A wideband high efficiency V-band 65 nm CMOS power amplifier with neutralization and harmonic controlling

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Abstract: A wideband high-efficiency V-band CMOS power amplifier (PA) is proposed in this paper. Neutralization technique is used to reduce the Miller effect and improve the power gain. A wideband on-chip transformer is used to adjust the transistors’ voltage waveform to improve the PAE performance. The PA works from 51 GHz to 64 GHz with 13 GHz absolute bandwidth and 22.6% relative bandwidth. The output power reaches 14.9 dBm with 16.3% peak PAE. The circuit is designed in a 65 nm CMOS technology.

Keywords: power amplifier, transformer, CMOS

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

With the need for high communication speed in the upcoming 5G communication system, the millimeter-wave (mm-wave) bands are attractive because of the large absolute bandwidth [1, 2]. PA is one of the key components that restrict the performance of mm-wave band transceivers. As PAs usually consume the largest current in the transceivers, the efficiency of PAs is urgently needed to be improved. However, with the frequency increasing, the performance of the transistors drops rapidly as the great impact of the parasitic components. Especially, the Miller effect generates a strong negative feedback and decreases the power gain and PAE performance. In this paper, a V-band PA is proposed with taking into account the above challenges. The neutralization technique is used to compensate the Miller effect and improve the power gain. A compact on-chip transformer with harmonic control is used to adjust the output waveform and improve the PAE performance. As the transformer is less sensitive to wavelength, a wideband matching is achieved. The PA works from 51 GHz to 64 GHz with 13 GHz absolute bandwidth and 22.6% relative bandwidth. The output power achieves 14.9 dBm with 16.3% PAE. The chip is fabricated in 65 nm CMOS technology.
2 Neutralization and harmonic control

2.1 Neutralization

The Miller effect is more serious in the power amplifier because the transistors’ size is usually large to deliver large output power. There is a large negative feedback current ($I_{cgd}$) through the parasitic capacitor ($C_{gd}$) as shown in Fig. 1(a). The feedback current degrades the power gain and PAE. In order to compensate the Miller effect, a positive feedback cross-couple capacitor ($C_{neu}$) is added between the input and in-phase output terminal. A positive feedback current ($I_{neu}$) is formed and neutralize the $I_{cgd}$. The transistors form a unidirectional amplifier and the power gain and stability are improved [3]. The size of the $C_{neu}$ is almost the same as the $C_{gd}$. The Fig. 1(b) shows the variation of the maximum power gain ($G_{max}$) and stability factor ($\mu$) when the $C_{neu}$ changes. When the $I_{neu}$ is equal to $I_{cgd}$, the transistor has the maximum stability factor and a moderate power gain. When the $C_{neu}$ becomes larger, the power gain increases but the $\mu$ decreases.

![Fig. 1. The (a) neutralization structure and the (b) $G_{max}$ and stability factor versus $C_{neu}$.](image)

2.2 Harmonic control

To improve the PAE, the output voltage of the transistors can be adjusted by controlling the harmonic waves [4, 5]. Fig. 2(a) shows the transmission lines based harmonic control network for an inverse Class F PA. Multiple transmission lines are necessary to generate proper impedance at certain harmonic frequencies. Fig. 2(b) shows the network based on L-C resonant units. Parallel/series L-C

![Fig. 2. The harmonic control networks for class F PA. (a) a network based on transmission lines (b) a network based on L-C resonant tanks (c) a network based on a transformer (d) load impedance of the harmonic control network based on a transformer.](image)
resonant tanks are used to generate high/low impedance. Both of the methods need an additional matching network to match the impedance at the fundamental frequency. Fig. 2(c) shows the harmonic control network based on a transformer. The basic principle of the network is using the differential circuit to separate the even and odd harmonic waves. The even harmonic waves are the common mode signals, which have high load impedances at even harmonic frequencies. On the contrary, the odd harmonic waves together with the fundamental signal are the differential modes. The differential mode signal is transferred to the output terminal of the transformer. An L-C resonant tank working at $3f_0$ is set at the output to generate a zero impedance. The resonant unit shows capacitive impedance at the fundamental frequency and acts as a part of the matching network. By adjusting the turns ratio of the transformer, the optimized impedance can be obtained at the fundamental frequency. Therefore, no additional matching network is needed. The impedance variation of the network at different harmonic frequencies is shown in Fig. 2(d). Compared with the above methods, the network based on the transformer occupies smaller area since only one transformer and an L-C resonant unit are used. As the transformer is less sensitive to the wavelength and the function of separating the harmonic waves is independent of frequency, the network is easy to work in the broadband range. Furthermore, the differential structure provides a good virtual ground, which reduces the influence of package.

3 V-band high efficiency CMOS PA

A V-band PA is designed to validate the proposed method [2]. The schematic of the proposed PA is shown in Fig. 3. The input signal is converted to the differential signal by the input balun. To enhance the breakdown voltage and power gain, two stacked transistors are used. The supply voltage doubles so that the output power is enhanced. Cross-coupling capacitors are used to neutralize the feedback capacitor and reduce the Miller effect as stated above.

![Fig. 3. The schematic of the proposed V-band power amplifier.](image)

The output harmonic control network is shown in Fig. 4(a). The transformer separates harmonic waves and converts the differential signal to the single-end signal. The center-tap of the primary coil is connected to the power supply, and the inductance of the supply line further improves the impedance at the even harmonic frequencies in a wide band. An L-C resonate tank works at the 3rd harmonic frequency to generate a low impedance. Straight-line inductor is used to enhance the quality factor [6]. Metal-oxide-metal (MOM) capacitor is used to provide small
capacitance. Proper impedances at different harmonic frequencies are obtained. The PAE with and without harmonic controlling is shown in Fig. 4(b).

Proper radiuses of the coils are designed to make the impedance equal to the optimized impedance from the load-pull simulation. The equivalent circuit of the output matching network is shown in Fig. 5(a) [7, 8]. The L-C resonate unit works as a capacitor ($C_{\text{short}}$) at the fundamental frequency and is parallel with the parasitic capacitor of the pad ($C_{\text{PAD}}$). The equivalent circuit of the transformer is a T-branch circuit. The transformer forms a high order network with a small footprint. The impedance transformation is depicted in the blue line of the Smith chart in the Fig. 5(b). The curves concentrate in the high-bandwidth area compared with L-C network (red line) and no DC blocker or RF chock is needed. Therefore, the PA is able to achieve a wide bandwidth.

![Equivalent circuit](image)

**Fig. 4.** The (a) 3-D view of the output harmonic control network and the (b) PAE comparison with and without harmonic controlling.

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![Equivalent circuit](image)

**Fig. 5.** (a) Equivalent circuit of the output match network and the (b) impedance transformation in the Smith chart.

![Photograph](image)

**Fig. 6.** The (a) die photograph and (b) S-parameter of the PA.
4 Measurement result

The die photo of the V-band PA is shown in Fig. 6(a). The size is $0.6 \times 0.8 \text{mm}^2$ with all of the testing pads. As transformers are used instead of transmission lines and resonant units, the core area of the PA is less $0.07 \text{mm}^2$. The chip is measured on-chip using the G-S-G probe. The measured and simulated S-parameter is shown in Fig. 6(b). The saturating output power of the proposed PA is $14.9 \text{dBm}$ with a $2 \text{V}$ supply. The maximum PAE is $16.3\%$ at $57 \text{GHz}$. The PA works from $51 \text{GHz}$ to $64 \text{GHz}$ with $13 \text{GHz}$ absolute bandwidth and $22.6\%$ relative bandwidth. The power gain, PAE and output power versus input power at $57 \text{GHz}$ is shown in Fig. 7(a). The PAE and output power versus frequency is shown in Fig. 7(b). The comparison with the state-of-the-art $60 \text{GHz}$ PAs is listed in Table I.

5 Conclusion

A wideband harmonic controlling method based on the on-chip transformer is proposed in this paper. A V-band PA is implemented in $65 \text{nm}$ CMOS technology to validate the method. With the harmonic controlling and neutralization, the peak PAE reaches $16.3\%$. The PA works from $51 \text{GHz}$ to $64 \text{GHz}$ with $13 \text{GHz}$ absolute bandwidth and $22.6\%$ relative bandwidth.

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![Fig. 7.](image-url) The large signal performance vs. (a) input power and (b) frequency.

| Gain (dB) | BW_{3dB} (GHz) | P_{sat} (dBm) | PAE (%) | Stage | Size (mm²) | Tech. (nm) |
|-----------|----------------|--------------|---------|-------|------------|-----------|
| [3]       | 16             | 7            | 11.5    | 15.2  | 3          | 0.05      | 65        |
| [9]       | 19.2           | 8            | 17.7    | 11.1  | 3          | 0.83      | 65        |
| [10]      | 16.8           | 9            | 11.8    | 18.5  | 2          | 0.02      | 65        |
| [11]      | 13             | 27           | 13      | 16    | 2          | 0.335     | 28        |
| [12]      | 21.2           | 5.5          | 17.0    | 30.3  | 3          | 0.074     | 40        |
| [13]      | 17.7           | 12           | 16.8    | 14.5  | 3          | 0.32      | 65        |
| [14]      | 20.3           | 9            | 18.6    | 15.4  | 3          | 0.28      | 65        |
| This work | 11             | 13           | 14.9    | 16.3  | 1          | 0.0675*   | 65        |

*without PADs   **with PADs