Power Beaming and Its Application to Aerospace Propulsion

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Abstract

Wireless energy transmission system to a Micro Aerial Vehicle is now under development. A 5.8 GHz microwave phased array antenna and rectenna array receiver have been developed. An electric motor on a circling MAV model was driven by the transmitted power. In addition, 140GHz millimeter-waves of up to 1MW was beamed to a "Microwave Rocket" and its thrusting has been successfully demonstrated.

Introduction

Power beaming using electromagnetic waves has a potential for future applications in wireless energy transmission to automobiles, aircrafts, and space vehicles as well as to mobiles devices such as cellular phones, etc. Although a laser beam has better directionality than a microwave beam, microwave is much safer than laser for a human body. In addition, energy conversion efficiency is higher and price is lower in microwave oscillators and receivers than in laser ones.

In the University of Tokyo, a Micro Aerial Vehicle (MAV) flight using wireless energy transmission was planned as part of a 21st century Japanese Center of Excellent project. The technology has been studied intensively for the system from Solar Power Satellite (SPS) to the ground. [1,2] As its spin-off, phased array transmitter system has been developed. (Fig. 1) The system consists of a transmitting sub-system, rectenna sub-system, and tracking sub-system. Details of each sub-system are described in the following sections. It can steer the beam by tracking a MAV model while it is flying over the antenna. A motor on the MAV model was driven by transmitted power.

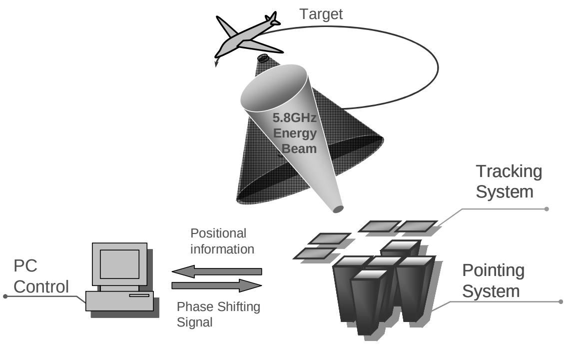

Fig. 1 The system of microwave energy transmission to a MAV.

A "Microwave Rocket" is one of air-breathing Beamed Energy Propulsions and the new concept space launch system which can deliver massive materials at quite low launch cost and is expected to be a primary transportation system for the construction of future space infrastructures.[3] Propulsive energy is provided to the vehicle by the energy transmitted from the ground instead of loading a heavy energy source on itself and atmospheric air is utilized as propellant during the air-breathing mode.

When a high power pulsed microwave beam is provided into a focusing reflector, atmospheric discharge arises. (Fig.2) Induced plasma absorbs the following part of the microwave pulse and expands outwards while generating a shock wave. The shock wave drives impulsive force to the reflector. In 2003, a single pulse experiment was conducted. The measured momentum coupling coefficient C_m, a ratio of propulsive impulse to input power, was over 400N/MW. A vertical flight experiment was also conducted and 2-m altitude flight was demonstrated.[4]

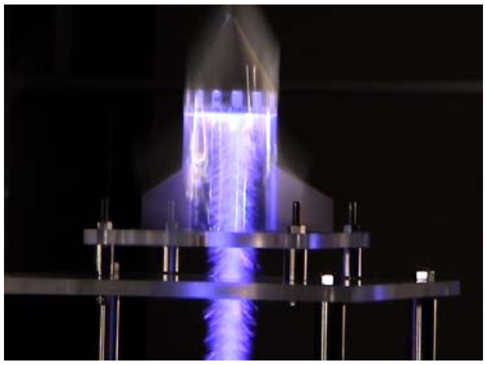

Fig. 2 Microwave Rocket

Energy transmission to a MAV

Transmission system

Figures 3 and 4 show a block diagram of the power transmitter system and the geometry of the five antenna elements of the array, respectively. Table 1 does its specifications [5]. Array of five rectangular horn antennas was used for a transmitter. Each horn antenna transmits 0.7W power with phase control. The phase shifter of each antenna element was controlled by a PC for element microwave beams to form a single beam in the far field.

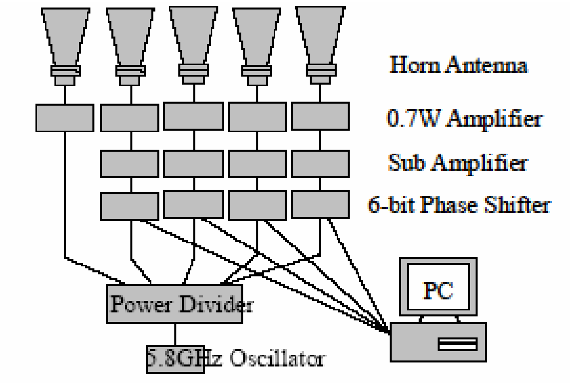

Fig. 3 Block diagram of the transmitter system.

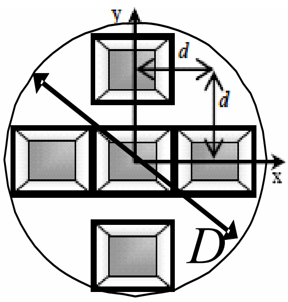

Fig. 4 Geometry of the five antenna elements of the array.

Table 1 Specifications of the transmitter system

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

The beam divergence was constant as about 9deg, which corresponds to the beam quality M^2=1.6. Beam steering angle θ_{str} is a function of the phase difference δ and array pitch d between the neighboring elements as $\sin\theta_{str}=\lambda\delta/2\pi d$. The beam was steerable from -9deg to +9deg.

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. Output voltage and current curves for single and eight-element rectennas were plotted in Fig.6. The maximum efficiency of 23% was achieved.

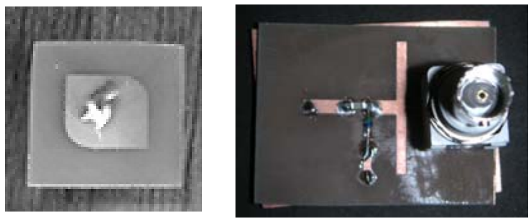

Fig. 5 A leaf pattern patch antenna (left) and rectifier circuit (right).

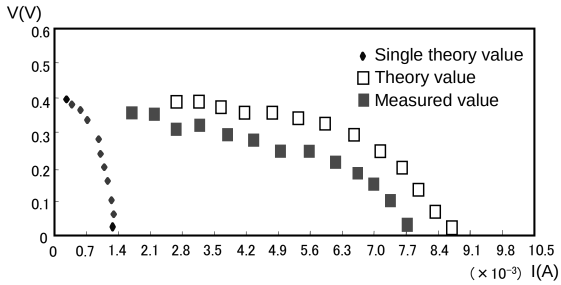

Fig. 6 Output voltage and current curve for single and eight-element rectennas at the altitude of 60cm, where microwave power density is about 10mW/cm^2.

Tracking System

Software retro-directive system is employed. Figure 7 shows the block diagram of tracking system. A MAV sends a pilot signal of 2.45GHz microwave. Two patch antennas were aligned with the pitch of λ. Phase difference of π/2 has been added between two antenna signals. The signals are divided, and coupled, and rectified. Finally three DC outputs V_0, V_{com}, V_1 are read by LabVIEW system in PC.

The relationship between incident angle α and output signal V_{com}/V_1 is shown in Fig. 8. The detectable range of α is -13deg to +13deg. With two pairs of the patch antennas placed in two axes, we can know the MAV position in two dimensional space.

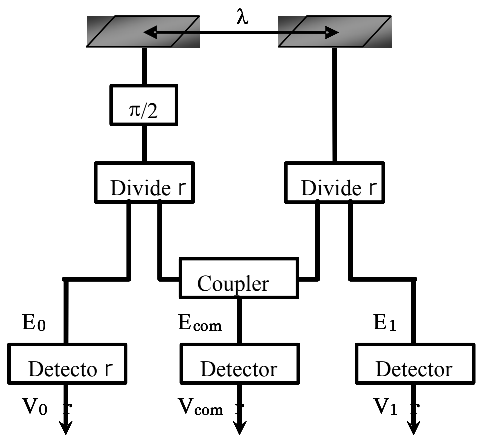

Fig. 7 Block diagram of tracking antenna system.

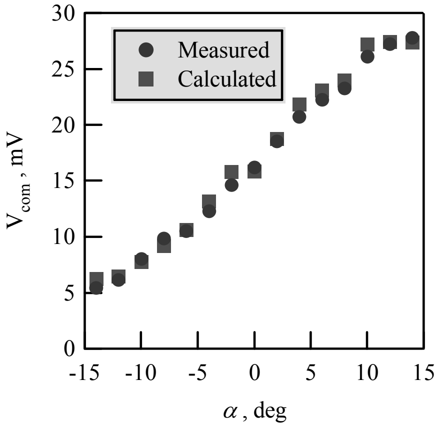

Fig. 8 Relationship between incident angle α and output signal V_{com}/V_1.

Demonstration of power transmission to MAV

An electric motor with a propeller of 6cm in diameter was mounted on a MAV model and driven by the transmitted microwave power while the model is circling. (Fig. 9) To drive the motor, 1.2mW in power and 200mV in voltage are needed.

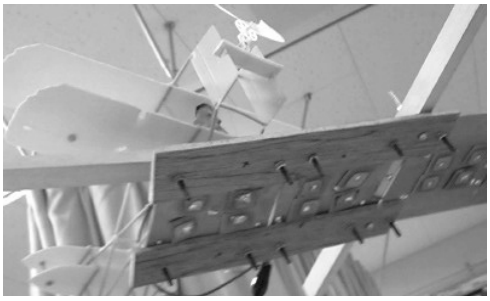

Fig. 9 The picture of the MAV model equipped with a rectenna array and an electric motor.

Although the transmitted power from the phased array was only 3.5W, an electric motor on a MAV model flying at the altitude of 60cm was successfully driven by the transmitted microwave power.

Microwave Rocket

Microwave Generator

A 170GHz gyrotron developed as a plasma heating device for International Thermonuclear Experimental Reactor (ITER) was used as a beam source. Its maximum output power and energy converting efficiency is 1MW and 50%, respectively.[6]

Microwaves are guided to the launch site using a corrugated waveguide and are transmitted from the waveguide outlet through a Si-N or a diamond window. The beam profile is 0th order Gaussian and its beam waist is 40mm.

Plasma Ignition and ionization front propagation

The microwave beam was focused on a parabola reflector. The high speed camera photographs show that the ignition occurs in the atmospheric air in the vicinity of the focal point. (Fig.10) The ionization front was propagated in three directions. [7] The left branch absorbs the microwave beam power directly and glows up to a big branch. On the other hand, two small spokes absorb the microwave reflected on the parabola reflector. The spokes are supported by leak power and cannot be a big branch.

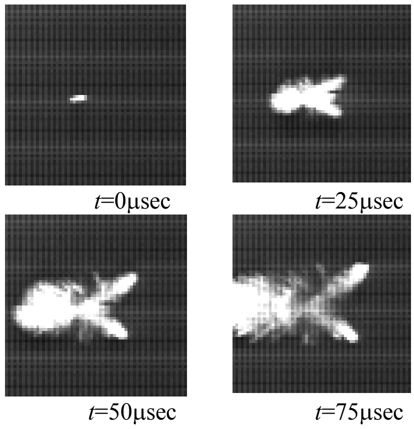

Fig.10 Plasma ignition. Beam comes from the left and parabola reflector is set on the right in pictures.

Figure 11 shows the photographs of discharge development. The ionization front propagates upstream of the microwave beam at a constant velocity.

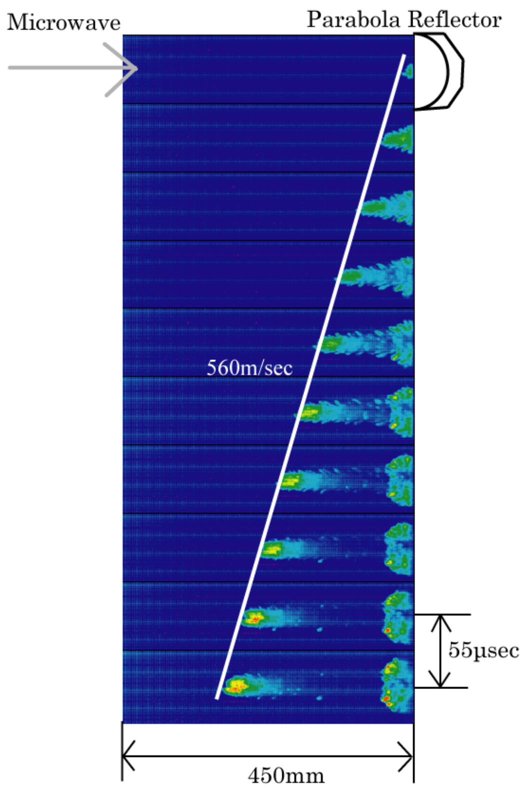

Fig. 11 An ionization front propagation in a microwave beam.

The dependency of propagation Mach number of the ionization front M on the microwave power density S was plotted in Fig.12. The propagation Mach number M increased with S and when power density is 75kW/cm^2 =S^*, M was equal to unity. The velocity become supersonic at the condition S>75kW/cm^2.

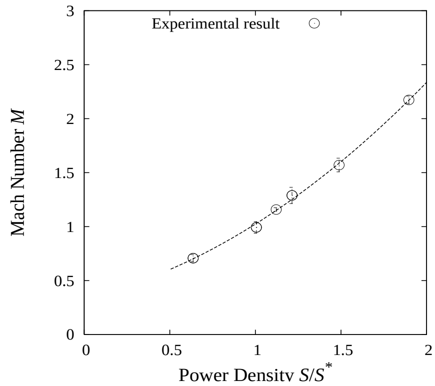

Fig. 11 Dependence of propagation Mach number *M* of the ionization front on power density *S*.

Single Pulse Operation

The momentum coupling coefficient C_m, a ratio of thrust impulse to the input energy, has a peak value of about 400Ns/MJ at the condition where M is about 1.2 as shown in Fig. 12. It suggests that the microwave power is efficiently converted to the pressure through a shock wave induced ahead of the ionization front.

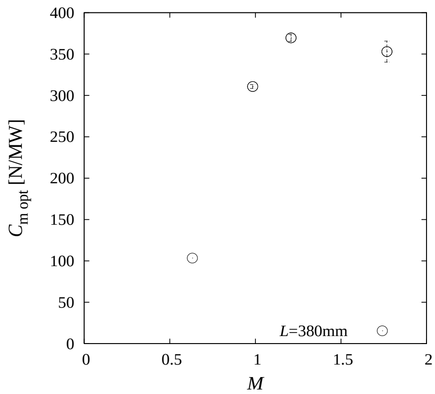

Fig.12. Momentum coupling coefficient C_m and propagation Mach number of the ionization front *M*.

Repetitive Pulse Operation

In repetitive pulse operation, fresh air replaces the heated gas in the thruster during the pulse interval. In the simple pulse operation, fresh air is partially refilled through pressure oscillation after the exhaust and passive air refilling takes far longer time than the pulse interval.[8] However, during the actual Microwave Rocket flight, fresh air will be taken from the front of the vehicle in its Ramjet mode flight and also the propellant gas be injected from the front in its Rocket mode flight. Therefore, a thruster model with a forced breath system was developed and pressure histories in the thruster were measured. (Fig. 13)

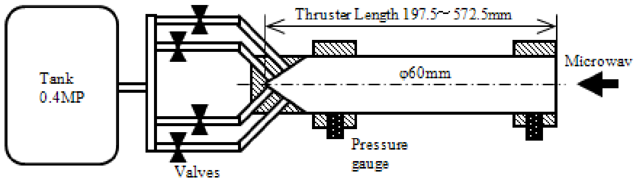

Fig. 13 A thruster model with a forced breath system for repetitive pulse operations.

Measured thrust impulse in the repetitive pulse operation I was smaller than that in the single pulse operation I_{single} in most cases. However, the ratio I/I_{single} was found a function of the partial filling rate u/Lf, which is a fraction of thruster volume that is replaced by the fresh air during the pulse intervals, as shown in Fig. 14. When the partial filling rate is unity or greater, I became identical to I_{single}.

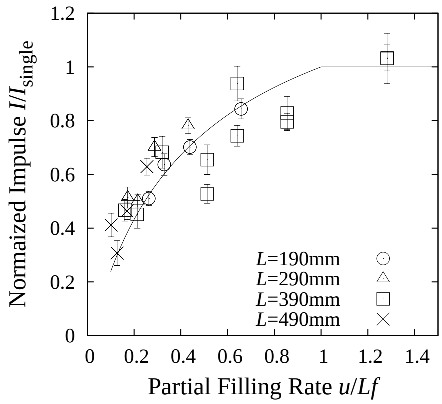

Fig. 14 Measured thrust impulse and the partial filling rate in the repetitive pulse operation.

Conclusion

In the wireless energy transmission to a MAV model, a phased array transmitter, software retro-directive tracking system, and rectenna array receiver with leaf patch antennas were developed.

Although the transmitted power from the phased array was only 3.5W, an electric motor mounted on a MAV model flying at the altitude of 60cm was successfully driven by the transmitted microwave power.

In Microwave Rocket development, microwave discharge was successfully ignited in the atmosphere by focusing a microwave beam. The propagation velocity of an ionization front was increased with the beam power density and became supersonic at the power density beyond 75kW/cm^2.

In the single pulse operation, peak C_m of 400Ns/MJ was obtained at the beam power with which the ionization front propagates at the Mach number M~1.2.

In the repetitive pulse operation, the thrust performance was identical to that in the single pulse operation when the partial filling rate, a fraction of thruster volume that is replaced by the fresh air during the pulse intervals, is grater equal unity.

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