A 3–5 GHz CMOS UWB power amplifier with ±8 ps group delay ripple*

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Abstract: A differential power amplifier (PA), designed using the linear-phase filter model, for a BPSK modulated ultra-wideband (UWB) system operating in the 3–5 GHz frequency range is presented. The proposed PA was fabricated using 0.18 μm SMIC CMOS technology. To achieve sufficient linearity and efficiency, this PA operates in the class-AB region, delivering an output power of 8.5 dBm at an input-1 dB compression point of –0.5 dBm. It consumes 28.8 mW, realizing a flat gain of 9.11 ± 0.39 dB and a very low group delay ripple of ±8 ps across the whole band of operation.

Key words: PA; UWB; group delay; linearity
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1. Introduction

For wireless personal area network (WPAN) applications, ultra-wideband (UWB) is the best solution since it offers a wider bandwidth and higher data transferring rates compared to its Bluetooth counterpart[1].

The power amplifier (PA) circuit of the transceiver for the UWB system faces a challenging task since it must be able to support wide bandwidth and sufficient linearity, while consuming very low power and small chip size. Especially in BPSK modulated UWB systems, phase dispersion is also a strict specification. Though expensive technologies like SiGe or GaAs are very suitable for wideband PAs, the ultimate goal is to have a low-cost UWB SOC solution which can only be achieved by using CMOS technology.

This paper presents the design and implementation of a differential linear phase filter model power amplifier. The PA is preceded by a differential-output mixer, and the high performance wideband on-chip balun is not suitable for CMOS technology, so differential PAs are always used in practice in UWB systems. We also describe the complete design methodology of the UWB power amplifier, and give details of the chip implementation and measurement results.

2. Circuit design and analysis

Due to the requirement of the BPSK modulated UWB transmitter (shown in Fig. 1), the power amplifier should have a flat power gain above 8 dB, with a relatively large 1 dB input compression point, also for the consideration of power losses of the antenna and power backoff to achieve better IP3 or ACPR[5]. Additionally, the phase dispersion should be as low as possible. The die area consumption is also a key factor in topology selection, especially in some RF blocks, where on-chip inductors consume large areas. So, the two-stage PA topology is not suitable for its worse linearity and larger die area compared with a single-stage PA topology. Also, the single-stage PA can also achieve about 10 dB power gain in 3–5 GHz.

This PA is preceded by an up-conversion mixer, the outputs of which are differential because of the inherent advantages of differential topologies like good isolation and noise immunity. Therefore the PA has to be differential. Moreover, differential PAs have a much lower impact from the parasitic effect of packaging and bonding-wire, and less interference with other circuits, especially the oscillator[2].

The proposed differential single stage UWB power amplifier is shown in Fig. 2. It mainly adopts wideband filter theory, cascade topology, and a shunt feedback network to obtain flat

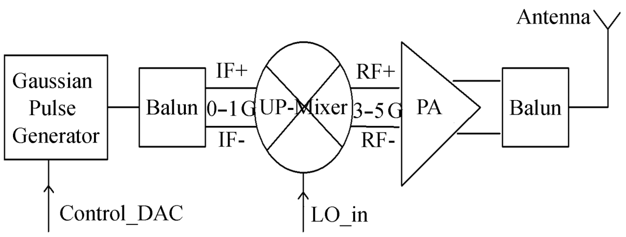

Fig. 1. Function blocks of the UWB transmitter.

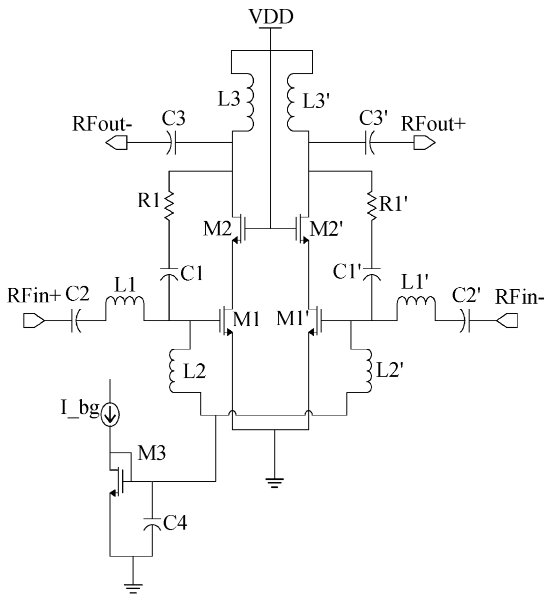

Fig. 2. Proposed UWB power amplifier.

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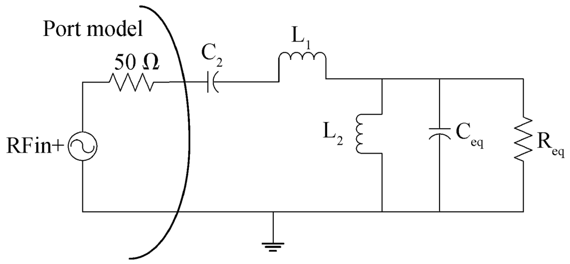

Fig. 3. Linear phase filter network.

power gain with wideband match, low group delay, and sufficient stability.

There are mainly three kinds of wideband matching techniques. Distributed amplifiers[6] are quite common for broadband circuit realizations. Though good linearity and matching can be achieved over a wide band of frequencies, these circuits consume much power and large die areas. So, these circuits are not suitable for low cost UWB chips.

2.1. Bandpass linear phase filter network

Typical narrowband applications use LC based networks to achieve matching at a particular frequency by exploiting the fact that the impedance of the network is resistive at the resonant frequency. Using filter theory, this approach can be extended for wideband matching conditions[3]. For the strict requirement for phase dispersion and a trade off between performance and die area, this PA utilizes the second order bandpass linear-phase filter model, which has a greater flat phase response than Chebyshev and Butterworth filters. Due to the frequency spectrum of the Gaussian pulse, our transmitter does not need strict stopband characteristics. So, the linear-phase filter's stopband performance can also meet the demands of our system. The phase characteristics of the linear phase filter are given by[4]

$$\phi(w) = Aw\left[1 + p\left(\frac{w}{w_{\mathrm{c}}}\right)^{2N}\right], \tag{1}$$

where $\phi(w)$ is the phase of the filter's voltage transfer function, and p is a constant. The phase dispersion within the signal bandwidth can be indicated by the group delay, given by[4]

$$\tau_{\mathrm{d}} = \frac{\mathrm{d}\phi}{\mathrm{dw}} = A\left[1 + p(2N+1)\left(\frac{w}{w_{\mathrm{c}}}\right)^{2N}\right]. \tag{2}$$

The 3–5 G bandpass linear phase filter, shown in Fig. 3, contains C_2, L_1, L_2 and C_{eq}, whose value is equal to the sum of parasitic capacitances between the gate of M1 and AC ground, and R_{eq} is the equivalent resistance value seen from the gate of M1.

In common source PAs, the input MOSFETs, like M1, always have large W/L to achieve sufficient linearity and power gain. So, the MOSFETs have correspondingly large parasitic capacitances, especially C_{gs} and C_{gd}. C_{gs} and C_{gd} seriously influence the value and flatness of the wideband RF PA's power gain. Meanwhile, the large parasitic capacitances have different impedances at different frequencies, causing relatively large phase dispersion. In this PA, the bandpass filter network absorbs C_{gs} of M1, eliminating its bad influence to the amplifier completely. Additionally, it does not bring additional phase dispersion due to its flat phase response. So, this PA can achieve much smaller phase dispersion.

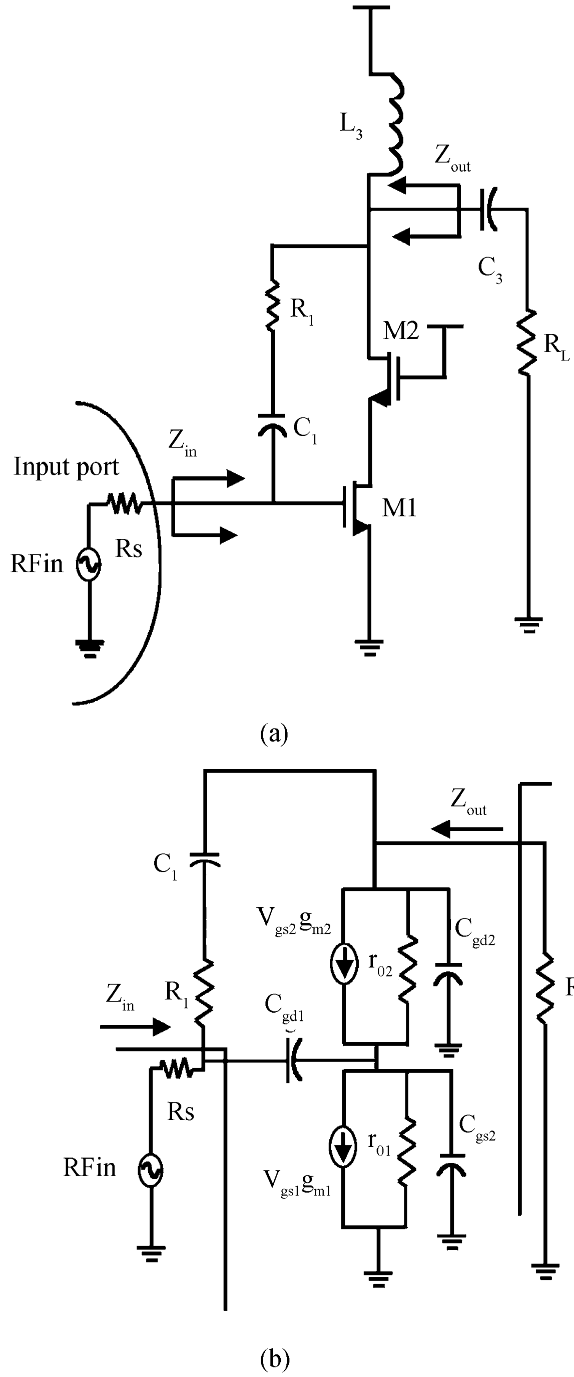

Fig. 4. (a) Simplified PA topology with resistive feedback network. (b) Small signal model of (a).

2.2. Cascode topology

By providing isolation between the drain of M1 and output ports with the common-gate stage M2, the proposed PA eliminates the potential of instability and the Miller effect from the common-source amplifier M1, thus allowing the realization of larger gain-bandwidth products[5].

Table 1. Summary and comparison of UWB PA performances.

Reference (Measurement)	CMOS technology (nm)	Frequency (GHz)	Gain (dB)	OP_{1dB} (dBm)	Power consumed (mW)	Avg. PAE (%) (@ OP_{1dB})	Group delay (ps)	Size (mm^2)
Ref. [6] (diff.)	180	3.1–4.8	19 ± 1	–4.2	25 @ 1.8 V	1.5 @ 4 GHz*	N/A	1.9 × 1.1
Ref. [7] (single)	180	3–5	17.5–21	2.57 @ 3 GHz 0.42 @ 4 GHz	N/A	5.8 @ 3 GHz 3.9 @ 4 GHz	N/A	1.57 × 0.97
Ref. [8] (single)	180	3–10	10.4 ± 0.8	8 @ 3–10 GHz*	84 @ 2 V	6.8 @ 3–10 GHz	> 300	2.32 × 0.76
Ref. [9] (single)	180	3.1–10.6	∼ 9	0 @ 3.1–10.6 GHz	25.2 @ 1.8 V	3.3 @ 3–10 GHz*	N/A	1.1 × 1
Ref. [10] (single)	180	6–10	8.5	5 @ 6–10 GHz	18 @ 1.5 V	14.4 @ 6–10 GHz	N/A	0.82 × 1.32
This work (single mode)	180	3–5	9.1 ± 0.4	5.45 @ 4 GHz	14.4 @ 1.8 V	21 @ 3–5 GHz	15.6	0.67 × 0.63
This work (diff.)	180	3–5	9.1 ± 0.4	8.46 @ 4 GHz	28.8 @ 1.8 V	21 @ 3–5 GHz	15.6	1.33 × 0.63

*Estimated values

2.3. Shunt feedback technique

Most class A/B PAs adopt passive impedance transformers to provide larger output power, given by

$$P_{\max} = \frac{V_{DD}^2}{2R'}, \tag{3}$$

where R' is the equivalent resistance value transformed from 50 Ω. However, with a 1.8 V supply, and 50 Ω load, the maximum output power that can be achieved is 15 dBm, already efficient for our UWB transmitter. So, there is no need for a passive impedance transformer in the output part, which thus saves area.

The proposed PA adopts a resistive shunt feedback network to achieve the proper input and output impedance. The feedback network is shown in Fig. 4. Because M1's C_{gs} is absorbed into the linear phase filter and the impedance of L_3 is much larger than R_L in 3–5 GHz, the small signal model does not include them.

For this configuration and under this PA's condition (7), the input and output impedance and the gain can be calculated to be about

$$Z_{in} \approx \frac{R_1}{1 + g_{m1} R_L}, \tag{4}$$

$$Z_{out} \approx \frac{R_s + R_1}{1 + g_{m1} R_s}, \tag{5}$$

$$A_v \approx g_{m1} R_L \frac{r_o g_{m2} + 1}{r_o g_{m2} + 2 + R_L / r_o}, \tag{6}$$

$$R_s = R_L \ll R_1, r_o = r_{o1} \approx r_{o2} \ll R_1,$$

$$\frac{1}{wC_{gd1,2}} > \frac{1}{wC_{gs2}} \gg r_o, \quad \frac{1}{wC_{gs1}} \ll R_1,$$

$$w \in (2\pi \times 3G, 2\pi \times 5G). \tag{7}$$

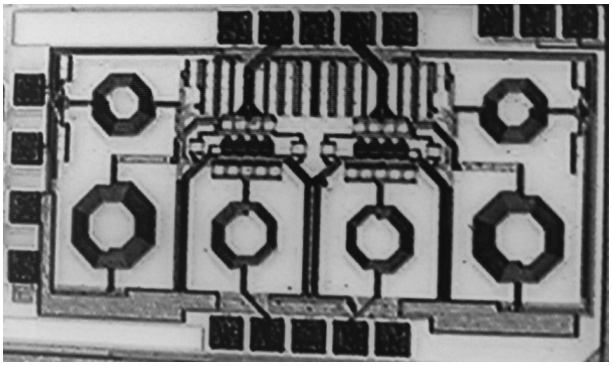

Fig. 5. Die photograph of the UWB power amplifier.

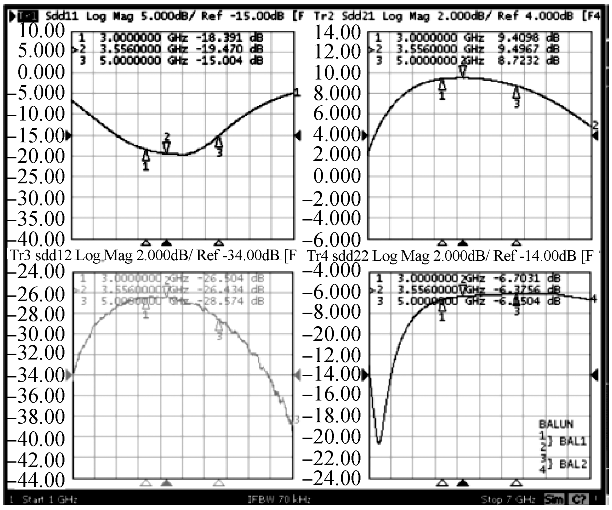

Fig. 6. Measured S-parameter of the PA.

3. Measurement results

The proposed UWB power amplifier has been fabricated in 180 nm SMIC COMS technology. The chip size is 1.33 × 0.63 mm^2. A die photograph is shown in Fig. 5.

Measurements were carried out on wafer with a Cascade probe station and GSGSG RF probes. The supply voltage is

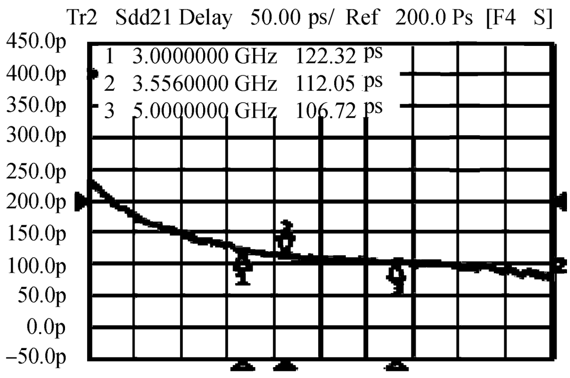

Fig. 7. Measured group delay of the amplifier.

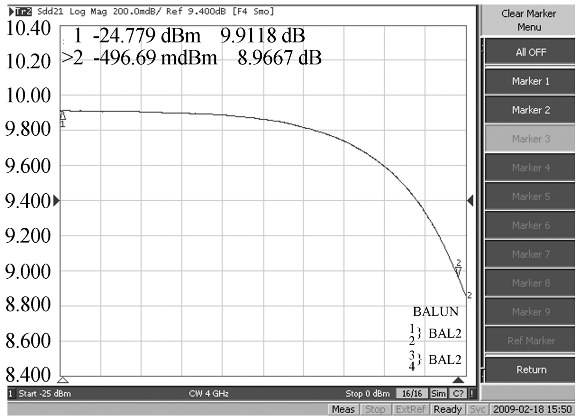

Fig. 8. Measured larger-signal transfer characteristics of the amplifier at 4 GHz.

1.8 V, and the current consumption is 16 mA. The measured S-parameters are shown in Fig. 6. The input return loss is less than –15 dB. The transmission gain can achieve 9.49 dB, and the ripple in 3–5 G is within ±0.4 dB.

Phase dispersion is an important specification for UWB systems, and it can be indicated by group delay. As shown in Fig. 7, the group delay ripple is within ±8 ps, about ±11.52° phase dispersion for a 4 GHz signal.

The linearity characterization was conducted with 1db compression point measurements. Figure 8 shows that the measured output 1 dB compression point is 8.46 dBm at 4 GHz, where the PAE (power-added efficiency) is 23%. The measured output 1 dB compression points are 8.41 dBm at 3 GHz with a PAE of 22%, and 7.60 dBm at 5 GHz with a PAE of 19%.

Because our PA is single-stage, and has a larger output power, which is closer to $V_{DD}^2/2R$ ($V_{DD} = 1.8$ V, $R = 50\ \Omega$) than other UWB PAs, it has a greater PAE.

The characteristics of the PA, accompanied by those of other wideband PAs, are summarized in Table 1. Although wideband PAs used in actual UWB systems are differential mode, the characteristic of this PA's single mode is presented only for comparison, since most of the other PAs listed are single mode.

4. Conclusion

We have presented the design and implementation of a 3–5 GHz CMOS power amplifier in SMIC 180 nm technology. The measured small-signal gain flatness is between 8.72 dB and 9.49 dB. The output P_{1dB} is above 7.6 dBm and PAE is above 19%. The amplifier achieves the lowest group delay ripple within ±8 ps among the reported wideband amplifiers. It has been verified in our UWB transmitter.

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