# COMPACT GAN HIGH POWER AMPLIFIERS FOR SPACE COMMUNICATION, SENSING AND GREEN POWER TRANSMISSION

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Abstract: On the base of a green-eco technology, S-bandhigh power GaN amplifiers have been developed with a microwave power transmission function in the space electronics equipment. High DC-to-RF conversion efficiency of 63 % was achieved in the 20W GaN amplifier operating at 2.25 GHz and its design technique was extended to realize 1 kW SSPA for the space communication. Furthermore, wireless sensor operation and battery charging was also demonstrated by means of microwave power transmission.

## 1 INTRODUCTION

The RF technology has been used for communication and sensing, so far. As the third usage of the microwaves, wireless power transmission and energy harvesting have been paid much attention as one of solutions of environmental problems. With the enormous interest brewing, researchers around the world started to develop the wireless energy transfer/power transmission and energy harvesting/scavenging. This is the green-eco wireless power technology for the green life (environmental issues), ecology (nature-human interaction) and economy (cost effectiveness). Specifically, it will have a great impact on many applications such as compact and battery-less wireless communications and wireless sensor systems. Wireless power delivery generated from clean energy may be called wireless green power transmission.

The wireless power transmission (WPT) is usually categorized into three, the EM Coupling, the Magnetic Resonance (MR), and the Microwave WPT (MPT). It has been known that the carrier wave without modulation can be delivered the energy wirelessly. This is the basic feature of MPT. Comparing with wired systems and other WPT technologies, the MPT has become one of the most important technologies on demand to future space missions as well as green eco technologies (N. Shinohara, 2009). For instance, the MPT module with some sensors can reinforce health monitoring functions in a space craft without wire-harness and solve a payload problem by removing some of onboard electrical power subsystems (EPS) in the space craft.

Reading the space electronics, a compact communication system is needed both in the onboard communication system and in the ground station. On behalf of operation of a space ground station, such as the Usuda Deep Space Center (UDSC) shown in Fig. 1, a high power and high efficiency solid state power amplifier is strongly requested. For this purpose, a wide band-gap semiconductor such as GaN and SiC is promising. Further, reduction of payload is important issue in the onboard system. In order to solve this problem, realization of a high power and high efficiency RF amplifier using the wide band gap semiconductor is requested. This is also the effective solution for the single event, total dose radio-isotope problem, and high temperature operation (N. Adachi, 2005).

Regarding power receiving in the MPT, power detection by a rectenna directory connected with an antenna and a detector is typical (M. Furukawa, 2006) (M. Hori, 2011) (T. ITO, 1979). As described before, wireless power is intentionally delivered to the rectenna. In the case of MPT, the high

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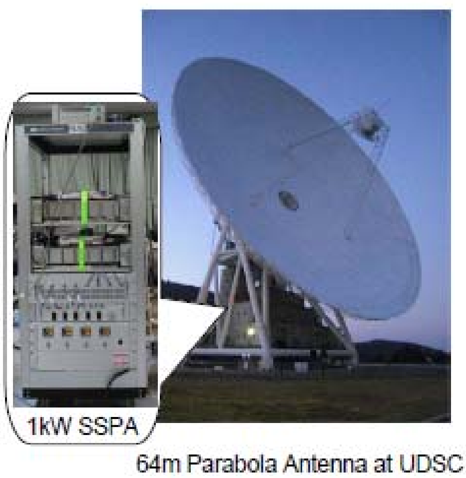


Fig. 1.The kW-class SSPA for the space communication

breakdown-voltage RF detector is required to obtain high converted DC power, for instance, battery charging due to MPT. On the other hand, electromagnetic energy harvesting can be done in the RF environment. This harvester also consists of the rectenna but the harvested RF energy includes leaked RF energy from a transmitter in other place. The harvesting energy which tune into RF energy may include that from a energy converter/transfer. When the collected energy is weak, this may be called as “scavenging”.

In this paper, the wireless power transmission is explained as the green-eco technology. From this view point, demonstration of space communication and wireless sensor by means of microwave power transmission is described by using high power GaN amplifiers. The 1kW SSPA combined with the high power GaN amplifiers is shown.In addition, thermal sensor operation and battery charging by microwave power transmission are introduced.

# 2 MICROWAVE GAN CIRCUITS FOR SPACE COMMUNICATION AND MPT

## 2.1 Semiconductor devices

In space communication, high efficient power device is necessitated. In this view point, a wide band-gap semiconductor is very promising. Among them, the gallium nitride (GaN) has recently been focused on as a high power and high efficiency device in the microwave region. Therefore, the GaN is one of the most significant elements to achieve effective use of energy in space not only for communications but also for power transmissions. The GaN has several superior material properties, such as wide band gap, high saturation velocity, and good thermal conductivity. Due to these properties, the GaN is considered to have advantages in high efficiency, and high temperature conditions in addition to the high power characteristics. Thus, GaN is expected to be used in space applications such as, high power amplifiers (DC-to-RF conversion modules) and rectifiers (RF-to-DC conversion modules).

## 2.2 High power amplifiers

The S-band GaN based high power amplifiers (HPAs) have been designed, developed, and evaluated for space applications of the communication, a wireless sensor and microwave energy transfer intended for the green-eco technology. As examples for the onboard application, the 20W and 100W GaN amplifiers with the high power added efficiency were developed.

### 2.2.1 The 20W-class GaN HPA

The 20-W-class single-stage high power amplifier was designed in the S-band by using the commercial available CAD(Agilent: Advanced Design System) with small signal S-parameters. The package type of 20-W-class GaN HEMT on a Si substrate and the circuit substrate (Rogers RO4350 : the copper thickness of 70 um, the substrate thickness of 0.762 mm, the permittivity of 3.46) were used. The size of the 20-W-class amplifier was 50*55*17 mm. The circuit overview is shown in Fig. 2.

The measured small signal S-parameters from the 20W-class GaN HPA are shown in Fig. 3. Between 2.1 and 2.4 GHz, it was observed from Fig 3 that peaks of measured return loss of S11 and S22were achieved below -10 dB and the peak of measured forward gain of S21 was larger than 15 dB. In addition, characteristics of input-output, gain, drain efficiency and power added efficiency (PAE) from the fabricated 20W HPA at 2.25 GHz are shown in Fig. 4. It is confirmed that P1dB and P3dB were 42.2 dBm and 43.7 dBm and the PAE at these points were 55.1 % and 63.3 %, respectively. (Y. Kobayashi, 2012)

### 2.2.2 The 100W-class GaN HPA Unit

The 100-W-class single-stage high power amplifier was also designed and fabricated in the S-band with the package type 100W-class GaN HEMT on the Si substrate and the circuit substrate (RogersRO4350). The size of the 100-W-class is 100*76*30 mm shown in Fig. 5.

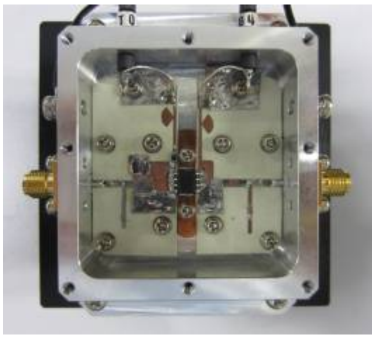


Fig. 2. 20 W-classGaN HPA

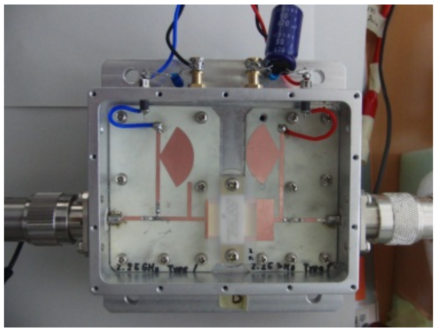


Fig. 5. 100 W-classGaN HPA

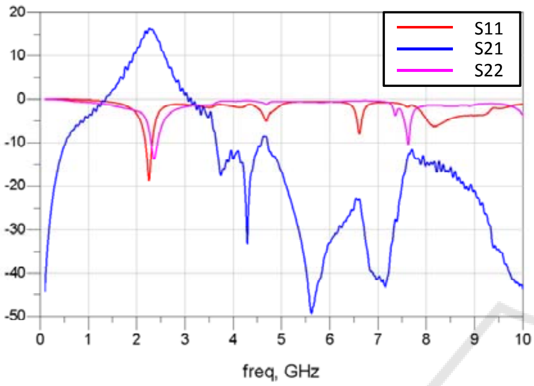



Fig. 3. Measured S-Parameters

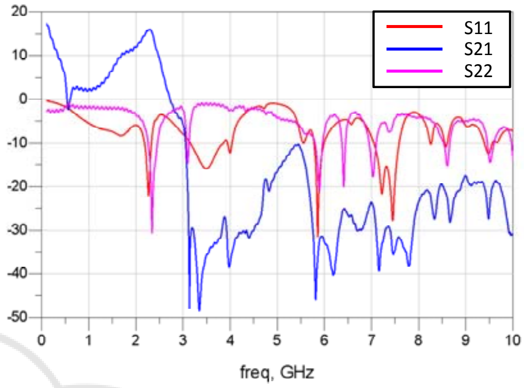



Fig. 6. Measured S-Parameters

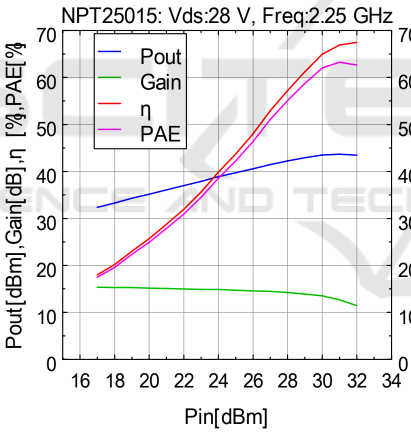



Fig. 4. Input-output characteristics

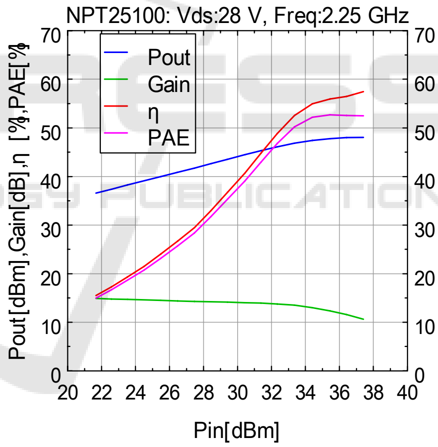



Fig. 7. Input-output characteristics

The measured small signal S-parameters of the 100W-class GaN HPA are shown in Fig. 6. In this figure, it was found that the S11 was measured with smaller than -11 dB, the S22 was smaller than -6.5 dB, and S21 was larger than 15 dB at the frequency rangebetween 2.1-2.4 GHz. In addition, the input-output characteristics of the 100W-class HPA at 2.25 GHz are shown in Fig. 7. It is confirmed that P1dB and P3dB were 45.3 dBm and 48.0 dBm and the power added efficiency (PAE) at these points were 43.0 % and 52.6 %, respectively.

## 3 APPLICATION AND TEST

For the space green power transmission as well as the ground-to-satellite application, the 1 kW GaN solid state power amplifier (SSPA) using a power combiner technique was fabricated. The total DC-to-RF conversion efficiency of more than 50 % was achieved. Using these components, some preliminary experiments of space power transmission have also been conducted.

Wireless power transmission (WPT) is one of the most important technologies for future space missions. WPT can be applied to not only inside of space crafts but also outside of ones. Comparing wired systems, there are various advantages using WPT. For instance, WPT with some sensors can easily reinforce health monitoring functions of space crafts and WPT between space crafts will be able to reduce onboard electrical power subsystems (EPS) of each space craft. However, the resources such as size, weight, power consumptions are generally limited in a space craft. In addition, mission requirements and environments are completely different in each mission, especially in space science or space exploration missions. Besides, from a radio frequency (RF) technical standpoint, the higher the frequency of WPT is, the smaller the size of WPT components become. However, in high-frequency WPT, circuit designs are more complicated and free-space span losses are larger than those of low-frequency WPT. Therefore, the specifications of WPT such as frequency, power, etc. must not be determined without considering both mission requirements and RF features.

### 3.1 High power GaN amplifier combiner for space communication ground station

A 1kW-class GaN high power amplifier equipment was designed and fabricated in the S-band. It consists of three parts, a GaAs driver amplifier, 200W-classs high power amplifier units and a circular waveguide combiner. The Block diagram and overview of 1kW-class GaNSSPA Unit are shown in Fig. 8 and Fig. 9, respectively.

Input-output characteristics of the 1kW-class SSPA Unit including nonlinear amplification at 2.1 GHz, allocated for earth-to-space link are shown in Fig. 10. More than 60 dBm output power was achieved in this evaluation. In addition, measured combining efficiency can be seen in table 1. High combining efficiency of 87.1 % was obtained.

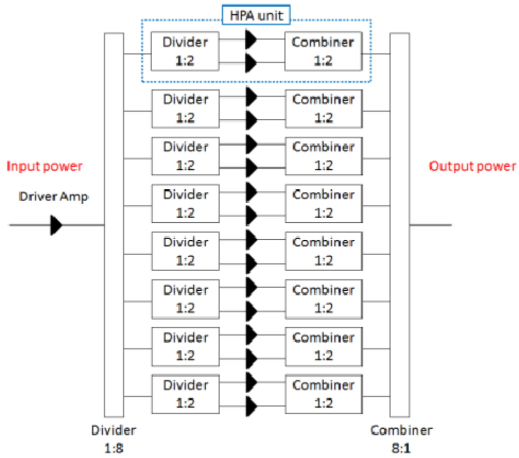



Fig. 8. Block diagram of 1-kW-class GaN HPA equipment

Fig. 9. 1-kW-class GaN HPA equipment

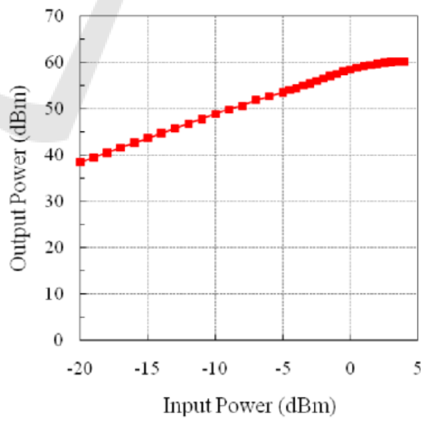



Fig. 10. 1-kW-class HPA equipment characteristics

Further, the output power stability during more than half an hour operation is shown in Fig. 11. About 5 % degradation of the output power was observed. (H. Noji, 2011)

Table 1 Combining efficiency of 1-kW-class HPA equipment

| | |
|---|---|
| HPA1 output power | 158.5 W |
| HPA2 output power | 141.3 W |
| HPA3 output power | 154.9 W |
| HPA4 output power | 147.9 W |
| HPA5 output power | 154.9 W |
| HPA6 output power | 138.0 W |
| HPA7 output power | 147.9 W |
| HPA8 output power | 144.5 W |
| Total input power to combiner | 1188 W |
| Output power from combiner | 1035 W |
| Combining efficiency | 87.1 % |

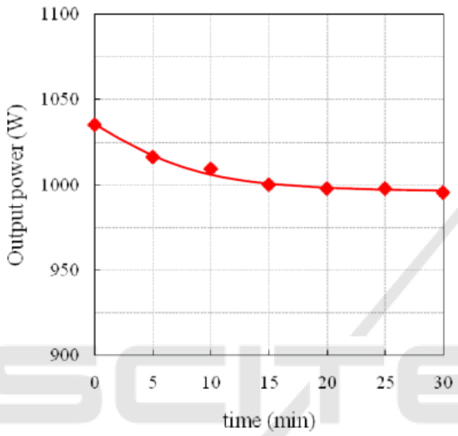



Fig. 11. Ouput power stability of 1-kW-class HPA equipment

## 3.2 The wireless sensor and batter charging by MPT

The applications of GaN modules for space use are numerous such as onboard communication system, ground station communication system, wireless power transmission system, and wireless sensor network system. Here, the combination of microwave power/energy transmission with the sensor network, namely the wireless sensor and energy transfer (WiSEnT), was conducted. The WiSEnT with a thermal sensor was evaluated inside an anechoic chamber as the first step toward future spacecraft health monitoring system. The thermal sensor was connected with the rectifier directly and it can operate without any batteries. The thermal sensor was operated as the normal sensor system with a battery and the fundamental data were obtained through the preliminary experiment. These are indicated in Fig. 12.

Further, the application of the GaN based HPA to MPT for the purpose of battery charging with a rectifier was checked inside an anechoic chamber. The block diagram of MPT experiment is shown in Fig. 13. The inside and outside appearances of the anechoic chamber are shown in Fig. 14 and 15 respectively. In Figs. 13 and 14, the distance between transmission and receiving antenna was 1.2 m.

In Fig. 13, 2.25 GHz sine wave generated by the SG was amplified by the GaN HPA. Then, the amplified signal was supplied to the divider. After that, the divided signals were radiated by the 16-element transmission array antenna. The radiated signal was received by the 16-element receiving array antenna and combined by the power combiner. Then, the combined signal was converted into DC signal by the rectifier. After that, the DC signal was supplied to the DC/DC converter and the converted signal was supplied to the battery. The transmission and receiving RF powers divided by directional couplers were measured by power meters. The measured power of transmission antenna (EIRP) and that of rectifier realized 58.8 dBm and 33.3 dBm, respectively.

The battery voltage during the MPT experiment is shown in Fig. 16. The Figure 16 indicates that the charging achieved totally up to 1615.5 Ws (=0.449 Wh) in about 6 hours 43 minutes. The DC/DC converter was inserted between the rectifier and the battery so as to keep the conversion efficiency of the rectifier high. In general, the efficiency strongly depends on the load resistance of a rectifier and it is important to keep the resistance at the optimum value. However, a load resistance of a battery is usually changing while it is charging. Therefore, when the output signal of a rectifier is directly supplied to a battery, the conversion efficiency changes widely. In Fig. 13, however, it is indicated that the battery charging rate was not constant. Therefore, the load resistance of the rectifier must have been changing although the DC/DC converter was used.

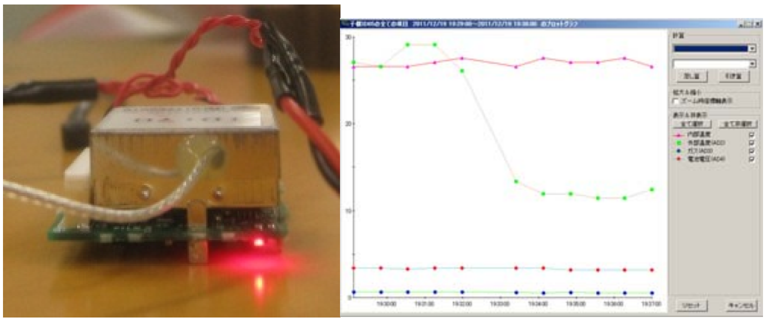


Fig. 12. The preliminary experiment for the thermal sensor operating with microwave power transmission

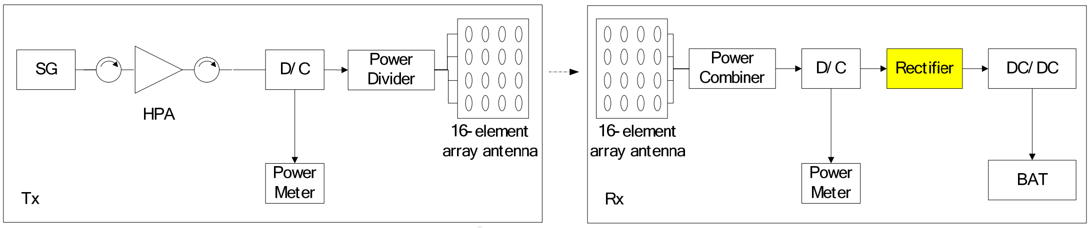



Fig. 13. Block diagram of WPT experiment

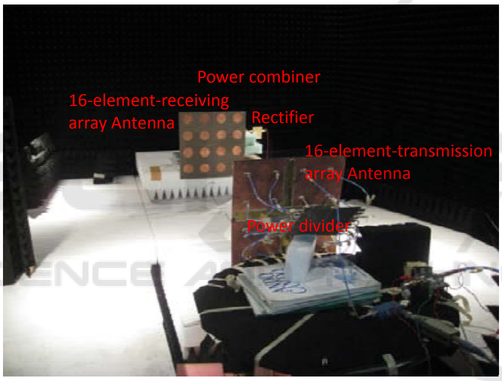



Fig. 14.Componentsused inside of anechoic chamber

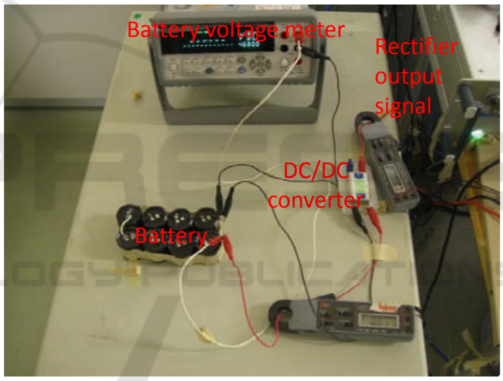



Fig. 15. Components used forbattery charging

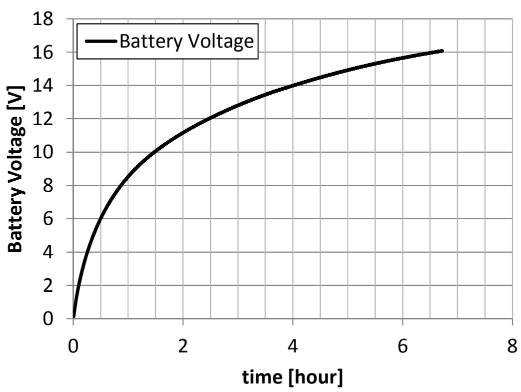



Fig. 16. Battery voltage

## 3.3 Space environmental testing

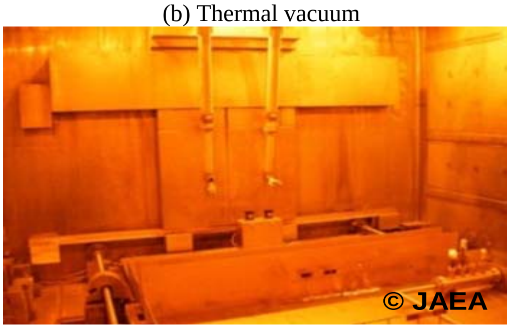
For an actual space use, the space environmental testing such as temperature, thermal vacuum, and radiation are significant. GaN is expected to tolerate these harsh environmental testing due to its characteristics. The space environmental testing listed in table 2 was conducted with the 20-W-class GaN HPA. The test facilities are shown in Fig. 17.

Table 2
Conditions of space environmental testing

| Test name | Conditions |
|---|---|
| Temperature | -5 degC ,25 degC, 55degC |
| Thermal vacuum | Thermal cycle(-20 to 60 degC) 1E-4 ~ 1E-3 Pa |
| Radiation | $^{60}$Co, Total Ionizing Dose (TID) : 320 krad (Rate: 20krad/h) (After radiation test, aging test was done.) (100 degC, 168hours continuous operation) |

(a) Temperature

(b) Thermal vacuum




(c) Radiation (@JAEA)

Results of thermal vacuum testing and radiation testing are shown in Figs. 18 and 19 respectively. Figure 18 indicates that the GaN amplifier continued to function normallyduring the thermal cycle although the PAE of each temperature were a little different. Further, Fig. 19indicates theGaN amplifier, once degraded by the radiation, came back to its previous operation by the aging test. This is named as annealing effect. From these results, it was greatly enhanced that the GaN will be able to be used in the space.

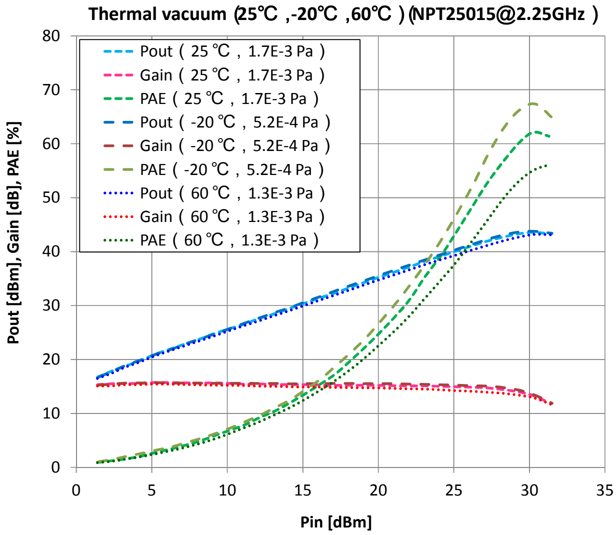



Fig. 18. Result of thermal vacuum testing

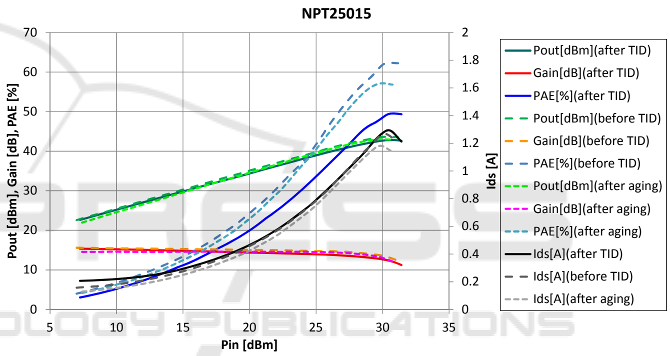



Fig. 19. Result of radiation testing

## 4 SUMMARY

In this paper, the design, fabrication, and evaluation of high power and high efficiency GaNHPAs were described. Further, the battery charging experiment for the space MPT to a rover was demonstrated. In addition, the environmental testing results for space use are shown.

The 20W-class GaNHPA realized 43.7 dBm output signal power with 63.3 % PAE at 2.25 GHz, the 100W-clas HPA realized 48.0 dBm with 52.6 %, and 1kW-class SSPA unit realized 60.1 dBm output signal power with 87.1 % combining efficiency at 2.1 GHz.The experiments of thermal sensor operation and battery charging by MPT using the GaN HPAs werecarried out. The thermal sensor operated as the normal one with a battery supported by MPT. In addition, the battery was charged up by the converted DC power under the condition where the EIRP was 58.8 dBm, the rectifier input power was 33.3 dBm, and the distance between the power transmitter and the receiver was 1.2 m. Further, the GaN amplifier could continue to function normally during the space environmental testing of temperature, thermal vacuum, and radiation.

Through these experiments, it is believed that flexibilities for the future missions in terms of size, weight, and power consumption using GaN will be improved.

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