Discharge phenomena experiment on patch antenna surface radiating microwave in space environment

Hyounggwan Woo, Arifur R.Khan, Hirokazu Masui, Mengu Cho

Kyushu Institute of Technology, 1-1 Sensui, Tobata-ku, Kitakyushu, 804-8550, JAPAN

Tatsuhito Fujita

JAXA/ARD

Abstract :

Space Solar Power System (SSPS) transfers enormous amount of electrical energy through microwave. Flight demonstration onboard a small satellite in Low Earth Orbit is now under consideration. When a high power microwave is radiated from antenna in LEO plasma environment, there is a concern about multi-pactoring discharge caused by interaction between the plasma and the microwave. There has been no experimental observation on such interaction phenomenon. Verification experiment is essential for Space Solar Power System to become a reality. According to experiment results, Teflon based patch antenna is more efficient and durable than FR4 based patch antenna.

1. Introduction

The power demand on the Earth is growing exponentially and the associated environmental consequences are becoming significant. Therefore, Space Solar Power System (SSPS) [1,2], is expected as one of the solutions to the problem. Dr. Peter Glaser proposed the concept of a Solar Power Satellite (SPS) in 1968 [3]. The SPS collects solar power using a large-scale photovoltaic array in space and transmitting it to Earth via microwave or laser beam. SPS has recently been renamed as Space Solar Power Systems (SSPS), emphasizing its “system” aspect [4]. Microwave-based SSPS, as shown in Fig. 1, transfers enormous amount of electrical energy in a form of microwave. Before commercialization of SSPS, we must go through various technological demonstrations in orbit. Although the commercial SSPS is envisioned at GEO to supply the continuous power to the ground, the first demonstration of the wireless power transmission between space and the ground will be done using a satellite in low Earth orbit (LEO) for its easy access to the orbit and short distance. The satellite will be surrounded by ionospheric plasma whose density ranges from 10^{10} to 10^{12} m^{-3} , six orders of magnitude higher than the plasma density at GEO. A severe interaction between the surrounding plasma and the antenna is envisioned [5].

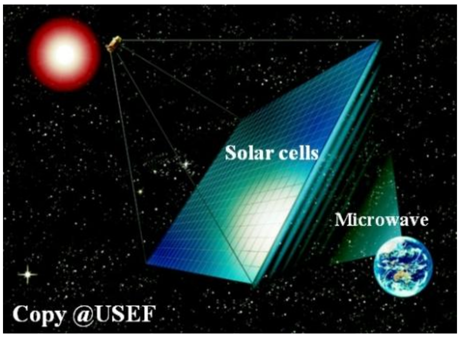


Fig. 1 SSPS concept of USEF

Therefore, before the experiment at LEO, the interaction phenomena must be studied in ground. The purpose of this study is to carry out laboratory experiments to observe the electrostatic discharge phenomena occurring on the antenna surface when it emits a strong microwave in a plasma environment similar to the LEO.

2. Experimental Setup

2.1 Experimental system

We have set-up an experimental system as shown in Fig. 2 that can simulate the radiation of high power microwave in dense plasma in a vacuum chamber. A cryogenic pump (ULVAC) backed by two rotary pumps evacuated the chamber up to a pressure of 1x 10^{-5}[Pa]. The chamber is square in shape with a width of 115cm, depth of 100cm, and height of 75cm. To study the discharge on the patch antennas surface, an antenna was placed inside a vacuum chamber, connected through a coaxial feed-through to the microwave generator (MMG-604V, Microelectronic) placed outside the chamber. It`s oscillation frequency is 5.8GHz±15MHz, and it can generate the power from 0～400W. For safety reason the entire vacuum chamber with all it accessories (plasma source and its power supplies, etc) were kept inside a microwave protective shield. The microwave was introduced to the antenna through the waveguide and coaxial cable. The waveguide and coaxial cable were connected from a waveguide to coaxial adapter.

The input power was measured by monitoring the anode current of the magnetron. A calibration table was made in advance by measuring the output power at the end of the coaxial cable inside the chamber by a power meter.

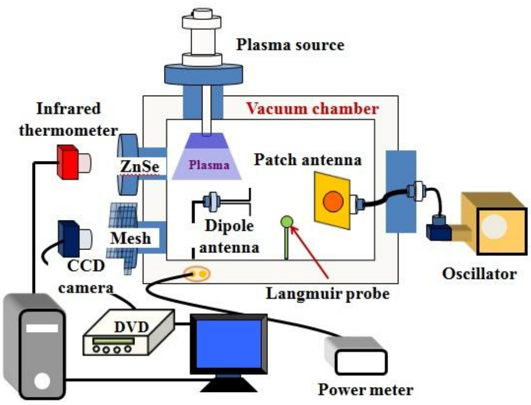


Fig. 2 Experimental System

The radiated power from the patch antenna was detected by a dipole antenna, placed 10cm away, and measured by a power sensor (HP8481B) and power meter (HP437B, Agilent) from the chamber outside. As CCD camera (MTV-6368ND) and an IR thermometer (PI-160, Optris) was also placed outside the chamber to detect the light emission during discharge and monitor the temperature distribution over the antenna surface. To protect the camera and the thermometer from the interference of the microwave, we covered the viewports (glass and ZnSe windows, respectively) by a metallic mesh. The thermometer can measure the temperature from 0℃ to 275℃. The chamber pressure, the radiated power, the input power was recorded simultaneously by a DAQ connected PC run by Labview® program with a sampling rate of 8 Hz. A RF excited radical beam source and RF generator (T857-2, CREATE) placed on the top of chamber produced argon (Ar) plasma, density ranging from 10^{11} to 10^{13}[m^{-3}] with 1eV to 3eV temperature under a back pressure of 2.8×10^{-2}Pa.

2.2. Patch antennas

Microstrip patch antenna basically consists of a radiating patch on one side of a dielectric substrate, which has a ground plane on the other side. The idea of microstrip patch antennas arose from utilizing printed circuit technology not only for the circuit components and transmission lines but also for the radiating elements of an electronic system. The basic structure of the microstrip patch antenna is shown in Fig. 3.

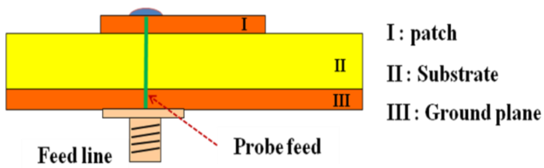


Fig. 3 The basic structure of the microstrip patch antenna

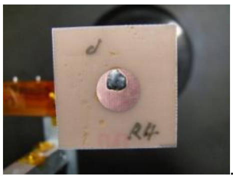
The patch shape can in principle be arbitrary; in practice, a rectangle or a circle is common shape. The antenna patch and the ground plane of the antenna used in this paper were made of copper. We used the 0.02mm thick patch with 8.97mm radius and 1.6mm thick Teflon with 6.68mm radius and 1.6mm thick glass epoxy with 6.83mm radius and 0.8mm thick glass epoxy substrates. The coaxial cable usually has a characteristic impedance of 50 ohms. The input impedance of the patch antenna varies with the feed location. Thus the location of the cable should be at a 50 ohm point of the patch to achieve impedance matching.

2.3. Experiment procedure

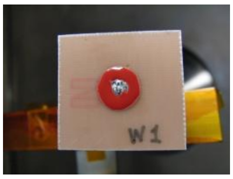
Microwave was transmitted to the patch antenna through the waveguide and the coaxial cable. A calibrated dipole antenna connected to a spectrum analyzer (R3132, ADVANTEST), confirmed the radiation frequency. The dipole antenna also measured the radiated power from the patch antenna. Both radiated and received power was measured by the power meter and recorded to the computer in a time domain. The microwave input power was increased by a 5W step keeping each value for 5 minutes to check whether discharge occurred or not. This process was continued until the discharge was detected by a CCD camera or sudden reduction in the power received. In case of plasma environment, the discharge was confirmed by the CCD camera only.

2.4. Experiment condition

Various substrate materials were tested in the vacuum chamber, such as, LEO equivalent plasma, and excess degassing to verify their effects on the discharge on the patch antenna. The various patch antennas are shown in Fig. 4. Plasma was generated by feeding Ar gas under the oscillation of 13.56MHz.



(a) FR4_1



(b) FR4_2


(c) FR4_3


(d) Circular Teflon

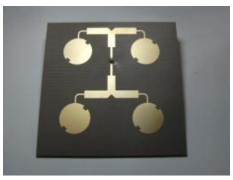

(e) Array Teflon

Fig. 4 Various patch antennas with different preparations

Degassing environment was simulated by painting non-conductive room temperature vulcanized silicon adhesive (RTV-S691). Disk type RTV painting was done on the sample FR4_2 (Fig. 4 _b). Table 1 shows various antenna properties.

Table 1. Various antenna properties

Samples	FR4_1	FR4_2	FR4_3	Circular Teflon	Array Teflon
Material	**FR4**	**FR4**	**FR4**	**Teflon**	**Teflon**
Permittivity[ε_r]	**4.6**	**4.6**	**4.6**	**2.6**	**2.6**
Substrate thickness[mm]	**0.8**	**0.8**	**1.6**	**1.6**	**1.6**
Patch type	**Circular**				**Array**
tan δ	**0.017**	**0.017**	**0.017**	**0.002**	**0.002**

3. Results

We monitored the antenna surface temperature, the radiated power and chamber pressure, etc. while we injected the microwave to the antenna up to 20~60W. Microwave power was raised manually with 5W step after every 5 minutes interval from 0W to 60W. Table 2 shows the results. As we raised the microwave power, temperature rising were observed. Fig. 5 shows the temperature (maximum point) profile on various antenna surface detected by IR thermometer (PI-160, Optris).

Table 2. Experimental result

Samples		FR4_1	FR4_2	FR4_3	Circular Teflon	Array Teflon
Pressure, ×10^2[Pa]		**2.8**	**2.7**	**2.4**	**2.9**	**3.0**
Plasma density, ×10^{12}[m^{-3}]		**0.25**	**0.42**	**3.3**	**4.8**	**2.5**
Incident power [W]	**when received power reduction**	**-**	**15**	**15**	**55**	**-**
	when Emission	**-**	**20**	**-**	**-**	**-**
	Max	**25**	**20**	**25**	**60**	**50**
Max temperature [℃] with incident power[W]		**275, 20**	**275 15**	**252, 15**	**218, 50**	**150, 50**

In case of FR4 based antenna, temperature rising rate was much higher than the Teflon based antenna. Therefore, there is a chance of antenna melting or impedance mismatching that will increase the reflected power. When there was light emission, in case of FR4 type antenna, around power of 15W, the temperature rising became very high and went out of range of the IR thermometer. Therefore, Teflon based patch antenna is more durable.

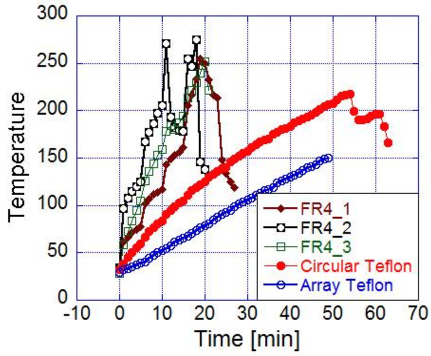


Fig. 5 Temperature variation of each antenna surface

Radiation power from the patch antennas were recorded by the dipole antenna placed 10 cm away. Received power was measured as a function of incident power of various antennas and is shown in Fig. 6. From this graph it is very clear that Teflon substrate antenna shows the better radiation capability based on both power and durability than Glass epoxy substrate antenna (FR4_1, 2, 3). Incident power increment was stopped when light emission or discharge was observed. In case of FR4 based patch antenna, maximum incident power was 25W, where as it was 50W for Teflon based patch antenna. We can conclude the following observation.

1) Light emission and/or discharge is observed on the patch antenna surface.

2) Reduction of radiated microwave power is observed from the patch antenna.

3) Reflected power is increased from the patch antenna

4) Temperature rising is observed on the patch antenna surface.

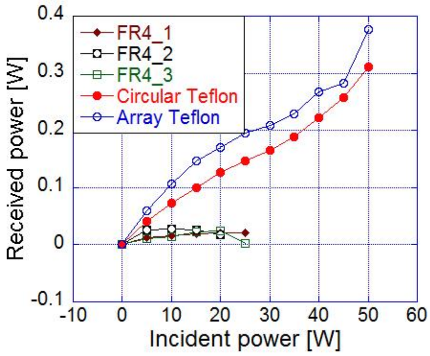


Fig. 6 Difference between the received power of each antenna

Discharge phenomena suggest that the microwave energy is absorbed by the plasma when discharge occurs on the surface of the patch antenna. Surface material is dissolved or evaporated due to temperate rising on the patch antenna surface, that might reduce the discharge threshold. In addition, the plasma changes the output impedance of the antenna. Therefore, there is mismatching of microwave circuit and output impedance so reflected power is increased.

4. Conclusion

From experiment results, it is clear that discharge threshold on the Teflon based patch antenna is much higher than the FR4 based patch antenna. Therefore, we can say that Teflon based patch antenna is more efficient and durable than FR4 based patch antenna.

5. References

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