A power amplifier by using asymmetrical branch-line coupler

Long Guo, Peng Heng, Guangming Wang, and Yin Tian

Abstract In this paper, a novel power amplifier (PA) is proposed. An asymmetrical branch-line coupler is exploited as the output matching circuits of the proposed PA. Meanwhile, by setting the impedance conditions with trade-off in desired pass-band appropriately, impedance matching and output power combination can be realized in a single circuit. A brief analysis of the asymmetrical branch-line coupler is presented. Compared with the traditional high-power PAs design method, this design method can meet the requirement of the miniaturization. To prove the validity of the proposed method, a PA works at 2 GHz is designed, fabricated and measured by using a 10-W gallium nitride (GaN) transistor (CGH40010F). The measured results show that a saturated output power of 42.8±5.2 dBm with a power-added efficiency of 52.0±6.6% is achieved and a saturated power gain between 7.9 and 10.1 dB.

Key words: high-power, amplifier, asymmetrical, branch-line coupler, impedance matching

Classification: Microwave and millimeter wave devices, circuits, and hardware

1. Introduction

With the rapid development of radar communication, power amplifiers (PAs) with high-efficiency, high-power and miniature advantages are highly desirable. After several decades of research, there are many forms of PAs [1]. Among them, the switching-mode PAs, such as class-E PAs [2, 3, 4, 5], class-F PAs [6, 7, 8, 9], class-J PAs [10, 11, 12, 13] and hybrid class PAs [14, 15, 16, 17, 31], can realize high-efficiency and high-power. Besides, impedance transformer is another effective method for PA design [18, 19, 20].

Generally, traditional high-power PAs in radar system usually consist of the output matching circuits and power combing circuits [21, 22, 23, 24, 25]. These two circuits are designed separately, and exploited a good performance in high-power PAs. However, such method usually leads to bigger sizes. It is not meet the miniature standard. A push-pull power amplifier using microstrip line balun has been proposed to tackle this confusion [19]. Nevertheless, the structure is still complex.

3-dB uniformly branch-line coupler is an effective circuit for power combining [26]. But, it cannot be a candidate for impedance matching. In [18], an asymmetrical branch-line coupler is used to design the output circuits of PA for a broadband high-efficiency power amplifier by appropriately selecting the impedance conditions of terminal ports. But, it is not realize power combination. In order to solve this confusion, the asymmetrical branch-line coupler [27, 28] is applied in this paper, which can not only realize impedance matching but also combines output power. By setting the impedance with trade-off in desired pass-band appropriately, an asymmetrical branch-line coupler is exploited as the output matching circuits of the proposed PA. A high-power PA with simple topology is designed, fabricated and measured to validate the proposed method. Excellent correspondence between the simulation and measured data is demonstrated. It should be notice that no attempt to design input matching circuits with the same method simultaneously as the goal is to validate the proposed statics.

2. Analysis and design

2.1 Analysis

The layout of asymmetrical branch-line coupler is shown in Fig 1(a). It consists of two quarter-wave-long transmission line sections with normalized characteristic admittance $H$ each, which are connected by two shunt branches [29, 30]. The shunt branches are quarter-wave-long transmission line sections with normalized characteristic admittance $G_1$ and $G_2$. The input/output admittance is normalized to input admittance, marked as $I$ and $L$, respectively. By properly choosing the value of $H$, $G_1$ and $G_2$, the circuit can be matched with $I$ and $L$.

The even-odd mode method is applied to analyze the parameters, as the symmetry of the asymmetrical branch-line coupler (PP') [29]. If the symmetrical port 1 and 2 are excited by equal magnitude and in-phase sources, the
symmetrical plane is equivalent to magnetic wall. It is called an even-mode excitation. Furthermore, if the symmetrical port 1 and 2 are excited by equal magnitude and out-phase sources, the symmetrical plane is equivalent to electric wall. It is called an odd-mode excitation.

![Diagram of asymmetrical branch-line coupler](image)

Fig. 1 (a) Layout of asymmetrical branch-line coupler, (b) Equivalent circuit of even-mode, (c) Equivalent circuit of odd-mode

The even-mode circuit is shown in Fig 1(b). The symmetry plane (PP') is equivalent to open circuit. The normalized ABCD matrix can be expressed as:

\[
a_{e} = \begin{pmatrix}
-G_{2} & j\sqrt{L/H} \\
-jL^{2} & L & jG_{1} & -G_{1}\sqrt{L/H}
\end{pmatrix}
\]  
\[
(1)
\]

Similarly, the odd-mode circuit is shown in Fig 1(c). The symmetry plane (PP') is equivalent to short circuit. The normalized ABCD matrix can be expressed as:

\[
a_{o} = \begin{pmatrix}
G_{2} & j\sqrt{L/H} \\
-jL^{2} & L & jG_{1} & -G_{1}\sqrt{L/H}
\end{pmatrix}
\]  
\[
(2)
\]

To satisfy that port1 and port2 of the asymmetrical branch-line coupler are matched and isolated from each other, the following equations must be satisfied:

\[
S_{11e} + S_{11o} = 0 \quad \text{and} \quad S_{12e} - S_{12o} = 0
\]  
\[
(3)
\]

And the coupling of the coupler is labeled “C”. The parameters of the asymmetrical branch-line coupler are expressed as:

\[
G_{1} = \frac{1}{\sqrt{\lg^{-1} \frac{C}{10} - 1}}
\]

\[
G_{2} = \frac{1}{\sqrt{\lg^{-1} \frac{C}{10} - 1}}
\]

\[
H = \sqrt{\frac{1}{\lg^{-1} \frac{C}{10} - 1}}
\]  
\[
(4)
\]

2.2 Design of the proposed coupler

As known, the input/output impedance of the transistor is smaller than 50 Ω. Thus, the asymmetrical branch-line coupler should be adjusted. Port 1 is used as an output terminal with 50 Ω, port 2 is used as an isolated terminal, port 3 and port 4 are used as input terminal with 90° phase difference.

3-dB directional coupler, works as a power combiner, is a common component in high-power amplifier design process [21, 24]. In this case, the parameters of the asymmetrical branch-line coupler are

\[
G_{1} = 1
\]

\[
G_{2} = L
\]

\[
H = \sqrt{2L}
\]  
\[
(5)
\]

In order to prove the validity of the proposed method, a PA works from 1.7 to 2.3 GHz is designed and measured using CGH40010F transistor. Resorting to the datasheet of CGH40010F, 25Ω is set as matching terminal port of the asymmetrical branch-line coupler with the trade-off of impedance from 1.7 to 2.3 GHz. Based on previous analysis, the parameters of the asymmetrical branch-line coupler are \(I=\frac{G_{1}=1}{1}, \quad L=G_{2}=H=0.5\). The simulated S-parameters response of the asymmetrical branch-line coupler is shown in Fig 2. It shows that the proposed asymmetrical branch-line coupler has a typical response of branch-line coupler.

![Simulated S-parameters response of the proposed coupler](image)
The effect come from the parasitic parameters of transistor, as shown in Fig 3, should be considered in practical design process. Therefore, the asymmetrical branch-line coupler should be adjusted respectively. A microstrip line is introduced and the electrical length of H is adjusted to 76° to fit the practical impedance. The topology of the adjusted asymmetrical branch-line coupler is shown in Fig 4(a). The simulated S-parameters response with the parasitic parameters of transistor is shown in Fig 4(b). It shows that the amplitude of S21 has worsened, but it is still better than -12 dB in the desired pass-band.

3. Implementation and measurement

Based on the previous discussion, a works from 1.7GHz to 2.3GHz PA based on the proposed asymmetrical branch-line coupler is designed, simulated and fabricated by a Wolfspeed (Cree) CGH40010F 10W gallium nitride high electron mobility transistor (GaN HEMT) on silicon-carbide (SiC) with a ceramic packaged with the type number of 440166. The drain bias voltage is 28V, and the quiescent current is 200 mA.

The ideal simulation setup of the proposed PA circuits with asymmetrical branch-line coupler is shown in Fig 5(a), where the circuits are fabricated on the Rogers 4350B with the relative permittivity of 3.66, the thickness of 0.762 mm, and the tangent loss of 0.0037. A quarter-wave-long transmission line is set at up input port of the PA to offset the inherent phase difference of the proposed asymmetrical branch-line coupler in output circuits. The DC blocking and decoupling capacitors at the input and output terminals are ATC600S 20 pF.

As a result, a saturated output power of 42.8 to 44dBm with a power gain of 9.7 to 11.3 dB was simulated. In this case, a power-added efficiency 48.0-57.4% were achieved across the required frequency range from 1.7 to 2.3 GHz, as shown in Fig. 6.

The fabricated PA is measured under small (0dBm) and saturated continuous-wave input signals in room temperature, as shown in Fig 6. It can be observed that the small-signal gain of 15.9-17.1 dB and the saturated power gain of 7.9-10.1 dB are achieved in the entire band with 30% of the fractional bandwidth. Meanwhile, the saturated output power is 42.8-45.2 dBm, and the power-added efficiency is 52.0-62.6% in desired bandwidth. The test PCB board of the implemented PA is shown in Fig 5(b).
4. Conclusion

In this work, the theoretical analysis of an asymmetrical branch-line coupler is presented, which is developed as the output circuits of the proposed PA. The asymmetrical branch-line coupler realizes impedance matching, as well as combines output power. For demonstration, a PA is designed, fabricated and measured. The achieved saturated output power is 42.8-45.2 dBm with a power-added efficiency of 52.0-62.8%, and the saturated power gain is between 7.9 and 10.1 dB in desired bandwidth. It demonstrated the validity of the proposed statics for development high-power PAs.

Acknowledgments

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