Feasibility Study on Microwave Power Transmission to an Airplane for Future Mars Observation

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Abstract: The objective of the present study is to investigate the feasibility of microwave power transmission to an airplane for future Mars observation. Airplane is a possibility of Mars observation with wide range and high resolution, compared to rover or satellite. Since the surface pressure of Mars atmosphere is much thinner than the Earth, weight reduction is essential to realize airplane flight on Mars. We therefore propose long-time flight on Mars by using microwave power transmission. We conducted terrestrial experiments of microwave power transmission to a prototype airplane. We developed a magnetron-based microwave transmitting system, the frequency of which was fixed with signal injection locking method. Rectennas (receiving antenna + rectifying circuit) were mounted on the prototype airplane for driving a propeller connected to an electric motor. Although autonomous flight was not successful yet, we demonstrated that the prototype airplane could fly by receiving the microwave power.

1 INTRODUCTION

Mars, the fourth planet from the sun, is always of interest to space scientists and astronomers. Lots of Mars exploration programs have been executed since 1960s. The Mars rover “Curiosity”, launched in 2011 and landed on Mars in 2012, provides numerous observation data including images of Martian landscape and properties of Martian rocks and soils.

Airplane is expected as an alternative Mars observation sysytem to satellite and rover. It can move around more widely and quickly than rover, and can take images with better resolution than satellite. However the airplane is technically difficult to gain sufficient aerodynamic lift, because the surface pressure of Mars is only 0.6 % on Mars of that of the Earth. Weight reduction of the airplane is therefore essential to realize the flight on Mars.

We propose microwave power transmission (MPT) as power supply to a Mars observation airplane. MPT can reduce the airplane weight by replacing battery or fuel with rectenna (receiving antenna + rectifying circuit). It can also realize a long-time flight by supplying electricity continuously from a long distance. Figure 1 shows a conceptual image of a Mars observation airplane driven by MPT. The transmitting system will be placed on Mars and electricity will be transferred to the airplane via microwave. With detecting the airplane position, the microwave beam will be always focused on the airplane.

The objective of the present study is to investigate the feasibility of MPT to an airplane for future Mars observation. In this paper we describe a magnetron-based microwave transmitting system, a prototype airplane, and terrestrial MPT demonstration to the prototype airplane, with referring to the previous research outcomes (Iwashimizu, 2014, Nagahama, 2012, 2011).

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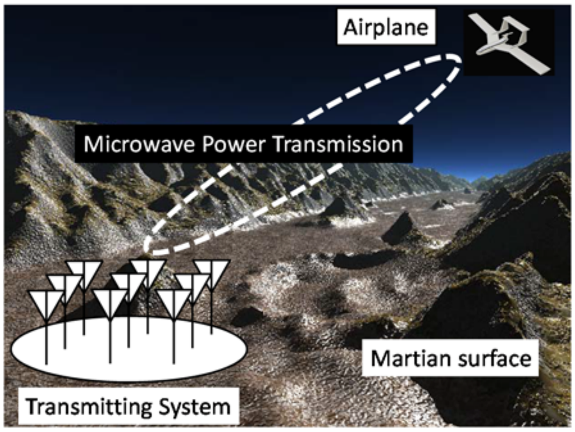

Figure 1: Conceptual image of a Mars observation airplane driven by microwave power transmission.

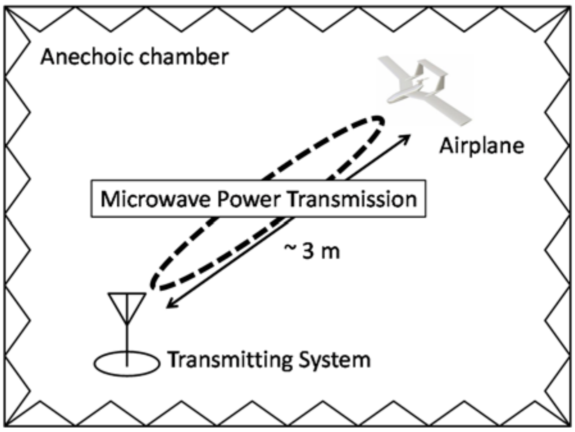

Figure 2: Schematic of terrestrial MPT experiments to a prototype airplane.

2 SYSTEM REQUIREMENTS OF TERRESTRIAL EXPERIMENTS

Specifications of Mars observation airplane under consideration are shown in Table 1. When we utilize MPT for a Mars observation airplane, the power required for a propeller motor must be transferred continuously. Then the power density at the main wing, on which rectennas will be mounted, is estimated to be 818 W/m^2, assuming that the rf-dc conversion efficiency of the rectenna is 63 %. Since we cannot conduct MPT from such a long distance of 100 m as a feasibility study, the estimated power density becomes the criterion for the power density of terrestrial MPT experiments.

Table 1: Specifications of Mars observation airplane (under consideration).

Airplane weight	1.81 kg
Velocity	50.9 m/s
Main wing area	0.256 m^2
Power required for motor	132 W
Flight altitude	Order of 100 m

The objective of terrestrial experiments is to realize battery-less stable flight by MPT. A schematic of the terrestrial experiments is shown in Figure 2. The experiments were conducted in an anechoic chamber and the distance from the transmitting system to a prototype airplane is about 3 m. Under the configuration, kW-class microwave power is necessary to meet the required power density. We therefore adopt magnetron, which is available for microwave oven, as microwave generator.

3 MAGNETRON-BASED MICROWAVE TRANSMITTING SYSTEM

The transmitting frequency of MPT must be fixed from the viewpoint of rectenna design with high rf-dc conversion efficiency. Also the output power must be controlled to realize stable flight because the distance between the transmitting systems and the airplane fluctuate constantly. Moreover, the output phase of each transmitting antenna element must be controlled when we introduce phased array for the transmitting system. However a magnetron is a free-running oscillator and its frequency shifts by its driving current (anode current), temperature and output load.

We therefore developed a power-variable phase-controlled magnetron (PVPCM). A great feature of PVPCM is that its output power can be controlled with keeping its frequency and phase locked to those of reference signal. A schematic diagram of a PVPCM is shown in Figure 3. An injection locking method (Sivan, 1994) is used for locking the magnetron frequency to the reference signal frequency. Also phase synchronization is realized by comparing phases of the magnetron output and the reference signal and adjusting the reference signal phase via the phase shifter 2. The phase shifter 1 is used for controlling the microwave beam direction when we apply phased array to the transmitting system.

We succeeded in developing a PVPCM, whose frequency was fixed at 2.44575 GHz and whose output power could be controlled from 450 W to 860 W (Nagahama, 2011).

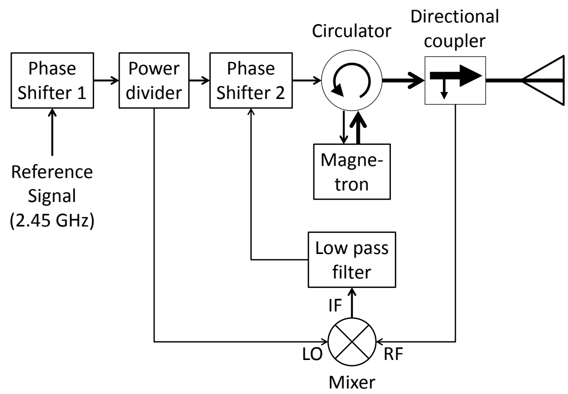

Figure 3: Schematic diagram of a power-variable phase-controlled magnetron (PVPCM).

We demonstrated microwave beam forming by a phased array composed of two PVPCMs. Figure 4 shows a photograph of the PVPCM phased array. Two PVPCMs were set in a horizontal plane. The horn antenna spacing was 0.409 m.

Figure 5 shows experimental results of microwave beam patterns by the PVPCM phased array. When two PVPCMs were in phase, the microwave beam was focused on the broadside direction. We confirmed that the beam direction was controlled by setting the phase difference between two PVPCMs. We obtained the antenna gain of 20 dBi including array factor and element factor of horn antenna. Also we confirmed that we could adjust the power density at the receiving point by controlling the output power.

Figure 4: Photograph of a PVPCM phased array. The phased array was composed of two PVPCMs.

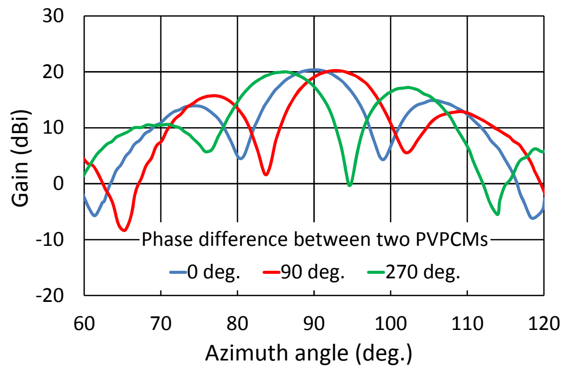

Figure 5: Experimental results of microwave beam patterns of the PVPCM phased array.

4 PROTOTYPE AIRPLANE

Figure 6 shows a schematic of a prototype airplane. The prototype airplane was made of polystyrene foam, and driven by a propeller attached to an electric motor. The red circles in Figure 6 indicate the places where rectennas were allocated. Six rectennas were mounted on the airplane without interfering with each other in the light of electromagnetic field.

Figure 7 shows a photograph of our developed rectenna. The rectenna consisted of cross dipole antenna and rectifying circuit. The cross dipole antenna was chosen because it can receive sufficient microwave power even under a various attitude of the airplane. The measured rf-dc conversion efficiency of the rectrenna was 63 % when the output load was 100 Ω (Nagahama, 2012). On the airplane, all the rectennas were connected in pallalel for the purpose of impedance matching with the electric motor.

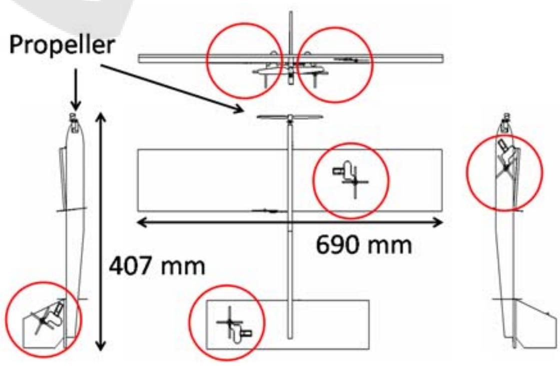

Figure 6: Schematic of a prototype airplane. The red circles indicate the places where rectennas were allocated.

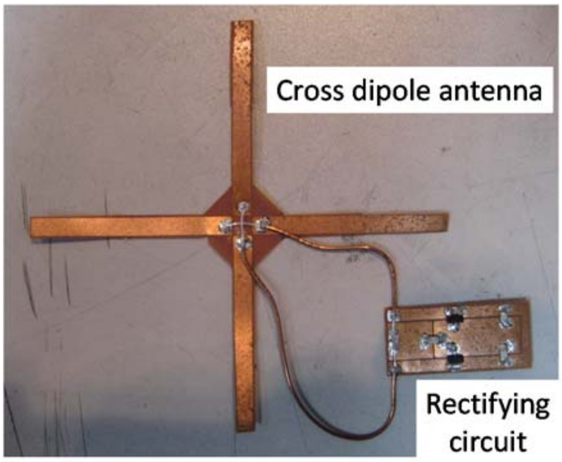

Figure 7: Photograph of a rectenna. The rectenna was composed of cross dipole antenna and rectifying circuit.

5 DEMONSTRATION FLIGHT

We conducted two types of demonstration flight in the anechoic chamber: straight flight and circular flight. Figure 8 shows a photograph of the demonstration of circular flight. In both cases, the transmitting system was composed of a single magnetron and horn antenna. The horn antenna direction was mechanically controlled towards the prototype airplane. The output power was 800 W. In the case of circular flight, the prototype airplane was suspended from above by gut. We confirmed that the prototype airplane was driven by MPT in both cases.

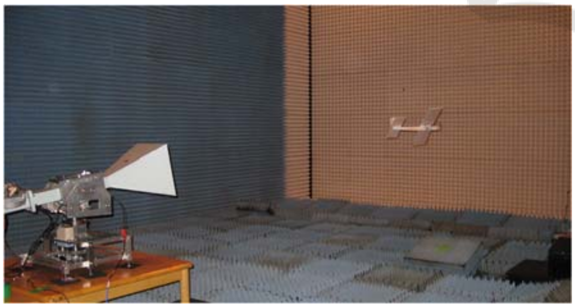

Figure 8: Photograph of demonstration flight. The transmitting system was composed of a single magnetron. The transmitting antenna direction was mechanically controlled towards the prototype airplane.

6 CONCLUSION

We succeeded in demonstration flight of the prototype airplane by MPT without battery and fuel. Adoption of phased array for the transmitting system will be the next step for a long-distance and long-time flight. Precise direction detection of the prototype airplane will be also necessary to realize autonomous flight.

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