Test and Development of Prototype
1000W X-band Microwave Solid-State Power Amplifier for Small SAR Satellite

Hiromi Watanabe
Keio University
3-1-1, Yoshinodai, Chuo, Sagamihara, Kanagawa, 252-5210 Japan; 81-42-759-8104
4-1-1 Hiyoshi, Kohoku-ku, Yokohama, Kanagawa 223-8526 Japan
h-watanabe@ac.jaxa.jp

Koji Tanaka, Koichi Ijichi
Japan Aerospace Exploration Agency, Institute of Space and Astronautical Science
3-1-1, Yoshinodai, Chuo, Sagamihara, Kanagawa, 252-5210 Japan; 81-50-3362-7027
tanaka.koji@jaxa.jp

Hirobumi Saito
Japan Aerospace Exploration Agency, Institute of Space and Astronautical Science
3-1-1, Yoshinodai, Chuo, Sagamihara, Kanagawa, 252-5210 Japan; 81-50-3362-2657
saito.hirobumi@jaxa.jp

Seiko Shirasaka
Keio University
4-1-1 Hiyoshi, Kohoku-ku, Yokohama, Kanagawa 223-8526 Japan; 81-45-564-2581
shirasaka@sdm.keio.ac.jp

ABSTRACT

Our team has been developing an X-band SAR (Synthetic Aperture Radar) system on 75cm*75cm*75cm (paddles folding), 130kg class small satellite including folding flat antenna paddles under ImPACT program [1,2]. SAR observation has advantages under cloudy or bad weather conditions and directly obtaining three-dimensional data, however, requires a high power microwave transmitter. Therefore, we are developing a 1000W solid-state power amplifier (SSPA) that can be mounted on a small satellite by utilizing latest technologies such as GaN HEMT, power combiner, low impedance capacitor and the like. We tested and measured the performances of our manufactured amplifier EM (engineering model). The weight of our amplifier EM was approximately 12.8 kg (including structural panel 4.4kg). It was confirmed that its output capability exceeded 1000 W and continuous operation for more than 5 minutes, which is equivalent to 2000 km observation, was possible.

SAR SATELLITE

SAR Observation

Most of the recent earth observation small satellites have passive sensors like high resolution cameras, but these passive observation instruments are sensitive to the environment. These passive observation instruments are sensitive to the environment. For example, it is said that about 50% of the Earth's surface is covered with clouds, and optical observation has difficulties at night. Even though the situation is bad, desires to immediately acquire observation data are increasing year by year. SAR, which enables stable earth observation regardless of surrounding circumstances, is very useful for such applications. This is because SAR is an active observation device that generates radio waves necessary for observation by itself.

Our SAR is mounted on a small satellite located at an altitude of 600 km and has a strip-map mode with a maximum resolution of 10 m and a sliding-spot-light mode with a maximum resolution of 3 m. In order to balance bandwidth, equipment size and development difficulty, we decided to use the X band. In the strip map mode, we aim at observation distances equivalent to 2000 km at maximum 5 minutes.
Satellite Construction

The satellite we are exploiting has two large deployment paddles (figure 1, figure 2) [3]. Main components of each paddles are slot array antennas and SAP (Solar Array Panel). At the time of observation, direct the antenna radiation direction to the earth, otherwise point SAP toward the sun. Nearly all the power required for observation is supplied from the battery and the time taken for observation is less than 5 minutes, so SAP does not have to face the sun at observation. Other components are basically mounted inside the cabinet, but XPA (power amplifier), which generate large amount of heat, are integrated with the enclosure panel as described below.

XPA DESIGN

Requirements

As a result of calculating the parameters necessary for the observation, the following demands were made for the power amplifier. In order to obtain resolution and S/N ration, chirped pulse signal is used.

<table>
<thead>
<tr>
<th>Table 1: Required specifications</th>
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<tbody>
<tr>
<td>Frequency</td>
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<tr>
<td>Output power</td>
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<tr>
<td>Maximum continuous operation</td>
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<td>Input power</td>
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<td>Supply voltage</td>
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<tr>
<td>Architecture</td>
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<td>Operating Temperature</td>
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Amplifier Construction

It is quite difficult to design the required 1000 W with one SSPA (solid-state amplifier), so we decided to combine six 200 W SSPA modules (XMDL) as shown in figure 3. On the other hand, since the maximum duty is required to correspond to 25%, two output stages are combined inside XMDL (Figure 4). Since the XPA output is required to be a waveguide, we used a power combiner with waveguide output with coaxial input (figure 5) [4].

Figure 1: SAR satellite (folding)

Figure 2: SAR satellite

Figure 3: XPA construction
**Thermal Management**

The power amplifier is integrated with an aluminum alloy structural panel that works as a part of satellite cabinet for heat storage capacity and heat radiation to outer space (figure 7, figure 8). Figure 9 shows the arrangement of the main components in XPA. In order to minimize power loss in microwave, the power combiner is placed in the center, and six XMDLs are arranged radially to distribute heat generation points. Besides that, since the DC / DC module also generates heat, it is distributed between XMDLs.

We have designed this XPA aluminum panel to make it easy to dissipate heat, so we know that the temperature drops too much if it is not used for a long time. Our calculation and experiments confirmed that by placing system heaters with a power of 40 W, it can hold at least the minimum storage temperature of -20 °C.
As a result, the assumed temperature transition is as shown in figure 6. In operation time of up to 5 minutes, XPA temperature rises and the heat accumulates in the aluminium panel. After that XPA is being cooled down to steady state temperature over a maximum of several hours by radiation. At that time the satellite enters the shade, if cooling is excessive, the heater is turned on so that it does not fall below -20 ° C. XPA is available above -20 ° C.

Stably transferring heat among different solids is a difficult thing, so we mainly use two different types of sheets for that solution. The first is a sheet of graphite, which has high electrical conductivity in addition to the thermal conductivity reaching 700W/m·K. Although this sheet has high performance, it cannot absorb mechanical deviation of tens of um or more, so it is used for power transistor with small size and high power density. The second one is a lambda gel sheet, which is not so powerful but has excellent performance in absorbing mechanical deviation, so this soft sheet is used for XMDL and DC / DC.
**Microwave Circuit**

All microwave transistors in XMDL are GaN-HEMTs. They work in the AB class when transmit signal is required and are controlled to be cut off when the transmit signal is not needed (figure 13.). Adjusting so that the time when the radio wave reflected from the object is received is the timing of the cutoff when observation prevents noise from XPA from entering the weak received signal. The final transistor and driver transistor are driven to near saturation, and stable input-output characteristics and high power efficiency are obtained. A few μS of delay is place at the beginning of each signal in order to wait for circuit stability.

Meanwhile, by stabilizing the drain voltage at 40 V lower than the rated voltage, it realizes operation with high duty ratio of 25% even at high temperature, and reduces the risk of discharge.

Each XMDLs are designed to operate near the saturated operating point, reducing power instability (Figure 12). Meanwhile, the phase trimmer is put at the input of each XMDL to accommodate individual phase differences.

**Power Management**

The power supply circuit of the XPA must supply pulsed power that will be at least 4000 W at maximum and should not let its pulse noise flow to the satellite bus power line. Each XMDL has a large capacitor bank of approximately 1800μF and is designed to perform stable charging while suppressing pulse noise using a coil and a resistor. 28 industrial grade polymer capacitors with a withstand voltage of 80 V and extremely low impedance of 28 mΩ are used for the capacitor bank (figure 14.). This polymer capacitor is extremely lightweight, unlike conventional tantalum capacitors, it can be mounted on a board without requiring a dedicated structure.

As a result of measuring this capacitor out gassing, its TLM was 0.026%, CVCM was 0.001%, and WVR was 0.004%. Moreover, the capacity reduction and ESR increase were not observed in the vacuum operation test for more than two months.

Furthermore, we have tightly tested modules that do not include opto-devices with protection against OC, OV, UV, short circuit and heat, and with a power density of 33 W/cm² to supply a stable voltage from a wide bus voltage range (Figure 15).
Figure 15: DC/DC Module

XPA EM (ENGINEERING MODEL)

Figure 16 and 17 shows our manufactured amplifier engineering model. The weight of our XPA EM was about 12.8 kg (including structural panel 4.4kg). Its shield cover is made by gluing aluminium sheet to CFRP and is designed to have no electrical gap for EMI reasons.

The power consumption was measured as 1350W as a standard, and fluctuated with temperature, but it did not exceed 1500W.

Figure 16: XMDL EM with Heatsink

Figure 17: XPA EM

XPA EM TEST

We conducted a Co60 total ionization test, a thermal vacuum test, a vibration test and an impact test on XPA

Components Co60 Total Ionization Test Result

In order to prevent the bias point of the high power circuit which operates linearly from changing or unstable operation, we measured the change of the characteristic by parts alone. As an example of representative parts, the results of BJT (Bipolar Junction Transistor) and voltage reference [5] are shown in following figures. As a result, circuits have to be designed by incorporating the reduction in the amplification factor of BJT, on the other hand, the reference voltage is found to be stable.

Figure 18: BJT test result

Figure 19: Voltage reference test result
**XMDL Co60 Total Ionization Test Result**

GaN devices said to have very high radiation hardness [6]. In order to confirm its stability, we irradiated single XMDL with 20kRad gamma ray, and compared characteristics before and after that. As shown in figure 20 and 21, its difference was as small as less than 0.054dB, 45mA (1%).

![XMDL total ionization test](image1)

**Figure 20: Co60 RF power comparison**

**Thermal Vacuum Test Result**

In order to confirm stability of our XPA in the space environment, we conducted a thermal vacuum test. XPA was covered with shroud of LN2 to simulate outer space (figure 22). Heat input was controlled by varying the temperature of the internal thermal panel. We installed a heater on the back of the XPA to simulate the radiation from the satellite body.

In consideration of observation conditions of actual satellite, we experimented with two cases of “COLD case” and “HOT case” in mind. The “COLD case” is when the satellite is in the shade of the earth and its temperature is maintained by system heater to be not lower than -20°C. The hot case is when the day is hit by a satellite and it is maintained at around 0°C. Furthermore, in addition to the hot case, we conducted an experiment assuming that the heat at the last observation remained and the temperature rose to 30°C. In either case, we confirmed that the temperature rose by about 50°C in 5 minutes of operation.

Finally we concluded that XPA operates stably in all defined temperature ranges in vacuum. Figure 23, 24, 25 and 26 shows “COLD case” and “HOT case2” result.

![XPA thermal vacuum test configuration](image2)

**Figure 22: XPA thermal vacuum test configuration**

![XPA thermal vacuum test (COLD case)](image3)

**Figure 23: “COLD case” temperature**
Vibration Test and Shock Test Result

Considering that there are several possibilities for the launch vehicle, we conducted a 3axis vibration test and a shock test at QT-level. As a result of careful comparison of the measurement results before and after the tests, it was found that there was no abnormality.

CONCLUSION

By carefully examining and designing using the latest devices such as GaN-HEMT, it is proving that high power SSPA can be installed even for a small satellite of 100 kg class. This greatly approaches the realization of a compact SAR satellite and is a major advance in expanding the application of small satellites.

Our first demonstration is planned in 2019.

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