X-Band 300 W High-Power GaN HEMT for Marine Radar Systems

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Magnetrons have long been used as transmitting devices for marine radar, however, gallium nitride high-electron-mobility transistors (GaN HEMT) are increasingly adopted due to their long life, high performance, and compliance with radio laws and regulations. This paper presents our internally-matched X-band GaN HEMT that feature the industry's highest output power of 300 W, targeting a variety of marine radars ranging from small-power radars for pleasure boats to high-power radar for large-commercial vessels. We also report on a prototype compact solid-state amplifier that has been made to demonstrate these transistors.

Keywords: GaN HEMT, X-band, marine radar, high output power, microwave integrated circuit (MIC)

1. Introduction

In recent years, although large and high-speed vessels have been used to achieve efficient marine transport, the need for support systems that ensure safe marine navigation has increased because of a tight maritime labor market due to an aging population. Marine radar, one of the navigation support systems, is a useful system that helps in preventing collisions by locating the position of the vessel, tracking other ships, and presenting a real-time view of the surroundings.

Magnetrons, which feature high peak power, have been widely used as amplifiers of marine radar. Since magnetrons must be periodically replaced every one to two years, they are being replaced with solid-state devices, with long-term reliability of over 10 years, to reduce maintenance costs. Although one solid-state device has about one-hundredth peak power of conventional magnetrons, the application of power combination and pulse compression techniques makes it possible to achieve comparable or better radar performance than conventional magnetrons.

This paper presents X-band*[1] 300 W gallium nitride (GaN) high-electron-mobility transistors (HEMT)*[2], which are adopted increasingly into marine radar, and an X-band 25 W GaN HEMT microwave integrated circuit (MIC)*[3], which was developed for small-power radar. It also reports on a prototype of a solid-state amplifier using these products.

2. Development of X-Band 300 W GaN HEMT

We have commercialized an X-band 200 W GaN HEMT for marine radar.[(1),(2)] This product has already been used in the final stage amplifier of a transmitter, and the market requires high-output GaN HEMT products to improve the output power level. To address this requirement, we developed X-band 300 W GaN HEMT with much higher output power than existing products.

First, we used the package for X-band 300 W GaN HEMT with dimensions of 24.0 × 17.4 mm, which is the same as those of existing X-band 200 W GaN HEMT. The use of the existing package made it possible to use developed products for solid-state amplifiers that we had already designed, resulting in a shorter development period. Next, the GaN HEMT chips integrated into the package measured 5.68 × 0.76 mm to achieve long-term reliability and ease of assembly and to meet the desired radio frequency (RF) characteristics, and two chips were arranged in parallel. The chip size, which is larger than that of the X-band 200 W GaN HEMT, enlarged the total gate width from 44.8 to 64 mm. Photo 1 shows an internal view of an X-band 300 W GaN HEMT. Matching circuits implemented in the package were designed so that the impedance was equal to the optimal impedance obtained from the load pull*[4] measurements on the unit chip. The input matching circuit was a two-stage transformer circuit that changed the impedance optimal for the chip gain to 50 Ω at the end of the package, and the output matching circuit was a two-stage transformer circuit that changed the impedance optimal for the output power to 50 Ω.

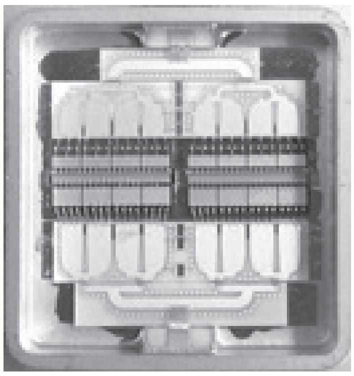


Photo 1. Internal view of the X-band 300 W GaN HEMT

Photo 2 illustrates the RF test fixture for the X-band 300 W GaN HEMT. Since the impedance was matched to

50 Ω at the end of the package, only 50 Ω lines and bias circuits that were connected to an open stub of λ/4 were used in the fixture.

Figure 1 shows the frequency response of the X-band 300 W GaN HEMT with an input power of 46 dBm (40 W). The device exhibited an output power of 55.3 dBm (340 W) and power added efficiency of 38% across a 9.3–9.5 GHz frequency range, which are the industry's highest levels.

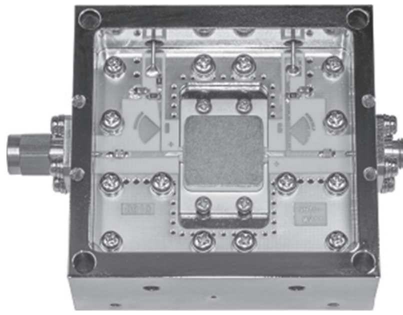


Photo 2. Test fixture for the X-band 300 W GaN HEMT

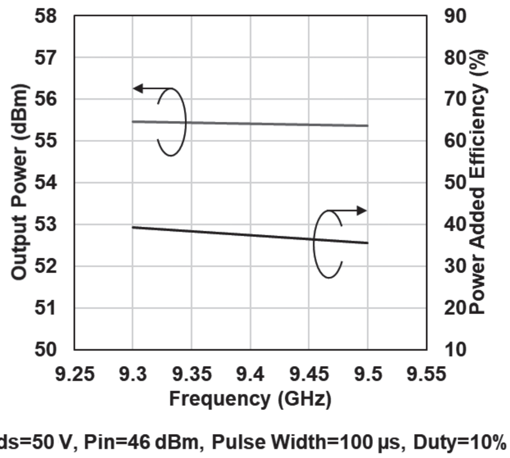


Fig. 1. RF characteristics of the X-band 300 W GaN HEMT

3. Development of the X-Band 25 W GaN HEMT MIC

There is a demand for not only high-power solid-state devices with an output of several hundreds of watts for marine radar but also low-power products with an output of several tens of watts for small radar, which is used, for example, for pleasure boats. We developed an X-band 25 W GaN HEMT MIC to meet the demand for low-power products.

In general, to cover a wide range of operating frequencies, many low-power products have been manufactured as discrete devices, which integrate only chips in a package. However, since discrete devices must form matching circuits on an external printed circuit board, the large size of the solid-state amplifier is a disadvantage. To avoid this disadvantage and achieve space savings, we developed an internally matched*5 MIC adopting a small package with dimensions of 6.7 × 8.3 mm. This made it possible to drastically reduce the size of solid-state amplifiers compared with that of amplifiers comprising discrete devices.

The circuit diagram of the X-band 25 W GaN HEMT MIC is shown in Fig. 2. Two GaN HEMT chips with outputs of 6 and 25 W are integrated in the package. In addition, matching circuits that match the impedance to 50 Ω at the end of the package and bias circuits formed on a printed circuit board outside the normal package were designed. The package also includes a filter circuit that combines inductances, resistors, and capacitors to attenuate unnecessary gain in frequencies lower than the main band.

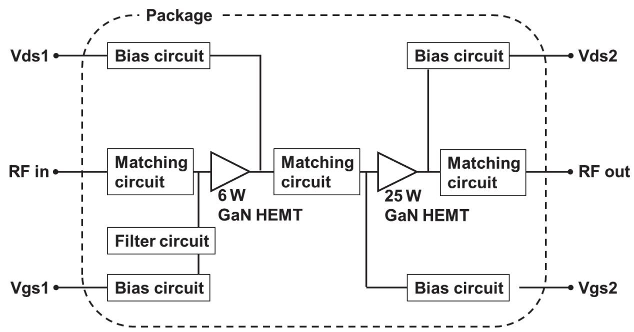


Fig. 2. X-band 25 W GaN HEMT MIC circuit diagram

Photo 3 shows the RF test fixture for the X-band 25 W GaN HEMT MIC. Since the impedance is matched to 50 Ω at the end of the package and bias circuits are integrated in the package, only 50 Ω lines and bias circuits were used in the fixture.

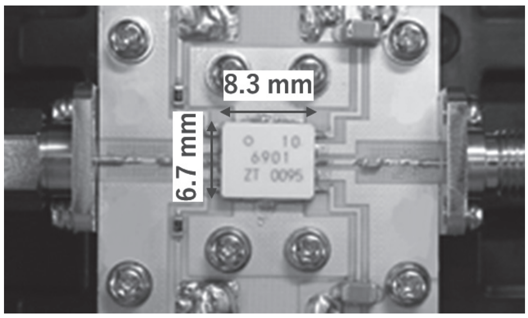


Photo 3. Test fixture for the X-band 25 W GaN HEMT MIC

Figure 3 shows the frequency response of the X-band 25 W GaN HEMT MIC with an input power of 22 dBm (0.16 W). The device exhibited an output power of 45.4 dBm (35 W) and power added efficiency of 38% across a 9.3–9.5 GHz frequency range, and the gain reached 23.4

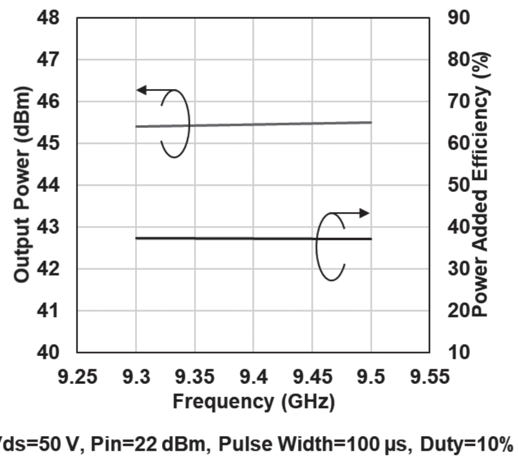


Fig. 3. RF characteristics of the X-band 25 W GaN HEMT MIC

dBm. A very high gain was obtained because of its two-stage hybrid structure, including two GaN HEMT chips.

4. Prototyping of Solid-State Amplifiers

We prototyped a solid-state amplifier for demonstration using the newly commercialized X-band 300 W GaN HEMT and X-band 25 W GaN HEMT MIC. The schematic diagram of the prototyped solid-state amplifier is shown in Fig. 4. Outputs from four 300 W products were combined in the final stage, and a 25 W MIC product, 100 W product, and 300 W product were used for the driver stage.

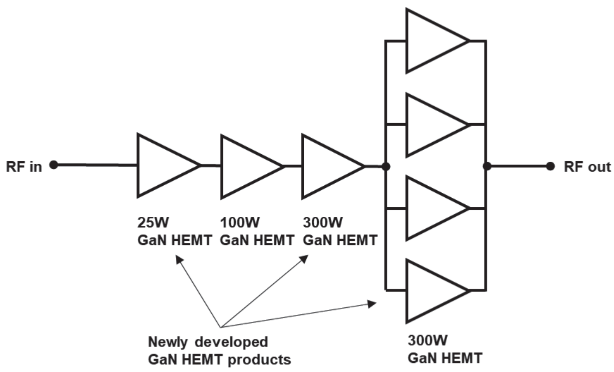
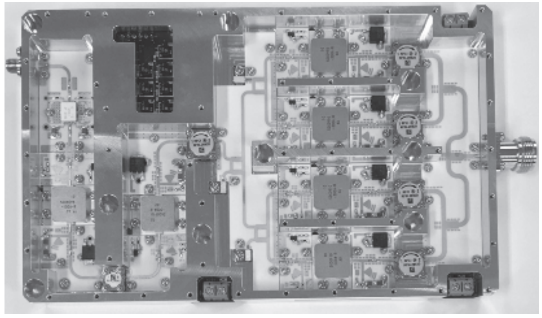


Fig. 4. Schematic diagram of a solid-state amplifier

Photo 4 shows the prototyped solid-state amplifier. It is very compact, measuring 200 (W) × 124 (H) × 20 (D) mm. The combined circuit in the final stage consisted of a 90° hybrid circuit on the input side and a tournament-type circuit on the output side for distribution/combination. The solid-state amplifier included a switching circuit, which can switch GaN HEMT products on and off at a high speed in synchronization with a transistor-transistor logic (TTL) signal for pulsed signals, with a direct applied voltage of −5 V/+5 V/50 V.



Dimensions: 200 (W) × 124 (H) × 20 (D) mm

Photo 4. Internal view of a solid-state amplifier

The input–output characteristics of the prototyped solid-state amplifier at a frequency of 9.4 GHz are plotted in Fig. 5. An output power of 58.5 dBm (700 W) and a gain of 53.5 dB were obtained at an input level of 5 dBm (3 mW). Since we used a simple planar power combiner, insertion loss is large, and the use of a low-loss combiner, such as a waveguide, will lead to a higher output power.

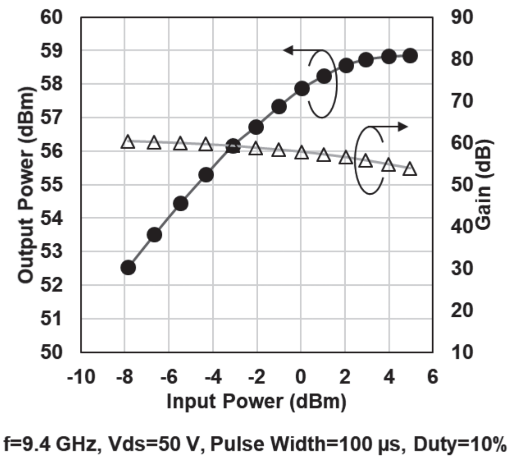


Fig. 5. Input–output characteristics of a solid-state amplifier

5. Conclusion

Table 1 summarizes the evaluation results for the newly developed X-band 300 W GaN HEMT and X-band 25 W GaN HEMT MIC for marine radar. The X-band 300 W GaN HEMT exhibited the industry's highest output power of 300 W or more because of our design optimization of the GaN HEMT chip and matching circuit. In addition, the X-band 25 W GaN HEMT MIC achieved downsizing and high gain because of its hybrid structure. Finally, using the developed GaN HEMT products, we prototyped a solid-state amplifier to achieve an output power of 700 W with a compact size of 200 (W) × 124 (H) × 20 (D) mm.

Table 1. Evaluation results of the X-band GaN HEMT products

Characteristic	X-band 300 W	X-band 25 W MIC
Drain Voltage, V_{ds}	50 V	50 V
Pulse Width	100 µs	100 µs
Duty Cycle	10%	10%
Frequency	9.3–9.5 GHz	9.3–9.5 GHz
Saturated Output Power, P_{sat}	340 W	35 W
Power Gain, G_p	9.3 dB	23.4 dB
Power Added Efficiency, PAE	38%	38%

Technical Terms

*1 X-band: A frequency range from 8 to 12 GHz in the microwave frequency range.
Since the shorter wavelengths of the X-band allow antennas to be compact, the X-band is often used for various types of radars, along with satellites and other types of wireless communication systems, including ship surveillance and weather radars, which use a range from around 8.5 to 10.0 GHz.

*2 High-electron-mobility transistor (HEMT): A transistor that uses two-dimensional electrons induced on a semiconductor junction interface. It can form a high-electron-density channel, less affected by impurity scattering.

*3 Microwave integrated circuit: A circuit comprising passive components or distributed-constant circuits operating at microwave frequencies formed on an insulating substrate, into which microwave transistors, diodes, and other active components are integrated, or an integrated circuit comprising components and circuits that are all integrated onto a semi-conducting substrate. The former circuit, comprising circuit components integrated onto alumina or other insulating substrates, is called a microwave hybrid integrated circuit (MIC), and the latter circuit, comprising components integrated onto a semi-conducting substrate with a semiconductor manufacturing method, is called a monolithic microwave integrated circuit (MMIC).

*4 Load pull: A technique for the characterization of high-power devices. Using an impedance tuning system called a tuner, load pull measures the characteristics under different impedance matching conditions.

*5 Internally matched: A high-frequency amplifier device comprising a substrate for matching circuits and transistors, implemented in a package and connected with each other. The material and shape of the substrate and wire length are adjusted according to the transistors and operating frequencies.

References

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