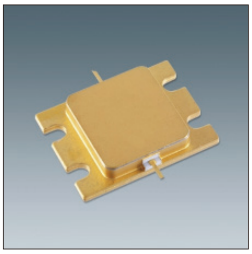

High Power and High Efficiency C-Band 100W GaN HEMT for Space Application

Akitada KODAMA*, Ken OSAWA, Shigeyuki ISHIYAMA, and Miki KUBOTA

We have developed a high-output, high-efficiency internally matched power amplifier*[1] for satellites using gallium nitride high electron mobility transistor (GaN HEMT).*[2] Today's wireless communication technology has become indispensable in our lives, not only for Internet and mobile phone communications, but also for electronic payment. Therefore, it has become an indispensable in our lives. Therefore, global information network is growing and the need for satellite communications is increasing as these are less susceptible to natural disasters.
The newly developed power amplifier achieves an output power of 100 W and power added efficiency of 60% under CW operation conditions in the C-band (f = 3.7 to 4.2 GHz), the main frequency for satellite communications. The GaN chip used in the development has a confirmed long-term reliability. In terms of both the performance and the reliability, the industry-leading device.

Keywords: GaN HEMT, high efficiency, high power, space application, 100 W

1. Introduction

In recent years, 5G mobile phone services have become mainstream, and data transmission for mobile devices has become faster and faster, making infrastructure for the general public remarkably convenient. Base stations that communicate with mobile devices are installed on the ground and are immobile. If they are damaged due to a natural or manmade disaster, recovering them requires time, perhaps resulting in major and prolonged communication shutdown. In contrast, satellite communication systems establish communications between satellites launched into space and earth stations on the ground. The earth station can be mounted in a vehicle, which can move to the necessary location to establish and recover communications swiftly. Moreover, even on the ocean where the installation of a base station is difficult, the satellite communication system can provide communication channels across a wide region. Thus, the satellite communication system has become an indispensable part of our lives owing to its multiple advantages as a communication means.

Communication systems mounted in satellites are required to be small, light, high-power, and highly efficient due to installation space and battery capacity limitations. Moreover, they need to offer long-term reliability.

Sumitomo Electric Industries, Ltd. develops and manufactures power amplifiers mounted in the transmit power block, which amplifies radio waves and transmits them from the satellite. The power amplifier is required to be high-power, high-efficiency, and small to reduce cost and power dissipation, to handle high frequencies for increased data communication speeds, and to offer high reliability. Due to the need to meet these requirements, attention is being given to microwave integrated circuits*[3] (MICs) consisting of high electron mobility transistors (HEMTs) that use a gallium nitride (GaN) material.

We have developed a C-band (3.7–4.2 GHz) 100 W GaN HEMT power amplifier for space applications. This paper reports on the results of the development.

2. Basic Characteristics of the GaN HEMT

The GaN HEMT used for the present development exhibits a high saturation current, its maximum drain current in saturation Imax reaching 780 A/mm. Meanwhile, the three-terminal breakdown voltage BVdsx in the pinch-off state is 300 V, which is more than three times the operating voltage of 50V. Consequently, the GaN HEMT is expected to operate stably at high output power.

Figure 1 presents source/load pull*[4] measurement results obtained at 4.2 GHz under pulse conditions of 12 µs pulse width and 10% duty.

The GaN HEMT source/load pull measurement results show optimal-efficiency loads determined from input/

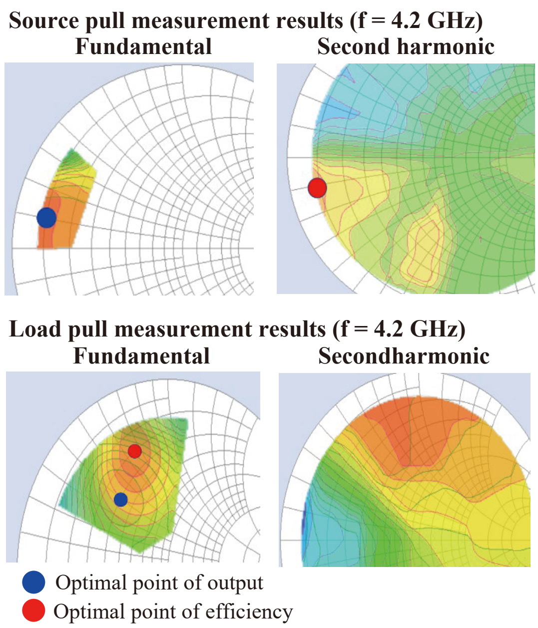

Fig. 1. GaN HEMT source/loadpull measurement results

output impedance matching for efficiency with the second harmonic taken into consideration. By designing the external matching circuit connected to the GaN HEMT to the same position as this load, the efficiency of the power amplifier can be maximized.(1)

Figure 2 plots the input/output characteristics of the GaN HEMT with the impedance set to the optimal-efficiency load. The output characteristic reached 41 dBm (12.6 W) and the efficiency characteristic reached 70%. According to these results, the output characteristic of a chip incorporating the GaN HEMT can reach 100 W. The performance results obtained so far have shown that the efficiency characteristic decreases by about 10 points compared to the load pull measurement value due to factors such as the frequency band, the heat generation of the GaN HEMTs, and losses attributable to the power amplifier circuit configuration. Even with this taken into account, the GaN HEMT is expected to achieve an efficiency of 60%.

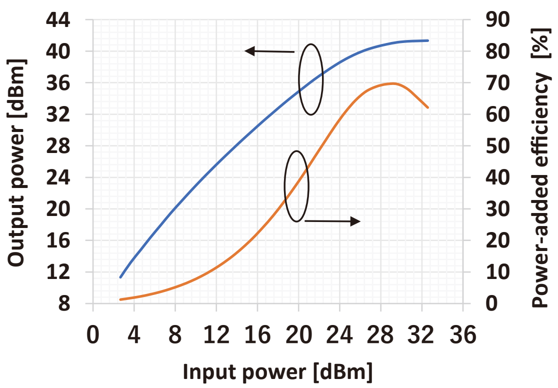

Fig. 2. Radio frequency (RF) characteristics of GaN HEMT (f = 4.2 GHz)

3. Designing of Internal Matching Circuit

Table 1 lists the target specifications for the power amplifier. The operating conditions are a supply voltage of 40 V, a supply current of 800 mA, a linear gain of 16 dB, an output power of 51 dBm (125 W), and a power-added efficiency of 60%. A hermetically sealed ceramic package is used to ensure resistance to humidity and dust

Table 1. Target Specifications for Power Amplifier

Bias Condition	V_{DS} = 40 V
	I_{DS} = 800 mA
Frequency	3.7 ~ 4.2 GHz
Output power	51 dBm
Linear gain	16 dB
Power added efficiency	60%
Package	Hermetically sealed ceramic package

For the power amplifier, the internal matching circuits were designed so as to achieve the optimal point of efficiency for a nonlinear GaN HEMT model and the fundamental and second harmonic determined by the source/load pull measurements results shown in Fig. 1. Photo 1 is a picture of the internal circuits of the power amplifier. Both input and output circuits are configured using low-pass matching for 4:2:1 in-phase division/combination like a tournament chart. The input/output matching circuits use alumina and ferroelectric substrates. Photo 2 presents a picture depicting the outline of the C-band 100 W power amplifier. The overall size of the package is 24 × 17.4 mm. Photo 3 shows the evaluation jig, which forms 50 ohm lines on an alumina substrate. Bias circuits are provided outside the jig for both the input and output ends.

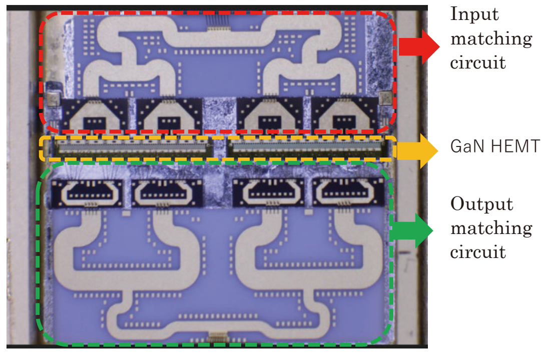

Photo 1. Internal matching circuits of C-band 100 W power amplifier

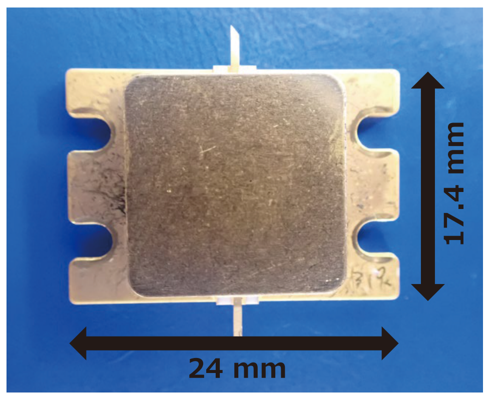

Photo 2. Outside shape of C-band 100 W power amplifier

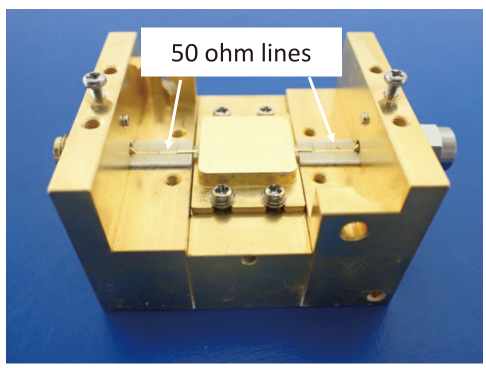

Photo 3. Outside shape of evaluation jig with C-band 100 W power amplifier

Figures 3 and 4 show the frequency dependence of output power and power-added efficiency, as determined by simulation (design results). The output characteristic reached ≥ 50 dBm and the power-added efficiency reached ≥ 60% at frequencies between 3.7 and 4.2 GHz. Figure 5 plots input/output and efficiency characteristics at f = 3.95 GHz, the center frequency of the band.

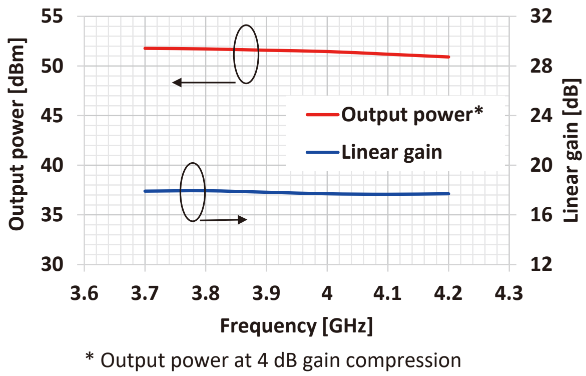

Fig. 3. Simulation results for frequency dependence of output power

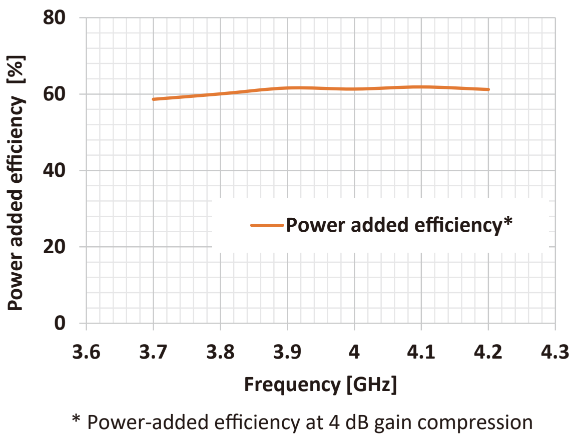

Fig. 4. Simulation results for frequency dependence of power-added efficiency

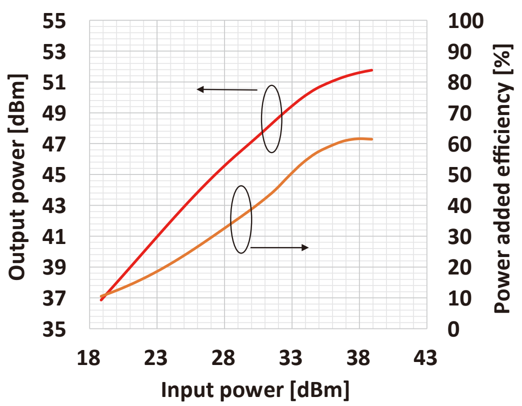

Fig. 5. Simulation results for input power dependence of output power and power-added efficiency

4. Results Obtained with a Prototype

Figures 6, 7, and 8 give the measurement results of the characteristics obtained with a prototype power amplifier built based on the above-described design. Supply voltage and supply current conditions were set as listed in Table 1. The results obtained with the prototype fulfilled the target specifications, with the output power reaching 50

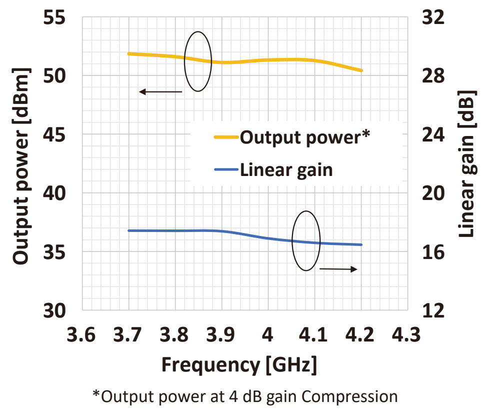

Fig. 6. Frequency dependence of output power

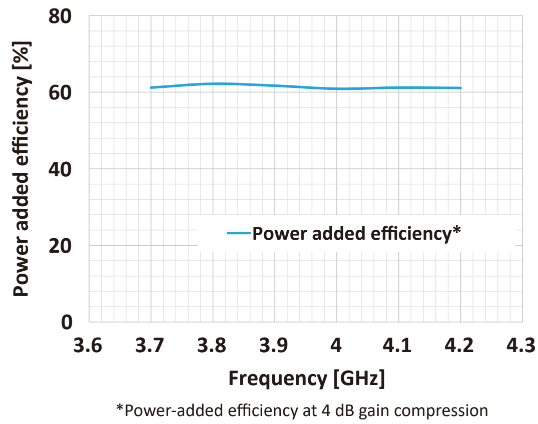

Fig. 7. Frequency dependence of power-added efficiency

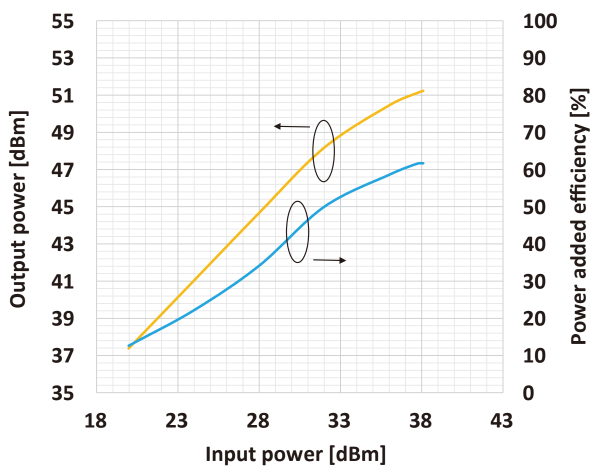

Fig. 8. Input power dependence of output power and power-added efficiency

to 51 dBm (100 W) and the power-added efficiency reaching 60%.

5. Reliability Tests

5-1 Space qualification test (SQT)

The GaN HEMT used in the above-described product was subjected to a space qualification test (SQT) as per the standard space qualification procedures based on MIL-PRF-19500, a global standard. Table 2 lists the conducted SQ tests except for radiation hardness testing. After direct current (DC) high-temperature operating life (HTOL), RF high-temperature operating life (RF HTOL), and RF step stress tests, the GaN HEMT proved to exhibit long-term reliability. Environmental tests for thermal environments (thermal shock and temperature cycle) and mechanical environments (shock, vibration, and constant acceleration) produced satisfactory results. The activation energy (E_a) determined by the DC HTOL was 2.10 eV, and that determined by the RF HTOL was 2.21 eV. The Ea of the DC HTOL was hence very close to that of the RF HTOL. Therefore, the failure modes of the DC HTOL and the RF HTOL are considered identical. Figures 9 and 10 show the mean time to failure (MTTF) values at the channel temperature of 200°C. The values are estimated at 2.34×10^7 h (2,671 years) for the DC HTOL and 1.18×10^7 h (1,347 years) for the RF HTOL. These MTTF values are sufficient for satellite applications whose service life is typically 15 years

Table 2. Space Qualification Test (SQT)

Category	Test	
Service life test	DC HTOL (V_{DS} = 60 V, Tch = 250, 275, 300, 315°C) RF HTOL (V_{DS} = 55 V, Tch=270, 290, 310°C, P4 dB) RF step stress (V_{DS} = 60 V, Pin=P3dB ~ P13 dB, 2 h each)	
Environmental test	Thermal environment	Thermal shock Temperature cycle
	Mechanical environment	Shock and vibration Constant acceleration

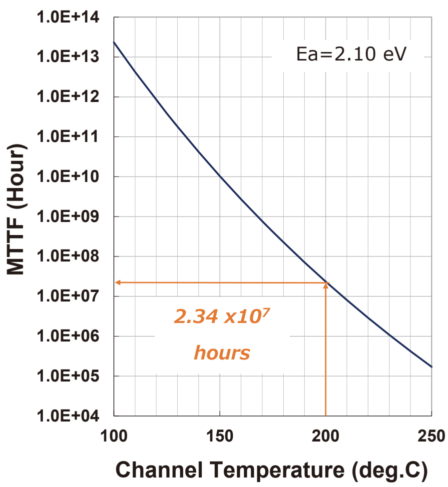

Fig. 9. MTTF of DC HTOL

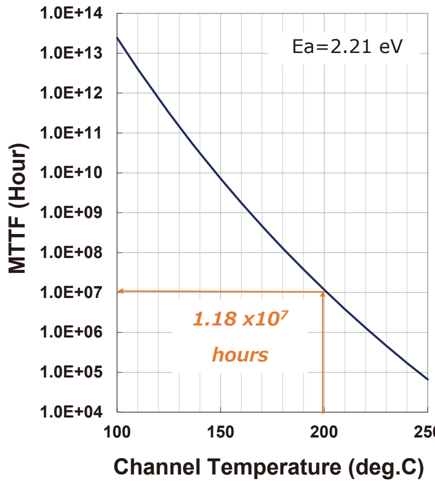

Fig. 10. MTTF of RF HTOL

5-2 Radiation hardness test

Radiation hardness is an important factor for applications in space. Three types of radiation test are commonly used: a single event effect (SEE),*5 a total ionizing dose effect (TID),*6 and a proton beam irradiation.[2] Among them, we conducted the SEE test, which is considered the most important for the GaN HEMT. The SEE test was conducted under two different conditions: RF operation under the normal bias condition (Condition A) and pinch-off with no RF signal input (Condition B). The SEE test results are presented in Table 3. The GaN HEMT showed no failures under Condition A. The safe operating area (SOA) was attained under Condition B, as illustrated in Fig. 11. The GaN HEMT burned out at V_{DS} = 195 V or more, which is at least three times the value of V_{DS} = 50 V and is sufficient for normal operation. These results demonstrate that our GaN HEMT offers sufficient reliability against radiation.

Table 3. Single Event Effects (SEEs)

Condition A: during RF operation

	132Xe
Energy [MeV]	650
Fluence [piece/cm^2]	~ 3×10^5
Flux [piece/cm^2/s]	~ 3000
LET*7(Si) [MeV•cm^2/mg]	66.3
Drain voltage V_{DS}	~ 53 V
Drain current I_{DS} (DC)	250 mA
OutpuOutput level	Gain compression point (up to 4 dB)

Condition B: pinch-off operation, no RF input

Source	132Xe	124Xe
Energy [MeV]	650	420
Fluence [piece/cm^2]	~ 3×10^5	
Flux [piece/cm^2/s]	~ 3000	
LET (Si) [MeV/(mg/cm^2)]	66.3	67.7
Drain voltage V_{DS}	~ 225 V	
Gate voltage V_{GS}	-6 V	

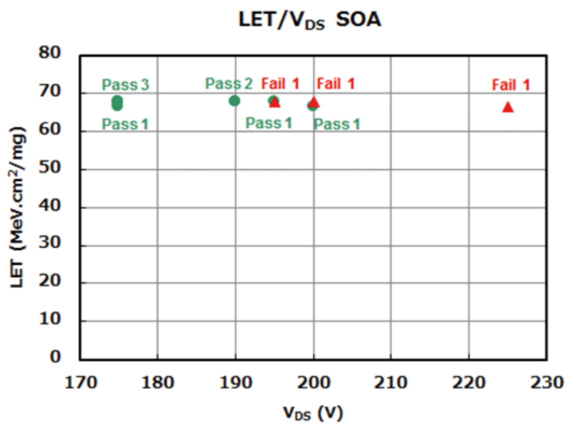

Fig. 11. Safe operation area by SEEs without RF input

6. C-Band 100 W/200 W Circuit

Figure 12 illustrates the evaluation results for the C-band 100 W package and its combination with the concurrently developed C-band 30 W module. The total gain and output of the circuit are 40 dB and 100 W. A parallel configuration of 100 W devices will realize a 200 W circuit.

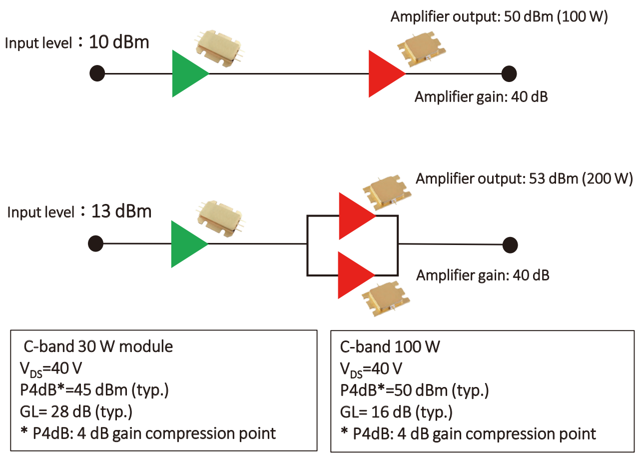

Fig. 12. C-band 100 W/200 W circuit configuration

7. Conclusion

This paper reported on the design of a C-band 100 W power amplifier incorporating the high-reliability GaN HEMT technology developed by Sumitomo Electric and on the results obtained with a prototype. The attained characteristics are sufficient for achieving the industry's leading performance as a C-band power amplifier, and the power-added efficiency of 60% in the full band (f = 3.7–4.2 GHz) was achieved for the first time in the industry. The GaN HEMT incorporated in the C-band 100 W amplifier passed space qualification and radiation hardness tests, proving itself to be sufficiently reliable for use in space. These results verify the feasibility of a GaN HEMT solid state power amplifier (SSPA) for space applications. Moreover, by combining it with the C-band 30 W module under concurrent development, it becomes possible to produce a C-band 100 W/200 W class circuit with a total gain of 40 dB for space applications. To respond to market demand, Sumitomo Electric will continue to develop the GaN HEMT technology and products with higher power, higher efficiency, and lower cost.

Technical Terms

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

*2 High electron mobility transistor (HEMT): A transistor that uses two-dimensional electrons induced at the semiconductor junction interface. A HEMT can form a channel with high electron density that is hardly affected by impurity scattering.

*3 Microwave integrated circuit: Refers to either a hybrid microwave integrated circuit (HMIC) or a monolithic microwave integrated circuit (MMIC). The HMIC is made of insulator substrates, such as alumina, on which passive elements or a distributed constant circuit that operates in the microwave band is formed, with additional active elements such as microwave transistors and diodes mounted on top. The MMIC is an integrated circuit in which all the elements and circuits are formed as a unit on a substrate in a semiconductor manufacturing process.

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

*5 Single event effect (SEE): An effect that causes temporary malfunctions or permanent failures when ionization generates a high density charge on a semiconductor device due to the incidence of one high energy particle (e.g., a proton or a heavy ion).

*6 Total ionizing dose effects (TID): Electrons and electron holes are generated by cosmic radiation. Electron holes accumulate in the insulating materials of the integrated circuits and change the device characteristics gradually, resulting in deterioration of the characteristics and failure. TID is also called a cumulative dose effect.

*7 Linear energy transfer (LET): LET indicates the energy of particles acting on matter (per unit volume density, per unit distance).

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