Wireless Power Transfer at Higher Frequency for SPS and for Commercial WPT

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Abstract: One of the promising future power stations is a solar power satellite (SPS) station in geostationary orbit (36,000 km above the surface of Earth) that uses wireless microwave power-transfer technology. In this system, the power generated would be transmitted to the ground by a microwave beam. The SPS would be a very large satellite with a large transmitting phased-array antenna that would work at 2.45 or 5.8 GHz. The size of the transmitting antennas is theoretically determined by Maxwell's equations. However, we must reduce the size of the antennas to reduce the cost and to produce a small prototype satellite as a first step to the SPS. The only way to reduce the size of the antennas is to use a higher frequency. We developed rectennas that are optimized for 24 and 60 GHz transmission. In addition, we developed a monolithic microwave integrated circuit (MMIC) rectenna for 24 GHz transmission and with dimensions of 1 mm × 3 mm. The maximum radio-frequency to direct-current (RF-DC) conversion efficiency is 47.9% for a 210 mW microwave input power with a 120 Ω load. We also designed a rectenna for 60 GHz transmission whose maximum RF-DC conversion efficiency is 46.2% for a 80 mW input power at 60 GHz with a 100 Ω load. Finally, based on rectenna technology, we propose other satellite experiments.

1 INTRODUCTION

A solar power satellite (SPS) station is a very suitable application for a wireless power transfer (WPT) via radio waves, especially via microwaves (microwave power transfer or MPT). SPSs are one of the promising future power stations for a sustainable power source that uses solar cells (Mankins, 2014). Current SPS design envisions a 2 km diameter antenna that would transmit at 5.8 GHz in space. The beam efficiency between such a transmitting antenna and a 2 km receiving rectenna 36,000 km away is approximately 90% (Shinohara, 2014). The size of antennas is determined by Maxwell's equations and cannot be reduced (Shinohara, 2014). In working toward the SPS, we must carry out small-scale satellite experiments. The low Earth orbit (LEO) of 400 km would be used for such an experiment. If the small satellite system is the same as the SPS at 5.8 GHz, the antenna and the rectenna must each be approximately 200 m long. However, a 200 m antenna is too large for a small satellite; the size limit is more on the order of 10 m. Therefore, instead of simulating a SPS, we use a small satellite to study the other objectives of MPT.

The same problem arises with commercial applications of MPT. Theoretically, the size of antenna required is over 10 m in diameter for MPT over 1 km at 5.8 GHz with 90% beam efficiency. This size is too large for a commercial MPT system to compete with wired power transmission. This is the reason that no commercial MPT system exists in the world. Therefore, we propose WPT at a higher frequency, for example, 24 or 60 GHz. However, there are two problems with WPT at a higher frequency: (1) an increase in absorption by air and (2) a decrease in circuit efficiency and power. The latter problem can be solved by technical means.

2 DEVELOPMENT OF 24 AND 60 GHZ RECTENNA

At Kyoto University, we propose a wireless system that simultaneously transmits information and power in the millimeter wave range. Higher frequency

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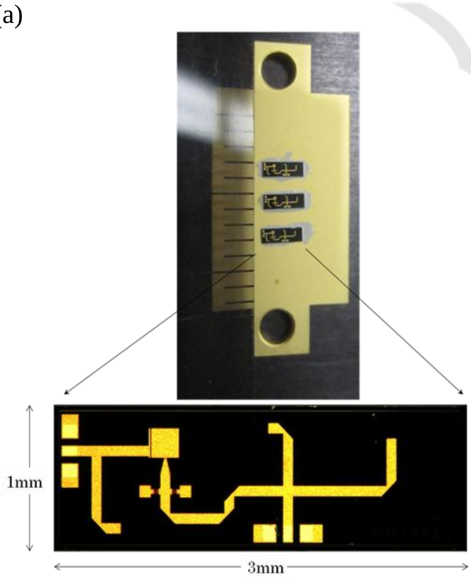
results in higher communication speed and lower antenna sizes. The first application considered is a fixed wireless access system proposed by NTT Corp., Japan (Seki, 2011).

First, we choose 24 GHz, which is in the industrial, science, and medical (ISM) band, and develop a rectifying circuit in the MPT receiver. We normally use a Schottky diode with $\lambda_g/4$ distributed line and a capacitance that is called a “single-shunt rectifier” and with theoretical radio-frequency to direct-current (RF-DC) conversion efficiency is 100%. For example, the maximum efficiency of the proposed single-shunt rectifier is over 90% at 2.45 GHz and is 80% at 5.8 GHz. For the millimeter wave system, we consider that the capacitance is a weak point that prevents optimizing the efficiency. Therefore, we propose a new single-shunt rectifier with a class-F load, which is composed of open stub resonators for even and odd harmonics, instead of the capacitance. The rectifying principle exploited by a conventional single-shunt rectifier and the class-F load rectifier is the same and both have a theoretical RF-DC conversion efficiency (with only one diode) of 100%.

The rectifying circuit is composed of a microstrip line and two diodes in parallel. Dimensions of the developed 24 GHz MMIC rectenna are 1 mm × 3 mm on GaAs [Fig. 1(a)], with a maximum RF-DC conversion efficiency of 47.9% for a 210 mW microwave input signal at 24 GHz with a 120 Ω load [Fig. 1(b)] (Hatano, 2013).

(a)



(b)

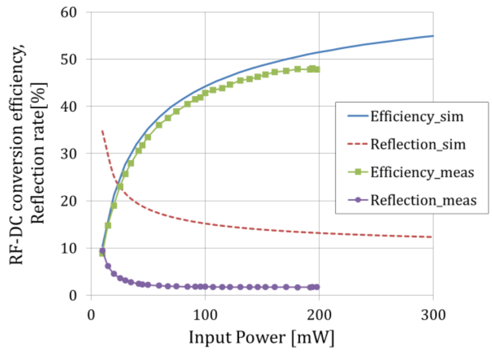


Figure 1 : (a) Developed 24 GHz MMIC rectenna and (b) RF-DC conversion efficiency (Hatano, 2013).

Next, we designed a rectifying circuit that operates at 60 GHz. The rectifying circuit is composed of a microstrip line on a Teflon substrate and two diodes connected in parallel. For the 60 GHz rectifying circuit, we focused on three points to increase the RF-DC conversion efficiency: (1) First is the length of the microstrip line between each diode with a through hall, which in turn is connected to ground plane. Upon changing the length of this microstrip line, the efficiency goes through a maximum and a minimum. (2) Second is the number of corresponding harmonics of the class-F load. We estimated a relationship between the number of corresponding harmonics of the class-F load and the efficiency, and concluded that to increase the efficiency, it is sufficient to use only one stub resonator for a fundamental wave. (3) Finally, the impedance of the class-F load. We increased the impedance of the class-F load. The rectifying circuit designed is shown in Fig. 2. An ADS simulation of the maximum RF-DC conversion gives an efficiency of 46.2% for 80 mW input power at 60 GHz with a 100 Ω load.

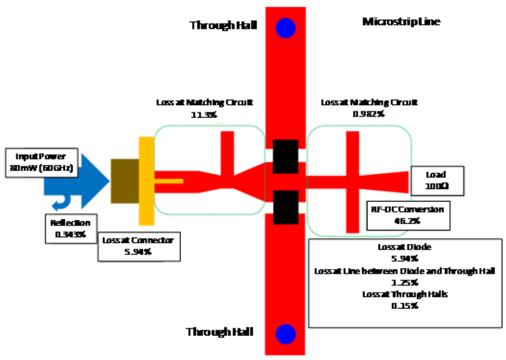


Fig.ure 2 : Designed and simulated 60 GHz rectifying circuit.

Figure 3 shows the frequency dependence of the RF-DC conversion efficiency of rectifying circuits for rectennas developed since the 1960s. The star marks are our contributions, which are at 24 and 60 GHz. The RF-DC conversion efficiency in the millimeter-wave frequency range is sufficient to use millimeter waves for WPT.

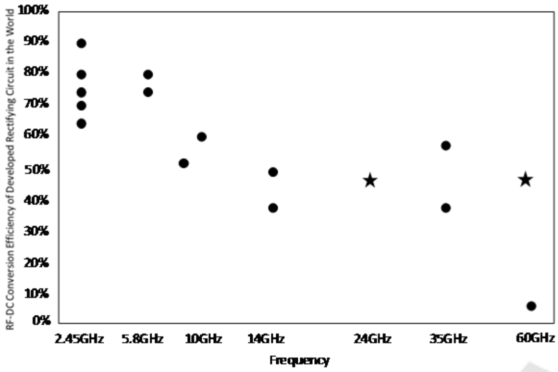


Figure 3 : Frequency dependence of RF-DC conversion efficiency of rectifying circuits for rectennas developed since the 1960s.

3 PROPOSED SATELLITE MPT EXPERIMENT FOR SPS

In 2009 in Japan, the Basic Plan for Space Policy was published, which states "As a program that corresponds to following major social needs and goals for the next 10 years, a Space Solar Power Program will be targeted for the promotion of the 5-year development and utilization plan." We thus need both a technical advance and a "surprise" in the next space experiment based on the Basic Plan for Space Policy. In 2013, the Basic Plan for Space Policy was revised, but it still promoted the SPS for Japan. In addition, the SPS figures in the Japanese "Basic Plan for Energy Policy" from April, 2014.

As a first step to the SPS, a WPT experiment in space or from space to ground is very important. Only three MPT rocket experiments have been done in the world, and they were done in Japan. In 1983, Professor Matsumoto of Kyoto University conducted the first MPT rocket experiment, which was called the Microwave Ionosphere Nonlinear Interaction Experiment (MINIX). This experiment was in collaboration with Kobe University and the Institute of Space and Astronautical Science (ISAS) (Matsumoto, 1986). In the MINIX experiment, they used a 2.45 GHz cooker-type magnetron and waveguide antenna as microwave transmitter. In 1993, Professor Matsumoto's group carried out their second rocket experiment, which was called the International Space Year Microwave Energy Transmission in Space (ISY-METS) experiment (Kaya, 1993). This experiment used a phased array at 2.411 GHz. The MINIX and ISY-METS were space-to-space MPT experiments. The third and last WPT rocket experiment was carried out in 2006, by Professor Kaya of Kobe University, ISAS, and the European Space Agency (Kaya, 2006). This is the only a rocket MPT experiment whose microwave was transmitted from the rocket back to the ground. However, the microwave was diffused and did not qualify as a power beam.

The difficulty of the MPT experiment from space to ground is caused by the low frequency of microwave radiation. A small satellite must orbit at 300 to 400 km. A distance of several hundred kilometers is too far to create a microwave beam at 2.45 or 5.8 GHz (these frequencies are too low). Therefore, we propose an MPT space experiment at 24 GHz that is based on the technologies described in Section 2. In the early 1990s, a 24 GHz MPT satellite experiment was proposed and studied in Japan (Matsumoto, 1993). However, this was a space-to-space MPT experiment. Herein, we propose a space-to-ground MPT experiment.

Using the microwave frequency of 24 GHz has the following advantages and disadvantages:

Advantages

(1) The antenna size of the MPT can be decreased to a tenth of the size of Tx × Rx antenna.

(2) 24 GHz is in the ISM band so there are very few users.

Disadvantages

(1) Efficiency and power are lower than at 2.45 GHz.

(2) Absorption in air is greater.

(3) Technical obstacles are greater.

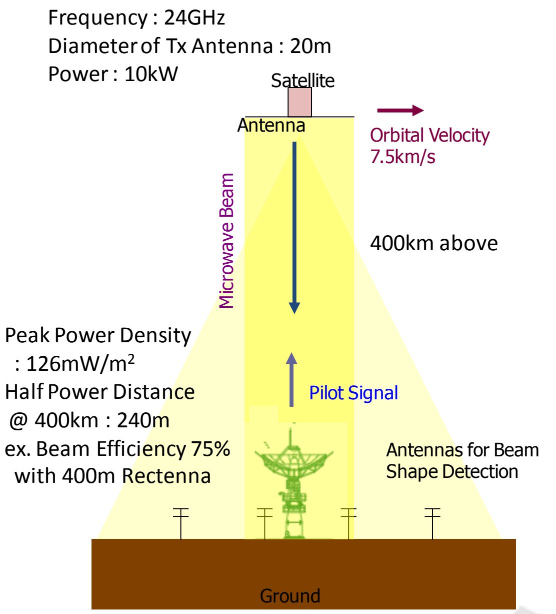


Fig. 4 Parameters of proposed 24 GHz satellite MPT experiment.

However, we can transmit microwave power from a 400 km orbit to the ground with higher beam collection efficiency if appropriately calibrate the values for experimental parameters. Estimated values for the parameters are shown in Fig. 4. With these parameters, we can receive sufficient microwave power from the space. Therefore, provided the requisite technical advance and "surprise," the 24 GHz space experiment can be conducted.

4 CONCLUSIONS

In working toward the SPS, an MPT satellite experiment is desired as soon as possible. However, Maxwell's equations and the required satellite orbit render an effective MPT experiment difficult. Therefore, to perform the MPT satellite experiment, we consider using frequencies of 24 GHz or higher. We have already developed 24 and 60 GHz rectifying circuits for a rectenna with sufficient RF-DC conversion efficiency.

There are still technical problems preventing an MPT experiment with higher frequency. For example, the experiment would require a high-power transmitter and amplifier with high DC-RF conversion efficiency. We hope the advance of radio-wave technologies will support the MPT satellite experiment and realize the SPS.

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