Ku-Band, 120-W Power Amplifier Using Gallium Nitride FETs

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***Abstract* — In this paper, we present a 120-W solid-state power amplifier (SSPA) for Ku-band applications. At the final stage of the SSPA, eight gallium nitride (GaN) field effect transistors (FETs) are combined. A suspended line type of combiner is designed using a three-dimensional electromagnetic (3D-EM) simulator so that the combiner can have a good performance in terms of insertion loss. To improve the linearity of the SSPA, we apply a linearization technique to the study of GaN FETs at the driver and final stages in the SSPA. Measurement results show a third-order intermodulation distortion (IM3) of -32 dBc and a power efficiency of 9% at an output power of 120 W at frequencies of 14.0 GHz to 14.5 GHz. This is the first report on a Ku-band SSPA with higher output powers than 100 W using GaN FETs.**

***Index Terms* — Power amplifiers, gallium nitride, intermodulation distortion.**

I. Introduction

Conventional power amplifiers (PAs) with several hundred watts of output power for Ku-band applications consist of electron tubes. The electron tubes need very high applied voltages and have to be periodically replaced with a new one owing to their limited lifetimes. They also require several minutes of preparation when they start transmitting at full output powers. This is not convenient for broadcasting and news gathering systems using Ku-band satellite communication.

In contrast, solid-state power amplifiers (SSPAs) are composed of semiconductor devices such as silicon (Si) laterally defused metal-oxide semiconductor (LDMOS) field effect transistors (FETs) [1], Si bipolar transistors (BTs) and gallium arsenide (GaAs) FETs. They need lower applied voltages, have longer lifetimes and require shorter preparation time than the electron tubes. Hence, SSPAs have been expected to replace electron tubes for PAs.

Recently, gallium nitride (GaN) FET has become available for high-power applications in the Ku-band [2]. GaN FET has excellent features such as a high power density and a high electron saturation velocity. The higher biased voltages to drain-source and lower drain currents than those other semiconductor devices result in simple and low-cost bias voltage circuits.

In designing the SSPA using GaN FETs, we have two issues to resolve. The first issue is that a power combiner with a low insertion loss is needed. An electron tube requires no combiner. The output power of GaN FET is not as high as that of an electron tube. We developed a new suspended line type of combiner that is optimized to the SSPA configuration using a three-dimensional electromagnetic (3D-EM) simulator.

The second issue is related to the linearity performance of the SSPA. Increasing the number of FETs at the final stage in the SSPA improves the performance in a third-order intermodulation distortion (IM3). However, it decrease power efficiency and increase the cost of the SSPA. The linearization technique that we apply to the SSPA results in a high linearity, a high power efficiency and a low cost.

II. Concept of 120-W PA

Fig. 1 and Table 1 show a block diagram and the target specifications of a 120-W SSPA, respectively. The SSPA is composed of a four-way divider, a four-way combiner and PA modules. The PA module uses GaN FETs. In Fig.1, power supply circuits that apply bias voltages to each FET are excluded for simplicity.

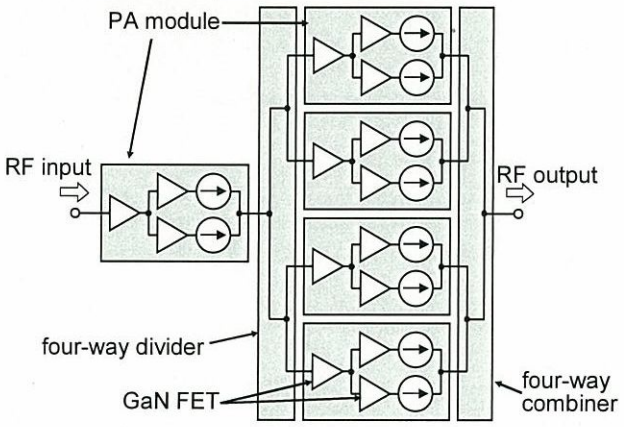


Fig. 1. Block diagram of 120-W SSPA

Table. 1. Target specifications of 120-W SSPA

Parameter	Target
Frequency	14.0 to 14.5 GHz
Output power	120 W (50.8 dBm)
Gain	27 dB min.
IM3	-25 dBc max.
Power efficiency	9 % min.

An RF input signal is amplified by the first PA module and is separated to four PA modules by the four-way divider. After each RF signal is amplified by each PA module, the four RF signals are combined by the four-way combiner and are transmitted to an output port of the SSPA.

III. Four-way Divider and Combiner

The insertion losses of the four-way divider and four-way combiner should be low. In particular, the combiner should be carefully designed, because it is set at the output port of the SSPA and seriously affects total power efficiency. In order to minimize the insertion loss of the combiner, we design a suspended line type of combiner. The circuit concept is a simple impedance matching type without isolation resistors.

Fig. 2 shows a simulation model of the combiner. The center substrate material is RT/duroid from Rogers. The relative permittivity and thickness of the substrate are 2.2 and 0.5 mm, respectively. At the output port, the suspended line is transformed to a waveguide line and the power level of RF signals is highest in the SSPA. We have to design from not only the electrical performance point of view but also the thermal performance point of view.

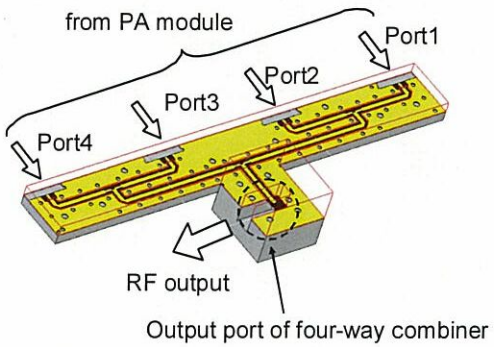


Fig. 2. Simulation model of four-way combiner

The four-way divider is a branch line type composed of microstrip lines on a dielectric substrate. When the divider is connected to the combiner, the line length of four ports should be equal to each other. The line patterns and configurations of the divider and combiner are optimized using the 3D-EM simulator.

The measured electrical performances of the divider are shown in Fig.3. The distribution of insertion losses for all ports is smaller than 1dB at frequencies of 14.0 GHz to 14.5 GHz. And the return losses of all ports are above 13 dB.

The measured electrical performances of the combiner are shown in Fig.4. The distribution of insertion losses for all ports is the same as that of the divider. The insertion loss of the combiner is 1dB lower than that of the divider, because the combiner has no dielectric layer that the divider has. And the return losses of all ports are above 12 dB.

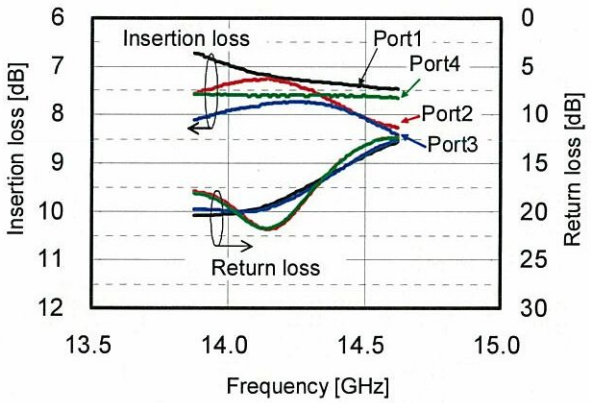


Fig. 3. Measurement results of four-way divider

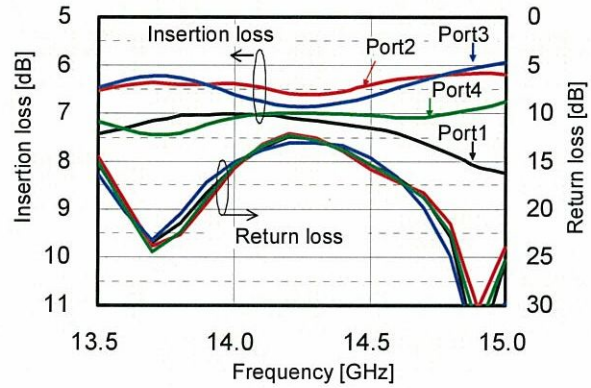


Fig. 4. Measurement results of four-way combiner

IV. PA Module

A. Fabrication of PA Module

Fig. 5 shows a top view of the fabricated PA module. The PA module is 70 mm wide, 121.5 mm long and 14.5 mm thick.

The PA module is composed of a GaN FET as a driver stage and two GaN FETs as a final stage. The GaN FET is TGI1414-50L from Toshiba. The divider between the driver and the final stage is of the branch line type. The combiner of the final stage is of the simple impedance matching type. Two conventional drop-in type isolators with a high linearity performance are set at the outputs of the final-stage FETs. The isolation resistors in the isolators have sufficient thermal performance so that the isolator would not break even if all output powers are reflected. To prevent waveguide modes from transmitting in the PA module, we separate each of the transmission lines into a small room whose size is determined by cut-off frequency.

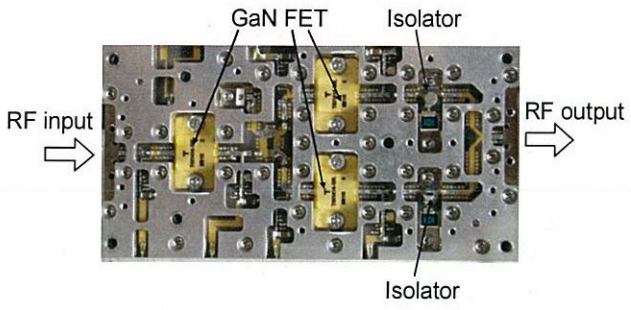


Fig. 5. Top view of PA module

B. Linearization Technique

Several methods such as feedforward, feedback and analog/digital predistortion are used in order to improve the linearity of PA [3]. We select an analog predistortion type because it needs several simple circuits. The amount of distortion improvement should be about 5 dB.

The concept of the predistortion technique is described as follows. Fig.6 shows spectrum masks at each stage of the PA module. The input signal is a two-tone continuous wave (CW). Let FET1 be a FET at the driver stage and let FET2 be two FETs at the final stage. FET2 usually operates as a class-AB FET so that its drain efficiency is higher than that of a class-A FET. However IM3 at the output of FET2 is worse. Hence, in Fig.6, the amplitude of IM3 at FET2 is larger than that of IM3 at FET1.

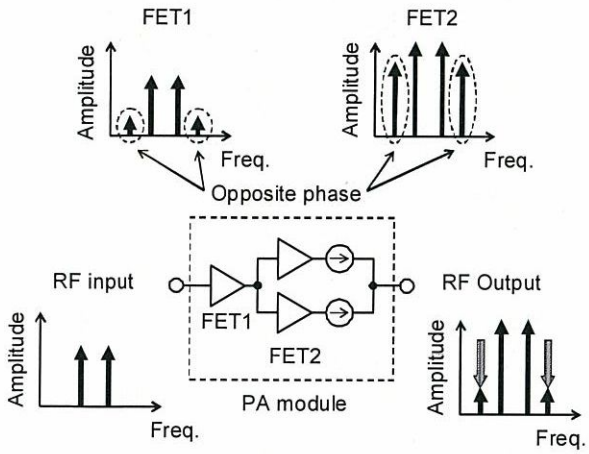


Fig. 6. Concept of predistortion linearization technique

The predistortion technique utilizes the distortion generated at a predistorter to eliminate the distortion at the final stage. The predistortion type usually needs an additional predistorter. In Fig.6, FET1 is used as the predistorter.

Under large signal conditions, the transfer characteristics of FET1 and FET2 are represented by (1) and (2), respectively.

$$Vout1 = \sum_{n=1}^{\infty} k1_n Vin1^n \tag{1}$$

$$Vout2 = \sum_{n=1}^{\infty} k2_n Vin2^n \tag{2}$$

Vout is the output voltage from FET, and Vin is the input voltage to FET. The coefficients k_n are complex quantities that are determined for each FET. We use three terms of (1) and (2) for the first-order approximation. When the relation between $k1_n$ and $k2_n$ is given by (3), the distortion of the PA module can be removed [4].

$$k1_3 = -\frac{k2_3 k1_1^3}{k2_1} \tag{3}$$

We adjust the bias voltages and modify the impedance matching circuits of FET1 to obtain the proper phase and amplitude of the distortion at FET1 according to (3). Thus, adding IM3 of FET1 to IM3 of FET2 results in a decrease in IM3 at the output port and an improvement in linearity.

V. Measurement Results of 120-W PA

Fig.7 shows a photograph of the top view of 120-W SSPA. The fabricated four-way divider, four-way combiner and PA modules are connected as shown in Fig.1. Only one PA module is opened without a lid.

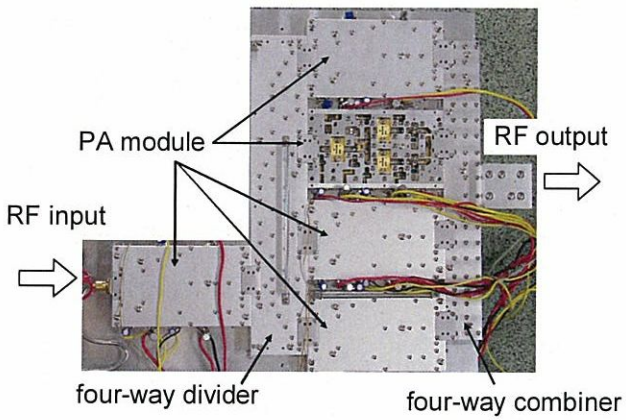


Fig. 7. Top view of 120-W SSPA

When the input signal is one-tone CW, the measurement results are shown in Fig. 8, which show gain and power efficiency variations as a function of output power. Fig. 8 shows a total gain of 27 dB and a power efficiency of 9% at an output power of 120 W.

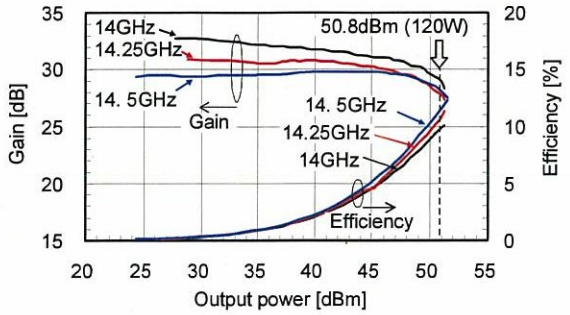
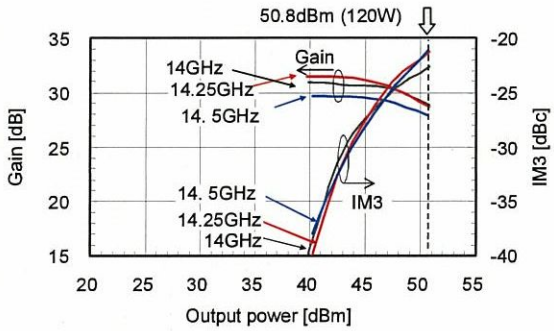
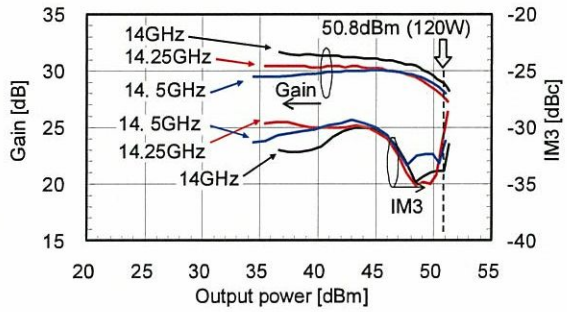


Fig. 8. Measurement results of 120-W SSPA: gain and power efficiency (one-tone CW)



(a) Before applying predistortion technique



(b) After applying predistortion technique

Fig. 9. Measurement results of 120-W SSPA: gain and IM3 (two-tone CW)

When the input signal is a two-tone CW, the measurement results are shown in Figs. 9-(a) and (b), which show gain and IM3 as a function of output power. Fig.9-(a) and (b) show the data before and after applying the predistortion technique, respectively.

Fig. 9-(b) shows an IM3 of -32 dBc at an output power of 120 W at frequencies of 14.0 GHz to 14.5 GHz. In Fig. 9-(a), IM3 decreases with an increase in the extent of the back-off from the saturated output power (Psat). However, in Fig. 9-(b), IM3 shows the best performance at output powers of 48 dBm to 50 dBm and constant with an increase in the extent of back-off from Psat. That means that the predistortion technique works as well, as expected at output powers of 48 dBm to 50 dBm.

VI. Conclusion

We designed and measured Ku-band 120-W SSPA. The SSPA is composed of a four-way divider, a four-way combiner and PA modules consisting of GaN FET. The structures and pattern layouts of the divider and combiner were optimized using a 3D-EM simulator. In order to improve the linearity of the PA module, the predistortion technique was applied. Measurement results showed an IM3 of -32 dBc, a power efficiency of 9%, and a total gain of 27 dB at an output power of 120 W at frequencies of 14.0 GHz to 14.5 GHz.

References

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