

Outphasing Amplifier Using GaN HEMTs

Takashi SUMIYOSHI* and Takashi MAEHATA

High-efficiency power amplifiers generate little heat and operate with a small heat dissipation function, making them effective in reducing the size, weight, and cost of communication devices. Since many amplifiers are used in massive multiple-input multiple-output (MIMO), higher efficiency amplifiers are required, and those based on gallium nitride high electron mobility transistors (GaN HEMTs) are becoming popular particularly for cell phone base station applications. On the other hand, load modulation is attracting attention as an amplifier technology for improving modulation efficiency. Among them, Outphasing amplifiers are known to achieve higher modulation efficiency than conventional Doherty amplifiers. In this study, we conducted a design prototype evaluation of an Outphasing amplifier using our GaN HEMTs. The result confirmed that the higher efficiency of the amplifier reduces power consumption by 1.1 W per amplifier compared to the conventional Doherty amplifier configuration. In a 64 transmitters Massive MIMO base station, a power reduction of 70.4 W is achieved, contributing to the miniaturization of the base station.

Keywords: GaN, HEMT, Outphasing amplifier

1. Introduction

Since amplifiers with high power efficiency generate less heat and can operate with a minimal heat dissipation function, they are effective for the downsizing, weight reduction and cost reduction of communication devices. In massive multiple-input multiple-output (MIMO), in particular, where a large number of amplifiers are used, more efficient amplifiers are required, and amplifiers based on gallium nitride high electron mobility transistors (GaN HEMTs)*¹ are becoming increasingly popular for mobile phone base station applications.⁽¹⁾ Gallium nitride (GaN) has a larger band gap and higher saturation electron speed than silicon (Si) and gallium arsenide (GaAs), making it suitable for high-power and high-speed electronic devices. In addition, forming a GaN HEMT structure on a semi-insulating SiC substrate with excellent thermal conductivity achieves excellent heat dissipation characteristics and high power efficiency. We started research and development of GaN HEMTs in 2000 and have been leading the GaN HEMT market since 2006, when we achieved the world's first mass production development of GaN HEMTs. In the meanwhile, load modulation is attracting attention as an amplifier technology aimed at improving modulation efficiency.⁽²⁾⁻⁽⁴⁾ Outphasing amplifiers,⁽⁵⁾ in particular, are known to achieve higher modulation efficiency than Doherty amplifiers.*² As shown in Fig. 1, Doherty amplifiers have been used at the practical level; however, the recent energy situation demands even lower power consumption for amplifiers. As the generation of cell phone base stations advances from 5G to 6G, high-efficiency amplifiers that amplify RF (Radio Frequency) signals with two input sources are becoming a promising candidate, and Outphasing amplifiers are attracting attention. We designed, prototyped, and evaluated an Outphasing amplifier with our GaN HEMTs, and report on the results in this paper.

This paper consists of an overview of Outphasing amplifiers in Chapter 2, design examples and measurement results in Chapter 3, and a conclusion in Chapter 4.

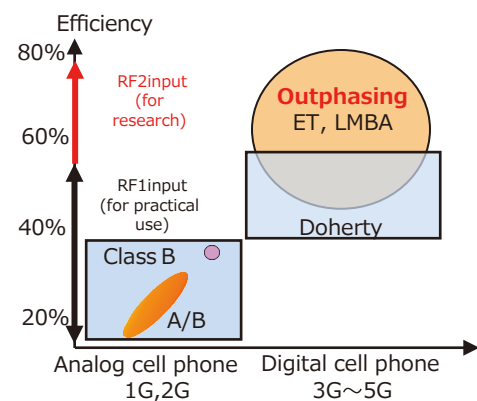


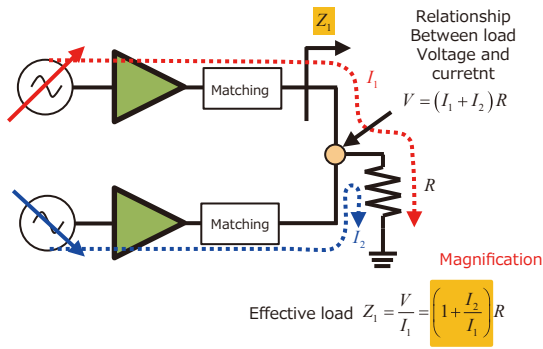
Fig. 1. Trends in amplifiers at cell phone base stations

2. Outphasing Amplifier

This Chapter explains Outphasing amplifiers. An Outphasing amplifier has two input signal sources as shown in Fig. 2 and changes the RF output by changing the multiplier of the load R (effective load) by the ratio and phase difference of I_1 and I_2 as shown in Fig. 3. By changing the effective load, the optimum load can be used according to the RF output as shown in Fig. 4, and high efficiency can be achieved even at low output. As shown in Fig. 5, the actual circuit has matching circuits for the device as input and output, and power for the two circuits is combined by a Chireix power combiner. Fig. 6 describes the Chireix power combiner circuit. The Chireix power

combiner consists of two types of reactance compensation ($-jB$ and $+jB$) to compensate for reactance caused by the input phase difference and an impedance converter. As described above, the Outphasing amplifier provides large load modulation when the two amplifiers combine power, achieving high-efficiency operation.

Each section of the following chapter presents the amplifier model used in the design of the Outphasing amplifier, the matching circuit design, and the Chireix power combiner.



Change in the magnification of R by the ratio of I1 : R ~ 8R

Fig. 2. Outphasing amplifier configuration

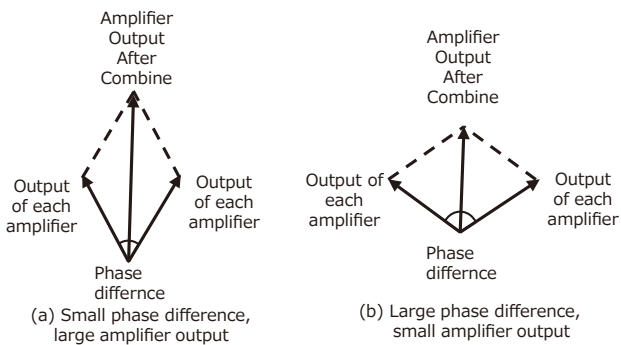


Fig. 3. Change in output by Outphasing amplifier

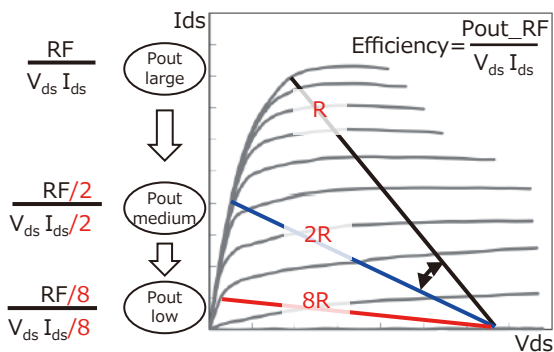


Fig. 4. Relationship between load and output power

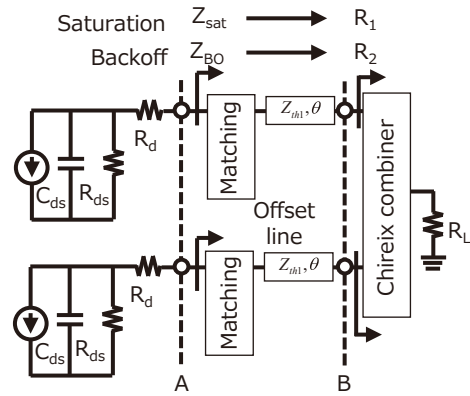


Fig. 5. Outphasing amplifier circuit configuration

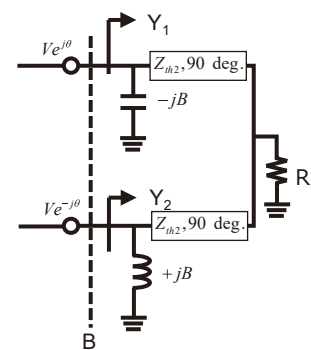


Fig. 6. Chireix power combiner

3. Design of Outphasing Amplifier

3-1 Amplifier model for design

We created an amplifier model for design as part of the design preparation. In this study, we used the Cardiff model created by the Model Generation from FOCUS and report on that case; however, we were not specifically limited to this model as an amplifier model available on the market. In the Cardiff model, the base radio performance of the amplifier model is measured by the load-pull*³ device shown in Fig. 7. The measurement data is compiled into a database using the Cardiff amplifier model and can be used in a high-frequency circuit simulator.

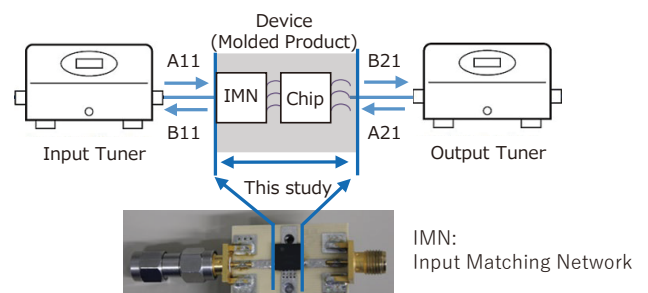


Fig. 7. Load-pull measurement system at model creation

The results of the gain and phase by the input power comparison between the model of the device created in this study and the actual measurement are shown in Fig. 8. Errors are 0.2 dB or less for gain and 0.1° or less for phase, indicating a significantly good correlation. We used this amplifier model and a high-frequency simulator to design a circuit for the Outphasing amplifier.

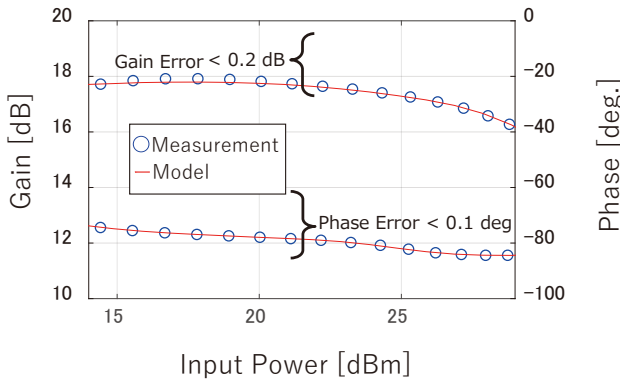


Fig. 8. Comparison of gain and phase in obtained GaN device model

3-2 Design of amplifier circuit

In this study, we set the design goal to achieve a drain efficiency of 50% at a frequency of 3.5 GHz, a saturation output*4 power of 48 dBm (60 W), and an output power of 38 dBm (6 W) with a back-off output*5 of 10 dB.

We utilized a harmonic balance analysis using a high-frequency simulator in Fig. 9, which shows the block diagram of Outphasing amplifier design. The block diagram consists of an input matching circuit, the amplifier model using our GaN HEMTs as described in Section 3-1, an output matching circuit, an offset line, an impedance converter, and a load Z_L . The output matching circuit performs power matching primarily at the saturation output, while the offset line (having the characteristic impedance which maintains power matching condition by using the matching load at the saturation output) is enable to convert the load at the back-off output to the resistive component. Therefore, the Chireix power combiner can be connected to the resistive load, which made it easy for us to design the circuit. We designed the circuit to reach the target performance by varying the load Z_L according to the

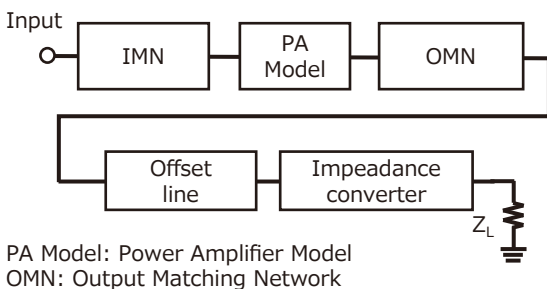


Fig. 9. Block diagram of Outphasing amplifier design

Outphasing phase as described in Figs. 2 and 4 and checking the drain efficiency characteristics to output power.

The design results are shown in Fig. 10. Figure 10 reveals that the design target of 50% drain efficiency is achieved at a saturation output power of 48 dBm (60 W) and an output power of 38 dBm (6 W) with a back-off output of 10 dB. A prototype performance was compared to the design results, which is reported in the next section.

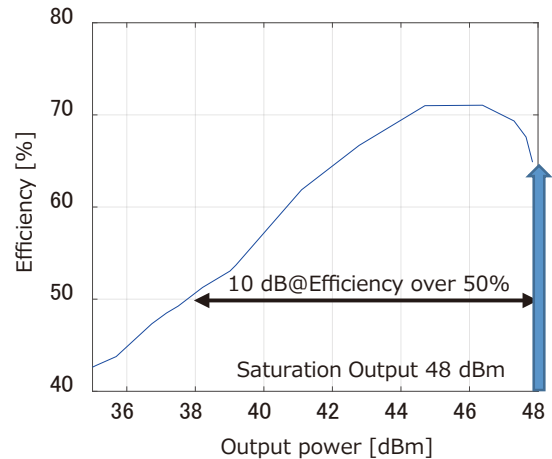


Fig. 10. Outphasing amplifier design results

3-3 Design of Chireix Combiner

As mentioned above, the Outphasing amplifier circuit is so designed that the amplifier output load is a resistive component by using an offset line; R_1 and R_2 in Fig. 5 can be matched to the input impedance of Y_1 and Y_2 of the Chireix Combiner in Fig. 6.

As shown in Fig. 6, the Chireix power combiner is designed to provide reactance compensation at the saturated output and back-off output, with the two load resistors R_1 and R_2 as input impedance elements. The input impedance Y_1 and Y_2 are expressed in Eq. (1) and are equal to $1/R_1$ and $1/R_2$ at saturated output and back-off output. By rearranging the real and imaginary parts of Eq. (1), the three design parameters (θ_m , B and Z_{th2}) can be obtained by Eq. (2), where θ_m is the phase difference of the RF signal at back-off, and at saturation, $\pi/2 - \theta_m$ is the phase difference of the RF signal and B is the reactance compensation. As for reactance compensation, reactance compensation 1 and reactance compensation 2 can be obtained using the Outphasing phase θ_m as shown in Fig. 11.

$$\begin{cases} Y_1 = \frac{2R_L}{Z_{th2}^2} \cos^2 \theta - j \frac{R_L}{Z_{th2}^2} \sin(2\theta) + jB \\ Y_2 = \frac{2R_L}{Z_{th2}^2} \cos^2 \theta + j \frac{R_L}{Z_{th2}^2} \sin(2\theta) - jB \dots\dots\dots (1) \\ B = \frac{R_L}{Z_{th2}^2} \sin(2\theta_m) \end{cases}$$

$$\begin{cases} \theta_m = \tan^{-1} \sqrt{\frac{1+m}{1-m}} \\ Z_{th2} = \sqrt{(1+m)R_1R_L} \\ B = \frac{1}{R_1} \sqrt{\frac{1-m}{1+m}} \end{cases} \dots\dots\dots (2)$$

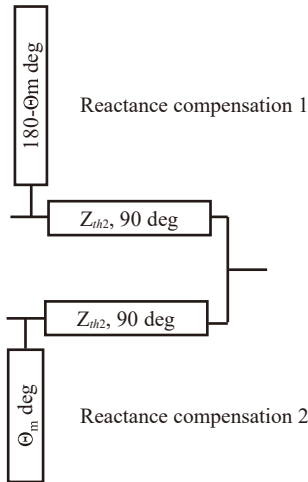


Fig. 11. Configuration diagram of Chireix power combiner designed in this study

3-4 Prototype evaluation results

The prototype Outphasing amplifier is shown in Photo. 1, and the prototype evaluation and design results are shown in Fig. 12. In photo. 1, MN stands for Matching Network. The input signal was evaluated with pulsed CW. Figure 12 shows that the results of the prototype evaluation correlate significantly well with the design results. An actual performance comparison between the Outphasing amplifier and a Doherty amplifier designed with the same device used in the Outphasing amplifier is also shown in Fig. 12. Figure 12 reveals that the Outphasing amplifier is more efficient than the Doherty amplifier. When the modulation efficiency of the amplifiers shown in Fig. 12 was checked using LTE modulation signals, the efficiency at 6 W output was 54% for the Outphasing amplifier and 49% for the Doherty amplifier, indicating a 5-point efficiency improvement for the Outphasing amplifier.

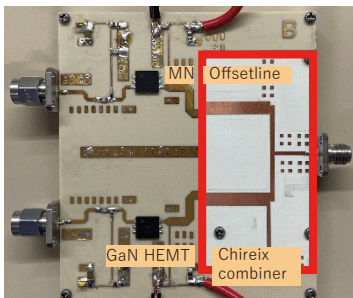


Photo. 1. Outphasing amplifier (Prototype)

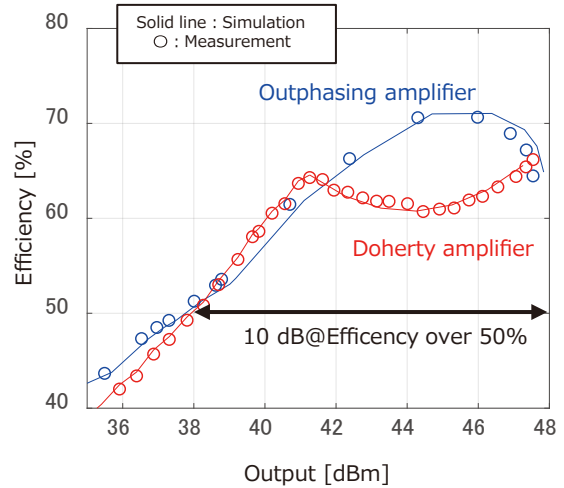


Fig. 12. Comparison of Outphasing amplifier and Doherty amplifier (Actual measurement and design)

4. Conclusion

In an evaluation with pulsed CW signals, the Outphasing amplifier using our GaN HEMTs achieved a drain efficiency of 50% at a frequency of 3.5 GHz, a saturation output power of 60 W and an output power of 6 W with 10 dB back-off output, and a higher modulation wave efficiency characteristic by 5 points than the Doherty amplifier. We confirmed that the high efficiency of amplifiers reduced the power consumption per amplifier from 12.2 W for the conventional Doherty amplifier to 11.1 W for the Outphasing amplifier in this study, resulting in a reduction of 1.1 W per amplifier. This is equivalent to a power consumption reduction of 70.4 W in the case of a 64-transmitter Massive MIMO base station, contributing to downsizing the base station.

These results were obtained from a study (JPNP20017) commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

Technical Terms

- *1 HEMT: High Electron Mobility Transistor: A transistor that uses two-dimensional electrons induced at the semiconductor junction interface. A channel with a high electron concentration can be formed with less impact from impurity scattering.
- *2 Doherty amplifier: One of the load modulation methods. The principle of the Doherty amplifier is to use a carrier amplifier and a peak amplifier arranged in parallel, with only the carrier amplifier operating at low power and the two amplifiers at high power.
- *3 Load-pull: One of the methods for evaluating large-signal characteristics of transistors. Using a load variable device called a tuner, RF characteristics are evaluated while changing matching conditions.
- *4 Saturation output: The output power in an amplifier that is saturated and thus does not increase further with increasing input power.
- *5 Back-off: Saturation output minus average output.

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