large and costly discrete component, so the use of isolators is not desired to realize small handsets. Moreover, the isolators have a narrow bandwidth, so several isolators for each frequency band are required for multi-standard RF front-ends as shown in Fig. 1(a). Thus, the use of isolators might become a more serious disadvantage in multi-standard RF front-ends. Even if a multi-band PA is realized, the isolators cannot be eliminated due to the output reflection. One of the ways to eliminate isolators in a multi-standard RF front-end is to use a multi-band PA achieving tunable- or wideband-impedance matching. At least, output reflection S_{22} should be less than -10 dB over the required frequency range to realize an isolator-less front-end.

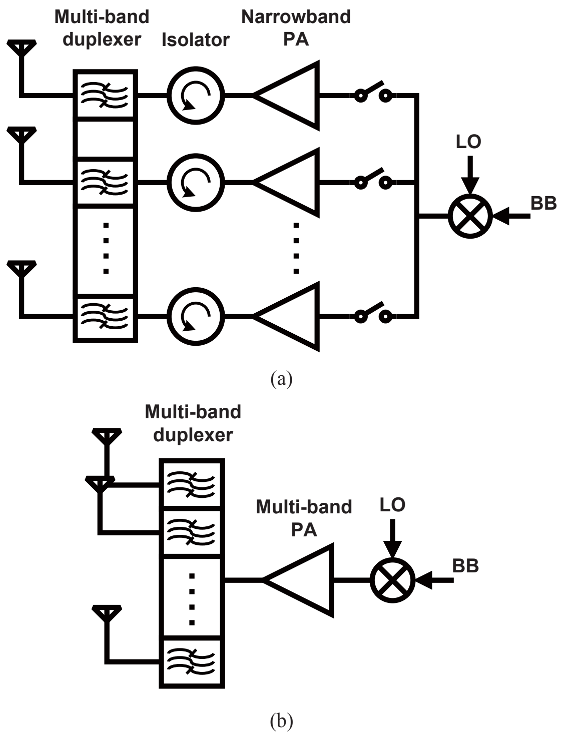

Fig. 1. (a) A conventional multi-band transmitter. (b) The proposed multi-band transmitter.

Fig. 1(b) shows our target architecture for multi-band transmitters, which consists of multiple/multi-band antenna, a multi-band duplexer, and a multi-band PA. Only one multi-band PA with tunable output impedance over wide frequency range covers multiple standards, and the PA does not need any external isolator due to the tunable impedance matching. From the viewpoint of suppression of harmonics and sidebands, the narrow-band LC-matching is better than wideband impedance matching. Thus, the proposed PA employs tunable LC-matching.

A PA utilizing a polyphase multipath technique is proposed to eliminate external filters [1], which can suppress harmonics and sidebands well. Even though it is desirable feature for multi-band transmitters, adequate output power has

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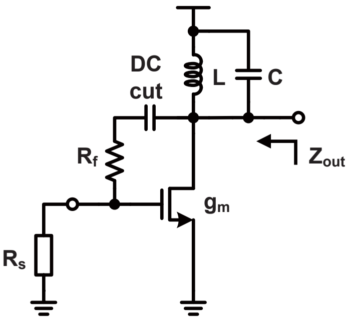

Fig. 2. A resistive feedback amplifier with parallel resonator.

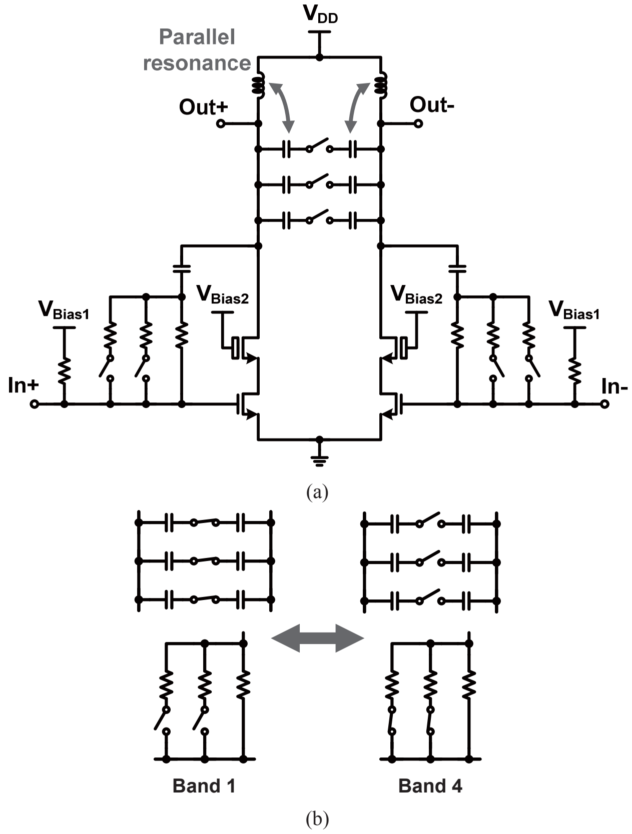

Fig. 3. (a) Schematic of the tunable power amplifier. (b) State of the switches.

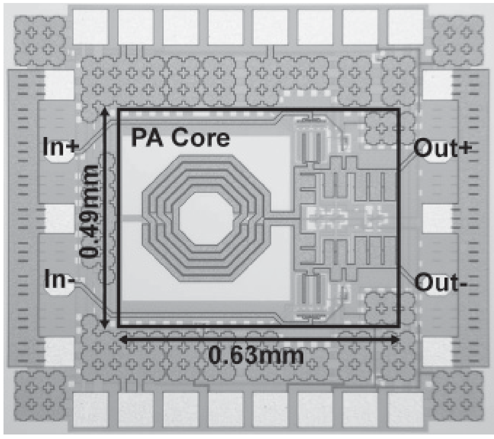

Fig. 4. Chip micrograph.

not been achieved yet. Pre-power amplifiers achieving very wideband output matching are reported in [2, 3]. However, these approaches need external PAs for each standard. Wideband PAs utilizing distributed amplification are presented in [4-6]. However, the output powers are not sufficient for the multi-band use, and the distributed amplifiers usually need large layout area. An output power of more than 30 dBm over a wide frequency range is demonstrated by utilizing a high coupling coefficient on-chip transformer [7], and high PAE is realized by using multiple power mixers. However, wideband output matching is not considered, and external isolators are still expected to be used.

In this paper, a tunable PA utilizing resistive feedback and parallel resonance is proposed. The parallel resonance consists of a differential on-chip inductor and a tunable capacitor array. This technique can tune output matching bands over a wide frequency range and deliver large output power with adequate linearity. Comparing with other circuits, the proposed circuit has wider frequency range and smaller layout area with better output impedance matching.

II. TUNABLE POWER AMPLIFIER

A resistive feedback amplifier is commonly used as a broadband low noise amplifier because the input impedance is a function of the feedback resistance, which can be adjusted to 50 Ω over a wide frequency range [8]. This technique can also be applied to the output impedance matching. Fig. 2 shows a resistive-feedback common-source amplifier. If the drain impedance of the transistor is large enough, the output impedance Z_{out} is expressed by

$$Z_{out} = \frac{R_f + R_s}{g_m R_s + 1} // \frac{1}{j\omega C} // (R_L + j\omega L), \tag{1}$$

where R_s is the output impedance of the previous stage, and R_L is the parasitic resistance of the inductor. At the resonance frequency $f_o = 1/2\pi\sqrt{LC}$, the imaginary part of Eq.(1) is cancelled, and the following equations are derived.

$$Z_{out} = \frac{R_f + R_s}{g_m R_s + 1} // R_p, \tag{2}$$

$$R_p = \frac{L}{CR_L}, \tag{3}$$

where R_P is the resonance impedance of the LC-resonator. The resonance frequency can be tuned by varying L and C. In this case, a MIM capacitor array is employed to change the resonance frequency. R_P is a function of capacitance, and the skin effect of the resistor also has influence. Thus, the feedback-resistance R_f also has to be tuned to compensate the output impedance depending on the frequency. The impedance

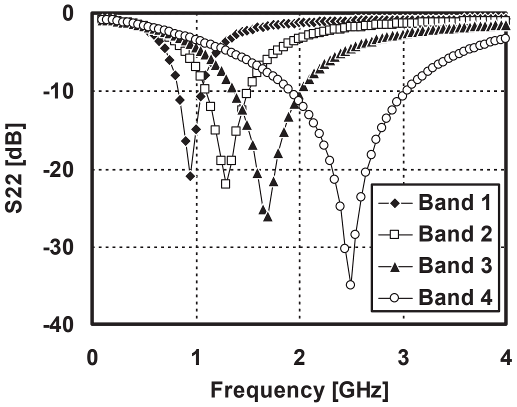

Fig. 5. Measured S_{22}.

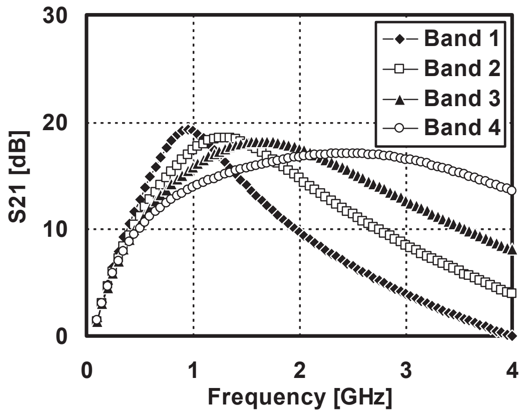

Fig. 6. Measured S_{21}.

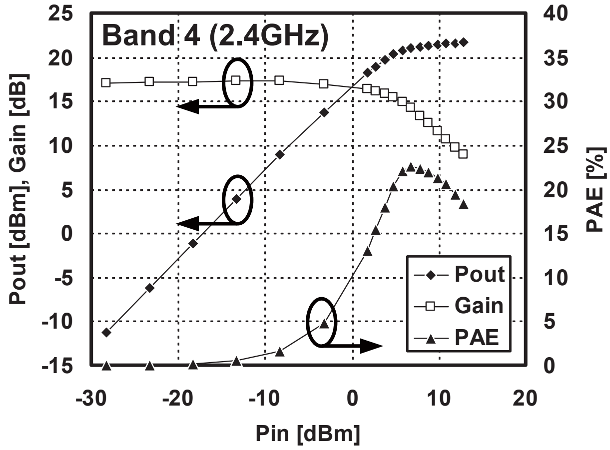

Fig. 7. Measured output power, gain, and power added efficiency versus input power at band 4 (2.4GHz).

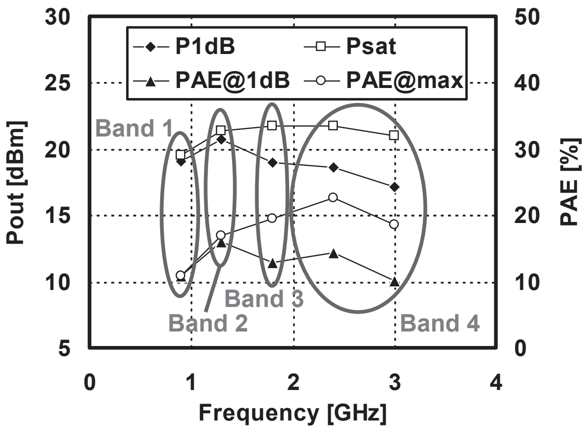

Fig. 8. Measured output 1-dB compression point, saturated output power, PAE at 1-dB compression point, and maximum PAE versus frequency.

transformation using a transformer can also be applied to the proposed PA to obtain larger output power under the class-A operation. In the equivalent circuit shown in Fig.2, the drain-source conductance is neglected, which degrades the relationship described in Eqs.(1)-(3). The size of the transistor is determined to obtain larger g_m, and the output conductance is usually large. Thus, a cascode topology is employed to obtain smaller output conductance of the transistor. Therefore, Z_{out} can be matched to 50 Ω at an arbitrary frequency by adjusting feedback resistance R_f and capacitance C.

Fig. 3(a) shows the schematic of the proposed PA. A differential topology is employed to deliver larger output power, which also contributes to neglect parasitic impedance on common-mode nodes. To sustain voltage stress, a thick gate-oxide transistor is used for the common-gate stage. A supply voltage of 3.3V is used to increase voltage swing at the output nodes. The switches in the capacitor array are also implemented by thick gate-oxide transistors because of the same reason.

The feedback resistance R_f is tuned depending on the switching state. There are some reasons for this. Firstly, the quality factor of the LC resonator depends on frequency and influence of the output impedance. Secondly, DC-cut capacitances in Fig. 2 cannot be very large because the parasitic capacitance of the output node determines the maximum resonance frequency. Thus, R_f has to be adjusted according to the frequency. The matching frequency can be switched from band 1 to band 4 in this case. The states of the switches are shown in Fig. 3(b). By increasing the number of switches, finer frequency tuning can be realized. In addition to output matching tuning, the resistive feedback topology has an advantage in enhancing the stability of the circuit.

III. MESUREMENT RESULTS

The proposed PA was designed and fabricated by using a 0.18 μm CMOS process. Fig. 4 shows the chip micrograph, and core size is 0.63×0.49 mm^2. The chip was measured by using RF probes with external DC blocks at input and output nodes.

Figs. 5 and 6 show the measured S_{22} and S_{21} of each frequency band, which are differential-mode S-parameters

TABLE I. PERFORMANCE COMPARISON

		Technology	V_{DD} [V]	Frequency [GHz]	P_{1dB} [dBm]	P_{sat} [dBm]	Max PAE [%]	Area [mm^2]	S22 [dB]	Output matching	Topology
Pre-PA	[2]	0.18μm CMOS	1.8	0.1 ~ 5.8	-1.0 ~ 2.4	4.4 ~ 1.0	—	0.31 (w/o pads)	< -11	Wideband	Feedback
	[3]	0.13μm CMOS	1.2	0.2 ~ 6.3	4.0 ~ 5.4	—	—	1.12 (w/ MIX, LPF)	< -9.5	Wideband	Source follower
Multi-band PA	[4]	0.13μm CMOS	2.0	2.0 ~ 8.0	3.5	7 ~ 10	2 @1dB	—	< -5	Wideband	Distributed
	[5]	0.13μm CMOS	1.5	0.5 ~ 5.0	10 ~ 17	14 ~ 21	3 ~ 16 (drain eff.)	3.6 (w/ pads)	< -6	Wideband	Distributed + Transformer
	[6]	0.18μm CMOS	2.8	3.7 ~ 8.8	14 ~ 16	16 ~ 19	8 ~ 25	2.8 (w/ pads)	< -8	Wideband	Distributed
	[7]	0.13μm CMOS	3.0	1.0 ~ 2.5	—	28 ~ 31	18 ~ 43	2.56 (w/ distributor)	—	Wideband	Power mixer + Transformer
	This work	0.18μm CMOS	3.3	0.9 ~ 3.0	17 ~ 21	20 ~ 21	11~ 23	0.31 (w/o pads)	< -10	**Tunable**	Feedback

calculated from measured 4-port S-parameters. The output matching frequency is shifted according to switching bands. From 0.9 GHz to 3.0 GHz, S_{22} keeps lower than -10 dB and S_{21} is larger than 16 dB.

Fig. 7 shows output power, power gain, and power added efficiency (PAE) versus input power at band 4 of 2.4 GHz signal frequency. To obtain a differential signal from a single-ended one, external 180 degree hybrid couplers were used at the input and output of the PA. Losses of cables, probes and hybrid coupler are carefully calibrated. The saturated output power is 21.7 dBm, the output 1-dB compression point is 18.6 dBm with 14 % of the PAE, the small signal gain is 17.0 dB, and the maximum PAE is 23 %.

The output power and PAE at other bands with different signal frequency was measured with the same method. Fig. 8 shows the saturated output power, the output 1-dB compression point, the PAE at 1-dB compression point, and the maximum PAE versus frequency. The output 1-dB compression point is larger than 17 dBm, and the PAE is larger than 10 % at 1-dB compression point over all the frequency range.

Table I summarizes state-of-the-art results of multi-band pre-PAs and PAs using CMOS technology. The proposed circuit demonstrates good output power with a small area, and the output matching S_{22} can be kept lower than -10 dB by using the proposed tunable matching mechanism.

IV. CONCLUSION

In this paper, a CMOS PA with the tunable output impedance matching over a wide frequency range is proposed for multi-band transmitters. A prototype was fabricated in a 0.18 μm CMOS process. Utilizing resistive feedback and parallel resonator with an inductor and a tunable capacitor array, the PA achieves wide-tunable output impedance matching from 0.9 GHz to 3.0 GHz. With a 3.3 V voltage supply, the PA realizes output 1-dB compression point of larger than 17 dBm with the PAE of over 10 %. Although the output power is not enough to use for cellular applications, the proposed PA demonstrates the potential to realize multi-band transmitters without isolators.

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