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Risk Analysis of Uber High Power System of Solar Power Satellite

Daichi. Ota[a]*, Takaya Nakamura[b] Tatsuya. Yamagami[c], Naoki. Sekiya[d], Soki Akutsu[a], Raza. Mudassir[c], Ryoya. Yamagishi[a], Yusuke. Kishida[d], and Koji. Tanaka[e]

[a] *Department of Applied Physics, Tokyo University of Science, 6-3-1, Niijuku, Katsushika, Tokyo, 125-8585, Japan, 1519509@ed.tus.ac.jp, 1520503@ed.tus.ac.jp, 1517103@ed.tus.ac.jp*
[b] *S Department of Mechanical Engineering, Tokyo University of Science, 2641 Yamazaki Noda Chiba 278-0022, Japan*
7519547@ed.tus.ac.jp,
[c] *Space and Astronautical Science, The Graduate University for Advanced Studies [SOKENDAI], 3-1-1 Yoshinodai chuo-ku Sagamihara City, Kanagawa 252-5210 Japan*
yamagami.tatsuya@ac.jaxa.jp , raza.mudassir@ac.jaxa.jp
[d] *Department of Mechanical Engineering, Hosei university, 372 Kajino Koganei Tokyo 184-8584 Japan*
naoki.sekiya.7r@stu.hosei.ac.jp, yusuke.kishida.3k@stu.hosei.ac.jp
[e] *ISAS/JAXA, tanaka.koji@jaxa.jp*
* Corresponding Author

Abstract

Solar Power Satellite (SPS) is expected as a clean and sustainable future energy system. However, SPS have some issues. One of them is a discharging phenomenon. Discharging caused a lot of satellite accidents so far, and some satellites lost their missions. To realize the operation for a long term, discharging must be avoided or mitigated. Although some research on general discharge on satellites, there is few reports focusing on discharge phenomena on RF devices for high power systems such as SPS. Then, how to mitigate discharging on RF devices is presented in this paper, and based on the results, a plan for on-orbit experiment with a piggyback satellite is introduced.

Keywords: Solar Power Satellite, Discharge phenomena, Multipactoring

1. Introduction

Solar Power Satellite (SPS) is expected as a new energy system for the next generation. Compared with the conventional energy systems, SPS has some advantages as follows: SPS can use more intense sunshine than that on the ground because there is no atmosphere in space, it is not affected by the weather conditions, in geostationary orbit, it can always get sunlight except a short periods, it is able to generate the power without emitting the environmental pollutant such as greenhouse gas.

To realize SPS, some following technologies are required: how to construct unprecedented large structure in the low costs (tethered SPS; about 2km×2km), how to realize high power efficiency, how to transmit high power microwave in any direction with high accuracy, and how to manage the effects due to the space environment including space debris, plasma, and high energy radiation. Among them, how to mitigate the charge/discharge problems of spacecraft is an important technology because it is one of the serious problems for spacecrafts.

The discharge phenomena cause some negative effects such as lowering the performance of electric devices and circuits, heating up devices, outgassing, increasing the signal noise and the power reflection, and in the worst case, spacecrafts become inoperative [1]. In fact, it is reported that ESD (Electro Static Discharge) accounts of more than 50% of all satellite accidents occurred caused by the space environment as shown in Fig. 1 [2]. In 2003, ADEOS-2 depicted in Fig.2, which is launched by JAXA, Japan, lost the power from 6kW to 1kW in only 3 minutes, and, eventually, stopped working. The cause was damage to the electric power lines due to charging and discharging [3].

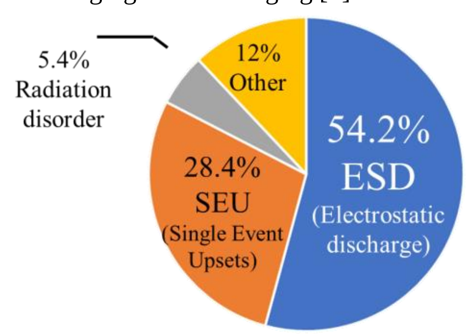

Fig. 1. Proportion of satellite accidents caused by space environment

Moreover, discharge phenomena are more likely to occur on SPS than conventional satellites because SPS generates and transmits GW-class electrical power, whereas conventional satellites transmit only kW-class.

In the past researches, the mechanisms of discharge phenomena are well understood, and the design guidelines for avoiding discharging are available by AIAA S-142- 2016 [4], ECSS-E-20-01-A [5], etc. However, there are a few researches regarding the discharge in high power microwave system such as SPS, and it is necessary to develop more reliable way to design for avoiding discharge.

Therefore, the purpose of this project is to propose a method to mitigate discharge effect in SPS and to introduce a plan of on-orbit experiments to demonstrate the technologies to suppress the discharge.

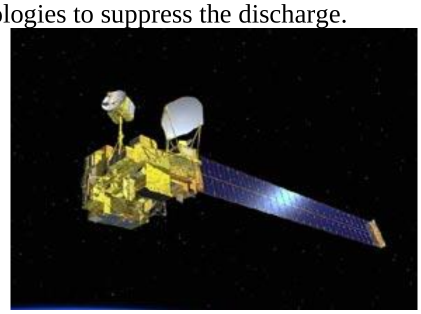

Fig. 2. ADEOS-2

2. Discharge phenomena

Discharge phenomena occurs under various conditions such as gaseous, liquid, solid states. In this chapter, two typical discharge phenomena are described; discharge in gas and vacuum.

2.1 Gas discharge

The schematic of gas discharge is depicted in Fig. 3. When voltage is applied between electrodes, free electrons in gases are accelerate and collide with the neutral particles. If the free electrons have enough energy, the neutral particles are ionized, and electrons and positive ions are generated. (It is called α mode.) Then, electrons caused by ionization collide with other neutral particles. Moreover, positive ion impact against cathode and secondary electrons are emitted. (it is called γ mode.) Generally, partial discharging caused by repeating these processes is called corona discharge. On the other hand, total discharging is named glow discharge.

Therefore, gas discharge depends on the probability of the electron's collision, that is, the product of the air pressure and the distance between electrodes [6].

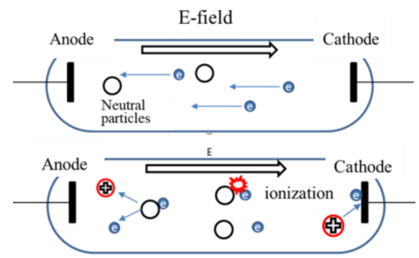

Fig. 3. The process of glow discharge

2.2 Discharge in vacuum

Multipactoring or multipactor discharge is a typical discharge phenomenon in a vacuum condition for RF components or devices. The ionization rarely occur in the vacuum so secondary electron emission is the main cause of discharging. Figure 4 shows the mechanism of multipactoring. Multipactoring is the resonance phenomenon between electrons and a period of RF.

Firstly, primary electrons (free electrons in the gap) are accelerated by RF electric field. When electrons impact against the surface of the component, secondary electrons are emitted from the surface. Then, if a period of RF is inverted, electrons are accelerated in opposite direction and collide with the surface. Repeating this process, the number of electrons increases exponentially, and it finally leads to multipactor [7].

Multipactoring is so sensitive to the surface condition because secondary electrons are emitted from the atomic layer of the surface. Therefore, inner surface is often coated with the material which has low SEY (Secondary Electron Yield) for suppressing multipactoring.

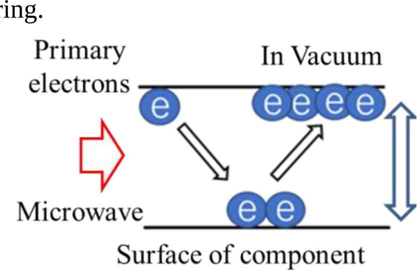

Fig. 4. The mechanism of multipactoring

In any case, the source of electrons is required to sustain discharge, and cutting off the source is important for preventing the discharge.

2.3 The risk of discharging on SPS

As stated above, all spacecrafts including SPS are at a risk of discharge. The most dangerous part is a solar array. Figure 5 shows the number of insurance claims by anomaly types. This survey was conducted by Frost & Sullivan and Airclaims [8]. Solar arrays have a triple junction, which is the boundary of vacuum, conductor, and insulator, and it is the most prone to attract the line of electric force. That is why the discharging on solar array is the most likely to occur. Moreover, the voltage of spacecraft bus is increased year by year, the bus voltage of DS-1 launched in 1998 was 100V, and that of ISS launched in 2000 was 120V. It is estimated that the about 400V is required for the bus voltage of SPS to suppress the transmission loss [9].

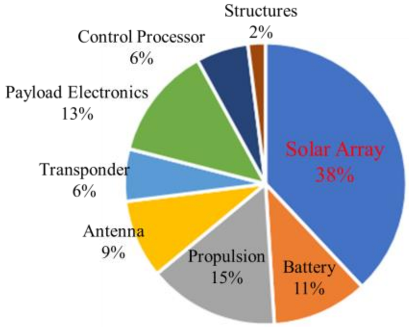

Fig. 5. The number of insurance claims by anomaly types

However, in the case of designing SPS, not only the discharging on solar arrays but also on the other components must be considered. It is because in recent years, it is reported that discharging also can be occurred on RF devices such as antenna, power combiner, and connector.

Figure 6 shows the luminescence on the slot array antenna due to discharging. When inputting 143W to the antenna, discharging occurred. In addition to this, a luminescence on the patch antenna as shown in Fig. 7 was also reported [10]. It was occurred in the plasma when inputting 30W, and it was also reported that the microwave from the patch antenna was absorbed into the ambient plasma.

Another discharging on RF devices is depicted in Fig. 8. The connector of the power combiner was burnout when inputting 2kW. Due to discharge, this connector was totally broken.

As a summary, SPS has higher risk of discharging than other conventional satellites. However, these discharge phenomena were unprecedented or not reported specifically so the mechanism of discharging on RF devices is still unknown. In the next chapter, we will introduce how to reduce the discharge of RF devices from the viewpoint of numerical analysis and experiments.

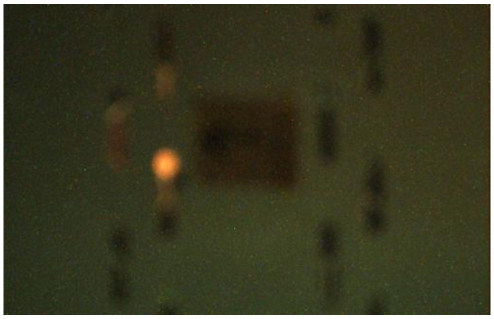

Fig. 6. The discharge on the slot array antenna

Fig. 7. The luminescence on the patch antenna [10]

Fig. 8. The burnout of the connector

3. How to prevent discharging

The mission of this project is developing how to mitigate the discharge phenomena in RF devices for high power systems. Some researches, such as ECSS [5], were already done. However, more reliable design methods are necessary for SPS. To accomplish that, we have two approaches; one is numerical analysis and the experiment. To evaluate the accurate of the results, we will compare the results of the two approaches.

In the numerical analysis, CST was used for 3D electromagnetic field calculation Spark3D was used for evaluation of RF breakdown level.

2.2 Coupled waveguide

To confirm the effect of the surface processing to prevent the discharging, the coupled waveguides were used.

Figure 9 shows the two waveguides coupled by a slot, and the inner surface is coated with different materials shown in Fig. 10. We evaluated the power level of the multipactor discharge of the components with each material to determine which material was most suited to prevent discharge.

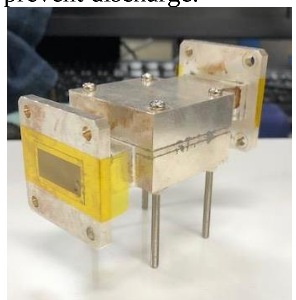

Fig. 9. Coupled waveguide

Fig. 10. Inner surface coated with some materials.

We set the frequency of 9.4 GHz for the discharge experiment due to the resonant frequency of the device. Numerical analysis using Spark3d can monitor changes in the number of electrons as shown in Fig. 11. Experimental configuration is depicted in Fig. 12. The Pulse microwave was generated by a function generator and a signal generator and amplified by TWTA. Then it was inputted to the coupled waveguide though vacuum window. Two power monitors measured the power of the incident wave and the reflected wave respectively, and two oscilloscopes measured the waveform of them. We regarded the increase of the reflected power or distorting the waveform of that as the occurrence of multipactoring.

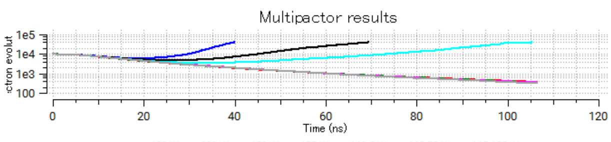

Fig. 11. Results from numerical analysis

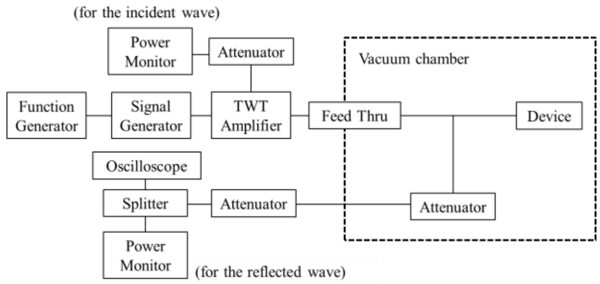

Fig. 12. Experimental setup

Threshold of multipactoring in this device is shown in Fig. 13.

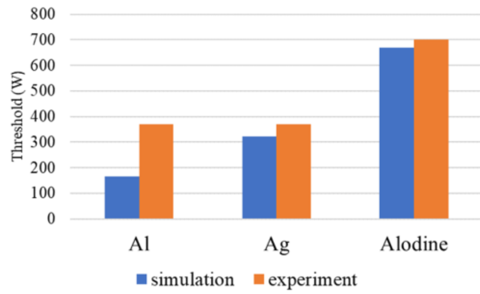

Fig. 13. Threshold of multipactoring

Figure 13 shows that Alodine has the highest RF breakdown power level of the three, which means that Alodine is best suited to prevent multipactors.

2.3 Connector

By inputting high power RF to connector, discharging can be induced as shown in Fig. 8. The gap with around 0.1mm between the connector and micro strip line is often set due to the accuracy of manufacture so this gap can be the cause of discharging as shown in Fig. 14. We focused on this gap and evaluate how the gap affects the occurrence of discharging. Moreover, in the same as the analysis of the coupled waveguide, the effect of material coating was also considered. The results from numerical analysis are only presented in this section.

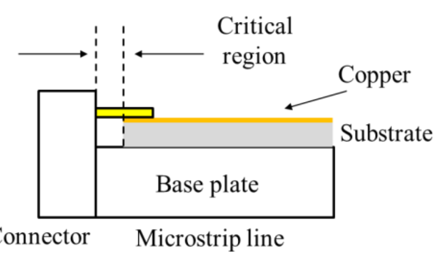

Fig. 14. Critical region for discharging

Frequency on numerical analysis was set 9.65GHz because the burnout was occurred at 9.65GHz. The result is shown in Fig. 15. The threshold of multipactor depends on not only surface coating but also the distance of the gap. Thus, 0.1mm is the resonant condition of electrons at 9.65GHz and we have to avoid this length of gap in the design process.

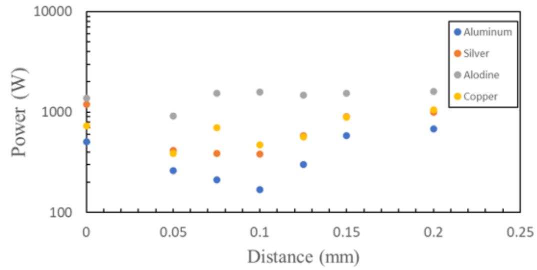

Fig. 15. Multipactoring power level of the connector

4. Future plans

To realize SPS, only ground test is not sufficient because the space environment is more complicated. Following factors of the space environment have a great influence on the discharging; plasma, debris, photoelectrons by sunlight and high energy radiation. It is difficult to simulate and evaluate such complex conditions by only ground testing. Therefore, to consider these effects, we have a plan for on-orbit experiment with the piggyback satellite. The specification of the piggyback satellite is that size is less than 50cm× 50cm× 50cm, and weight is less than 50kg as shown in Fig. 16.

We set two goals of this plan; one is observing the discharging in RF components due to the space environment, and another one is verifying that methods for suppressing discharge also work well in space environments.

To achieve them, there are some challenges. One challenge is how to measure the discharging in space. A simple configuration is depicted in Fig. 17. The power sources are solar arrays or battery and some cameras are used for observing discharge phenomena.

Another challenge is how to realize the high power microwave. High power microwave will be generated by combining of some amplifiers. The prototype of the amplifier is described in the next section.

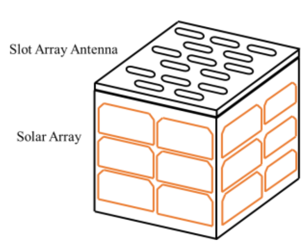

Fig. 16. The image of piggyback satellite

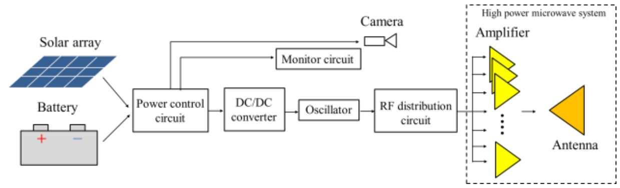

Fig. 17. The configuration of satellite

4.1 The prototype of the amplifier

We are developing the amplifier for small satellite as shown in Fig. 18, and the characteristic is shown in Fig. 19. This amplifier consists of the phase shifter, the driver amplifier, and the power amplifier. When inputting 10mW to this, the output is 2W, so the gain is 22dB. If 64 elements are combined, microwave with 128W can be generated. Based on the characteristic of the high efficiency amplifier, we will proceed the more detailed consideration about this project.

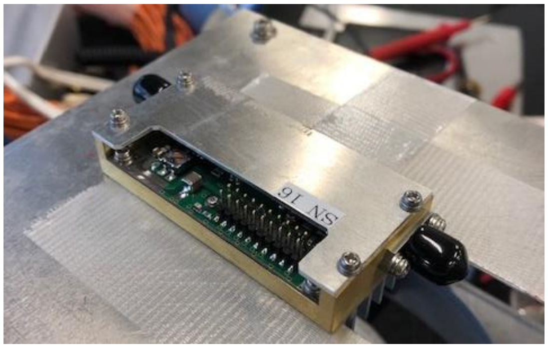

Fig. 18. The prototype of amplifier

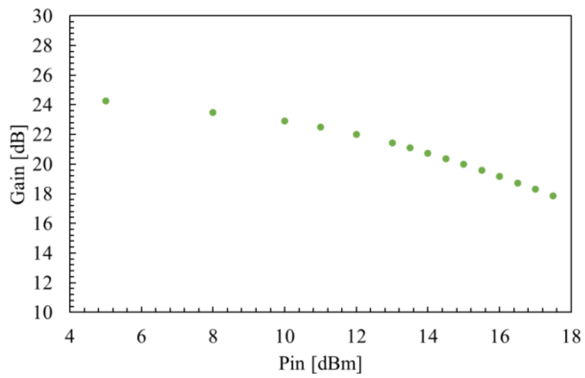

Fig. 19. The characteristic of amplifier

5. Conclusions

We carried out the discharge experiment on some RF devices, and it was found that both the surface coating and the geometry of the devices are critical for the discharging. However, not only discharge phenomena stated in this paper but also other phenomena such as creeping discharge must be considered [11]. Therefore, we will perform further experiment to discuss about the cause of discharge on the connector.

Developing the high efficiency amplifier is currently in progress. Also, we will consider about monitoring systems for discharging.

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