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A MAV Flight using Microwave Power Supply

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A Micro Aerial Vehicle flight system using microwave power supply was developed. In a rectenna system, eight rectennas were arrayed and connected in parallel to drive an electric motor on an MAV model. Output voltage of 250mV and current of 6.8mA was obtained at the altitude of 62cm from the transmitter emitting 3.5W power in total. In a tracking system, two pairs of receiver patch antennas with a leaf pattern were set in rectangular coordinates to detect the position of the MAV while it is circling over the transmitter. Moreover, real time output power measurement was conducted during the MAV circling.

Nomenclature

λ	=	wavelength
d	=	array pitch
D	=	array antenna diameter
θ_{str}	=	steering angle
δ, φ	=	phase difference
η	=	conversion efficiency
R	=	external load resistance
V	=	detector output
α	=	incident angle of the pilot signal to the antenna
x, y	=	coordinates

I. Introduction

A Micro Aerial Vehicle flight powered by microwave beam has been planned in the Department of Aeronautics and Astronautics, the University of Tokyo, as a part of 21st century Japanese Center of Excellent projects.

Wireless energy transmission using microwave has been intensively studied as the technology for the Solar Power Satellite (SPS) system, in which microwave is transmitted from a satellite to the ground. [1,2]

Figure 1 shows the concept of microwave power supply system. A MAV working over the area struck by disaster, for example, comes to the power station when its battery becomes low. The battery is charged by receiving the microwave beam transmitted from a phased array transmitter while it is circling above the power station and goes back to the working area without landing and take-off.

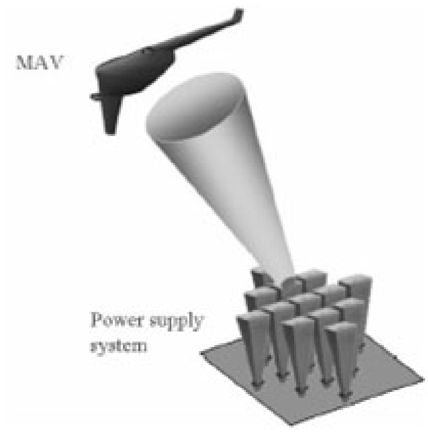

Figure 1. Concept of wireless energy transmission system to MAV.

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Figure 2 shows the system developed in our laboratory. [3] It consists of three systems; the transmitter system, the rectenna system, and the tracking system. In the transmitter system, a microwave beam is formed and steered using a phased array antenna and in the rectenna system, the microwave received by an antenna is converted to DC power by a rectifier. In the tracking system, the position of the MAV is detected using a pilot signal and the information sends to the transmitter system.

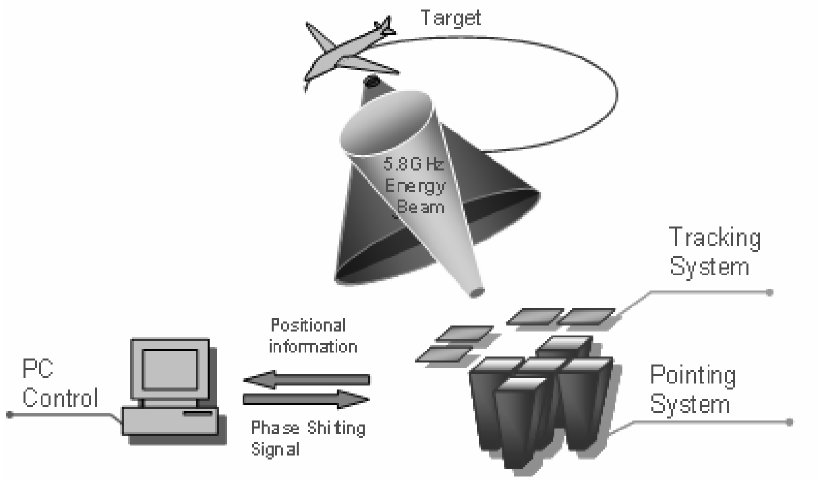


Figure 2. System of microwave power supply to MAV.

A. Transmitter System

Pointing of the microwave beam was achieved by controlling the phase of element microwaves of the antenna array called the phased array system, not by mechanical control of the antenna's attitude. Table 1 shows its specifications. Figures 3 and 4 show the picture of the microwave circuits and geometry of the antenna, respectively. Five horn antennas were used for the antenna elements. Each horn antenna transmits 0.7W power and each phase of microwaves was controlled by the phase shifter connecting a PC.

The beam divergence was about 9deg, which corresponds to the beam quality factor M^2=1.6. The beam steering angle was from -9deg to +9deg.

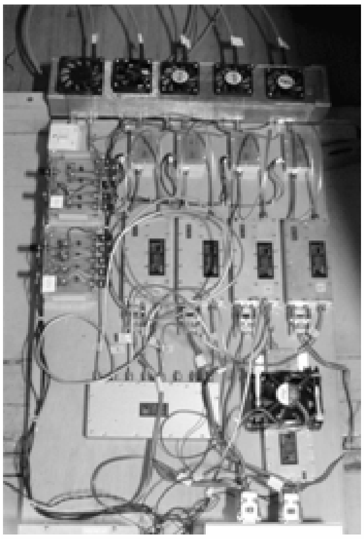


Fig. 3. The picture of the antenna array system.

Table 1. Specifications of the five-element phased array antenna.

Parameters	values
microwave frequency	5.8GHz
wavelength, λ	51.7mm
total transmission power, P	3.5W
array pitch, d	110mm (d/λ=2)
diameter of the array, D	330 mm

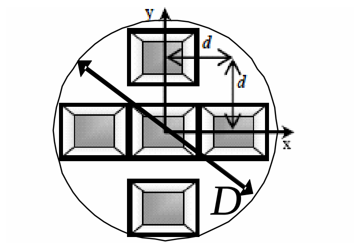
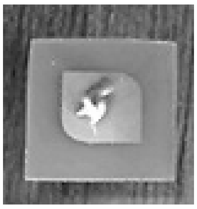


Fig. 4. Geometry of the five arrayed antenna elements.

B. Rectenna System

The rectenna system consists of a receiver antenna on the front side and a rectifier circuit on the back side. (Fig.5) The patch antenna for circular polarization with a leaf pattern was used as a receiver antenna for constant power conversion at various MAV's yaw angle with respect to the polarization axis of the transmitted wave. The dependence of rectification efficiency η on the external load *R* was measured and plotted in Fig. 6. The maximum efficiency of η=23% was obtained at *R*=150Ω.



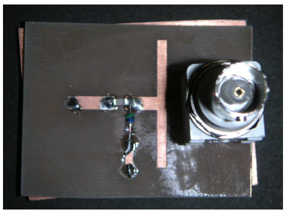


Fig. 5 A leaf pattern patch antenna (left) and rectifier circuit (right).

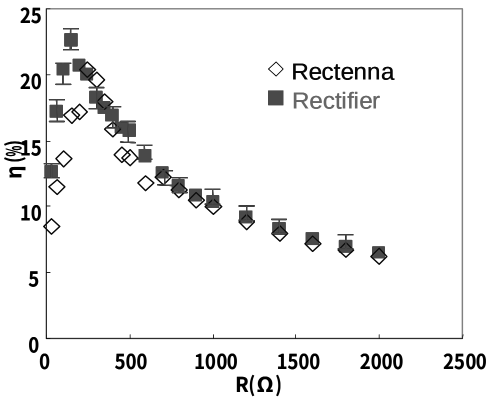


Fig. 6. Relation between the rectifying efficiency and the external load.

C. Tracking System

In the tracking system, the software retro-directive function is employed. This system receives the pilot signal of 2.45GHz microwave sent from the MAV and analyzes its current position using the phase difference. Figure 7 shows the block diagram tracking system.

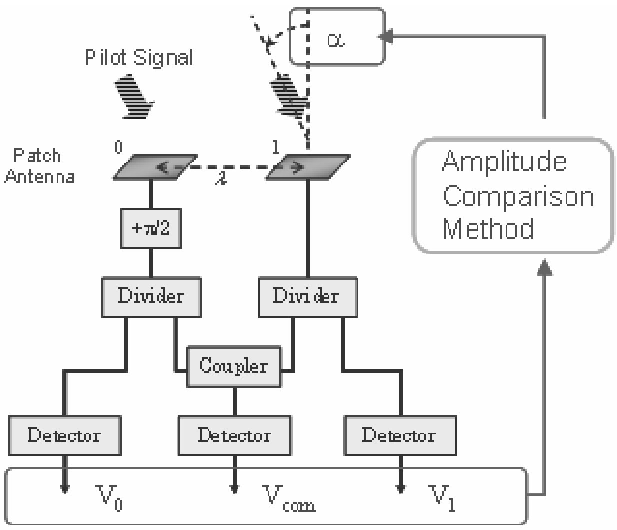


Fig. 7. The block diagram of tracking system.

As a receiver, two patch antennas were aligned with the pitch of λ. An analog phase shifter was inserted in one line to make π/2 of phase difference to each other. Divided and coupled microwave signals are rectified using a commercially available detectors. Finally three DC outputs V_0, V_{com}, V_1 are read in the PC. The incident angle of a pilot signal α is computed by a LabVIEW program. Figure 8 shows the relationship between incident angle α and output signal V_{com}.

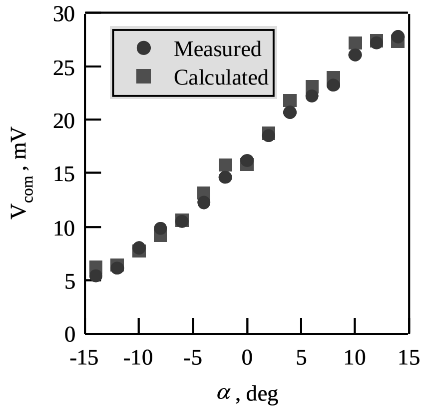


Fig. 8. Relation between incident angle α and output signal V_{com}.

II. Rectenna array

The rectification efficiency of single rectenna is plotted on a contour map taking the external load resistance on the ordinate and microwave power density on the abscissa in Fig. 9. The rectification efficiency is the function of microwave power density as well as of external load as previously shown in Fig. 6.

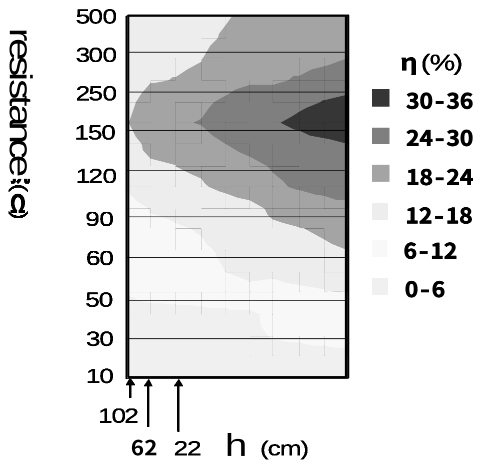


Fig. 9. Contour map of the rectification efficiency of single rectenna. The external load resistance is on the ordinate and microwave power density on the abscissa. Corresponding altitude from the transmitter is indicated by the arrows.

To obtain electric power enough to drive the electric motor on an MAV whose minimum driving power is 200mV and 6mA, rectenna must be arrayed and connected in parallel. Figure 10 shows the eight-element rectenna array. The rectifier circuit is attached perpendicular to the patch on its back side to minimize the pitch of the antennas and to maximize the power reception efficiency.

Figure11 shows the rectifying characteristic of single and eight-rectenna arrays at 62cm from transmission antenna. The measured output voltage of eight-element array was slightly lower than the predicted. Output voltage of 250mV and current of 6.8mA was obtained at the altitude of 62cm from the transmitter. It is enough to drive the electric motor we have.

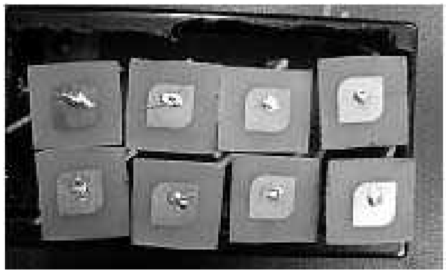


Fig. 10. The picture of eight-rectenna array. Rectifier circuit attached perpendicular to the patch on its back side to minimize antenna pitch.

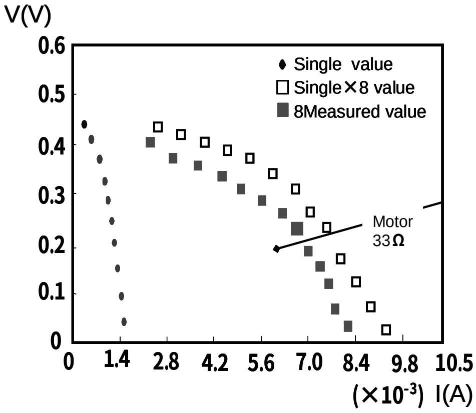


Fig. 11. *I-V* characteristics of single and eight-rectenna arrays. Solid line shows the motor load characteristics. The transmitted power was 3.5W in total.

III. Tracking in 2-Dimensional Space

For tracking a MAV while it is circling, two units of antenna system shown in Fig. 7 were set as indicated in Fig. 12. The incident angles in rectangular coordinates α_x and α_y are analyzed using a LabVIEW program in a PC. Leaf pattern antennas same is employed to detect the linearly-polarized wave despite the MAV yaw angle.

In our previous research, only V_{com} was used to analyze the incident angle because the distance between transmitter and receiver was constant and V_1 and V_2 are constant too. When the distance is not constant, variation of V_1 and V_2 as well as V_{com} will be analyzed for angle detection.

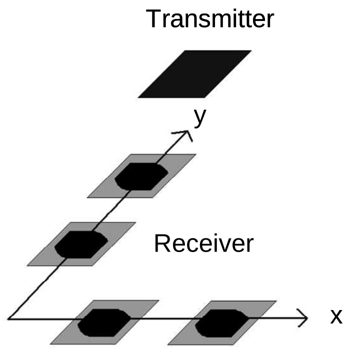


Fig. 12. Antenna arrangement for 2-dimensional tracking.

IV. Power Transmission Demonstration

An electric motor with a propeller of 6cm in diameter was mounted on a MAV model (Fig. 13) and the output voltage from the rectenna array was measured while the model is circling. Figure 14 shows the installation of equipment for power transmission demonstration. The MAV model circles over the transmitter antenna at the altitude of 62cm using another electric motor, while the microwave beam was steered and fixed on the point (α_x, α_y)=(0, -12deg). The output voltage from the rectenna array was measured in one cycle of the MAV as shown in Fig. 15, in which the solid line at 0.2V means the minimum requirement for operation of the motor on the MAV. The main lobe (the left side peak in Fig.15) and the side lobe (the right side peak in Fig.15) was measured at the expected point. At the point of main lobe the output voltage satisfied the condision of motor operation though it also satisfied at the point of side lobe.

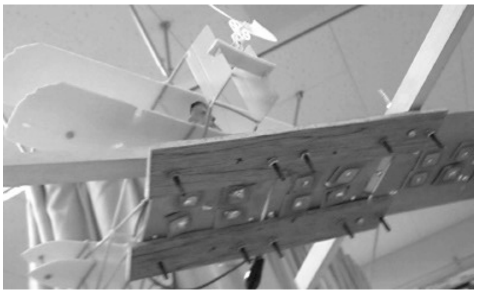


Fig. 13. The picture of the MAV model equipped with a rectenna array and an electric motor.

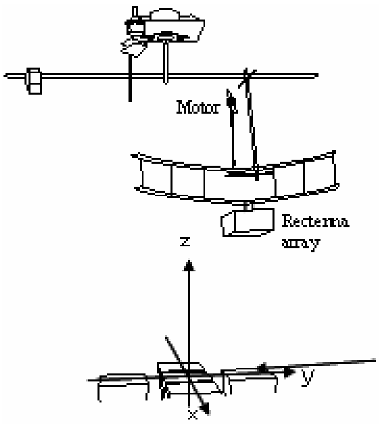


Fig. 14. Installation of equipment for power transmission demonstration.

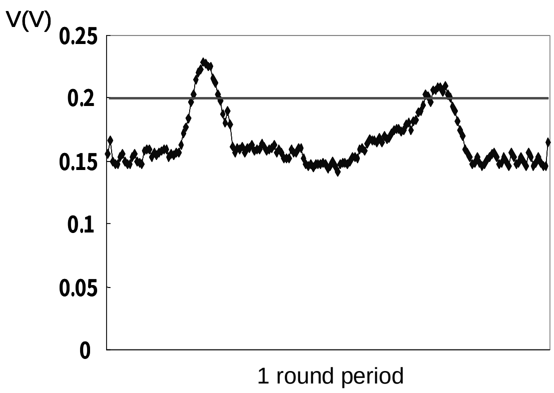


Fig. 15. Rectenna output voltage during one MAV model revolution. The MAV model circles while the microwave beam was fixed on the point (α_x, α_y)=(0, -12deg). Output voltage of 0.2V is the minimum requirement for operation of the motor.

V. Conclusions

In the rectenna system, eight rectennas were arrayed and connected in parallel minimizing the array pitch to drive an electric motor. As a result, output voltage of 250mV and the current of 6.8mA were obtained at the altitude of 62cm from the transmitter emitting 3.5W power in total.

In the tracking system, two units of antenna system with a leaf pattern patch were set in the rectangular coordinates to track a circling MAV. Three output signals V_{com}, V_1 and V_2 will be used for more precious position detection than the conventional method using only V_{com}.

Finally, the output voltage from the rectenna array was measured in one cycle of the MAV. Although real time tracking and synchronization between the beam and MAV have not been achieved yet, the power enough to drive an electric motor was obtained at the altitude of 62cm.

Acknowledgments

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