Development of a tapered-tube millimeter-wave receiver for distant wireless power transfer in Microwave Rocket system

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Abstract: A tapered-tube millimeter-wave receiver for microwave beamed energy propulsion rocket called Microwave Rocket is presented. The tapered-tube receiver was designed using ray-tracing method because its small-bore diameter was more than 1000 times larger than the wavelength. The millimeter-wave wireless power transfer was demonstrated using a low power level millimeter-wave beam. A beam power fraction transmitted through the tapered-tube receiver was measured, and the ratio of the transmitted beam power fraction to the injecting beam power fraction was estimated to be 0.89.

Nomenclature

D_{in}	=	Large-bore diameter of the tapered-tube receiver.
D_{out}	=	Small-bore diameter of the tapered-tube receiver.
L_t	=	Length of the tapered-tube receiver.
z_R	=	Rayleigh length.
η_{in}	=	Injecting beam power fraction into the tapered-tube receiver.
η_{trns}	=	Transmitted beam power fraction through the tapered-tube receiver.
θ_t	=	Tapered angle.
θ_{ray}	=	Tilt angle of the millimeter-wave.
λ	=	Wavelength.
ω	=	Beam spot size.

I. Introduction

Microwave Rocket is one of the Beamed Energy Propulsion (BEP) launchers[1)]. Kinetic energy is transferred from the ground as millimeter-wave beams. Figure 1 shows schematic of Microwave Rocket. In its engine cycle, ambient air is breathed to be utilized as a propellant and no on-board propellant is needed. Thus, the payload ratio increases drastically compared with conventional chemical rockets. Sucked air in the thruster is

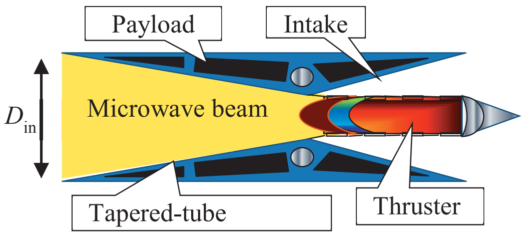

Figure.1 Schematic of Microwave Rocket

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pressurized through pulse detonation without turbo pump systems nor any other complex devices, resulting in a simple structure and a low manufacturing cost. Beam facility for Microwave Rocket is reusable and easy to maintain, because it is stationed on the ground. Therefore, the construction cost is amortized. With these reasons, Microwave Rocket is an innovative way to drastically reduce the transportation cost to space [2-8)].

A 100 GHz-band high-power millimeter-wave generator, gyrotron is a promising beam source. The gyrotron has been developed as a plasma heating device for nuclear fusion reactors. Megawatt-class high-power output and several-southland seconds longtime operation have already been available[9,10)].

Millimeter-wave wireless power transfer for Microwave Rocket is conducted by repetitive pulsed millimeter-wave beams. The wireless power transfer has been studied since 1960th and one of its main applications is space developments, such as Space Solar Power Satellite[11-13)]. In contrast with wireless communication systems using electromagnetic wave, the wireless power transfer system is required high transmission efficiency, and therefore the physical components and the transferred power level are different with these communication system. In most study, transferred microwave power is converted into electric power by a rectenna which comprise an antenna and a rectifier. Microwave frequency of 2.4 GHz-2.5 GHz ISM (Industrial, Science, Medical) band is often employed in these wireless power transfer, because it is easy to fabricate the rectenna in the low frequency nevertheless these low frequency beam requires large transmitting and receiving aperture size such as several hundred meters. Wireless power transfer in higher frequency has recently become available and conducted in 10 GHz, 35 GHz, 94 GHz and so on[14,15)].

Wireless power transfer system using the microwave supported detonation such as Microwave Rocket can utilize a compact receiver and a compact energy conversion system. In this study, wireless power transfer system for Microwave Rocket was described. A tapered-tube receiver for was proposed to guide the transferred beam into the thruster tube. Taper waveguides have been studied for gyrotron application as a part of transmission lines. In these application, mode purity after through the taper waveguide have to be preserved to transmit the energy through waveguides, and taper waveguides are designed by telegrapher's equation, FDTD and so on, which solve Maxwell equations resulting in long length compared with its diameter[16-20)]. The tapered-tube receiver used for Microwave Rocket has to be short length to reduce its weight and difficulty of the attitude control. The tapered-tube receiver proposed in this paper was designed using a ray-tracing method because the D_{out}/λ reaches more than 1000 and mode purity after through the taper-tube receiver is not significant for the Microwave Rocket's system.

In the section II, the design of the tapered-tube receiver is explained. A demonstration of the millimeter-wave wireless power transfer using the tapered-tube receiver was conducted to investigate transmission efficiency. The experimental results is described in section III, and section IV is for conclusions.

II. Design of the tapered-tube receiver

According to Ref. 8, Microwave Rocket is usable as a first stage rocket in the conventional chemical rocket system. Microwave Rocket is propelled up to an altitude, z of 20.7 km and is cutoff [8)]. The spot size, ω of the millimeter-wave beam is controlled to set the beam transfer distance at twice Rayleigh length because the Gaussian beam is collimated optimally. Beam spot size at the rocket side is determined by,

$$\omega = \left(\frac{z\lambda}{\pi} \right)^{1/2} \tag{1}$$

ω reaches to 4.2 m at the altitude of 20.7 km assuming millimeter-wave frequency of 110 GHz. 110 GHz gyrotrons have been used as a plasma heating device by DIII-D fusion reactor[9)] located in US and by JT-60 fusion reactor[10)] located in Japan.

Receiving aperture size was determined to be same as ω. Beam power fraction injecting into the tapered-tube receiver is determined by

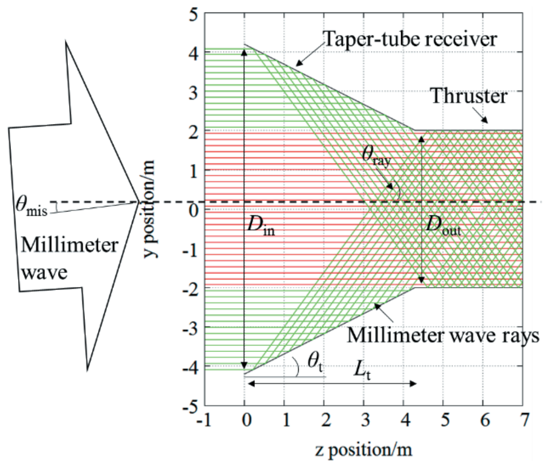

Figure 2 Two-dimensional ray-tracing result of the millimeter-wave beam incident on the tapered-tube receiver. D_{in}, D_{out}, and L_t were set at 8.4 m, 4 m, and 4.3 m.

$$\eta_{\rm in} = \left[1-\exp\left(\frac{-D_{in}^2}{2\omega^2}\right)\right]. \tag{2}$$

Receiving diameter, $D_{\rm in}$ was set at 8.4 m, and $\eta_{\rm in}$ was estimated to be 0.87. $D_{\rm out}$ was 4 m which is same as second stage of the H-IIB rocket.

The design of the tapered-tube receiver was conducted using the ray-tracing because $D_{\rm out}/\lambda$ is more than 1000. Figure 2 shows a two-dimensional ray-tracing results. $\theta_{\rm mis}$ is incident beam tilt angle due to a misalignment, and in the computation, $\theta_{\rm mis}$ is assumed to be null. In the tapered-tube receiver, beam tilt angle, $\theta_{\rm ray}$ which is same as $\theta_{\rm mis}$ at initial condition, increases by $2\theta_{\rm t}$ step by a reflection on the wall and $\theta_{\rm ray}$ <90 deg. is required to avoid backward reflection to the beam source. The shortest $L_{\rm t}$ and the largest $\theta_{\rm t}$ were estimated to be 4.1 m and 28 deg., respectively by the ray-racing method. However tolerance for $\theta_{\rm mis}$ is necessary, because misalignment of the rocket axis respect to the incident beam could be occur practically. Figure 3 shows relationship between tolerance for $\theta_{\rm mis}$ and $L_{\rm t}$. $L_{\rm t}$ was set at 4.3 m and tolerance for $\theta_{\rm mis}$ was set at 1 deg. The error of the center position of the tapered-tube receiver due to the misalignment of 1 deg. was 75 mm at the length of 4.3 m, which is enough to adjust the Microwave Rocket position.

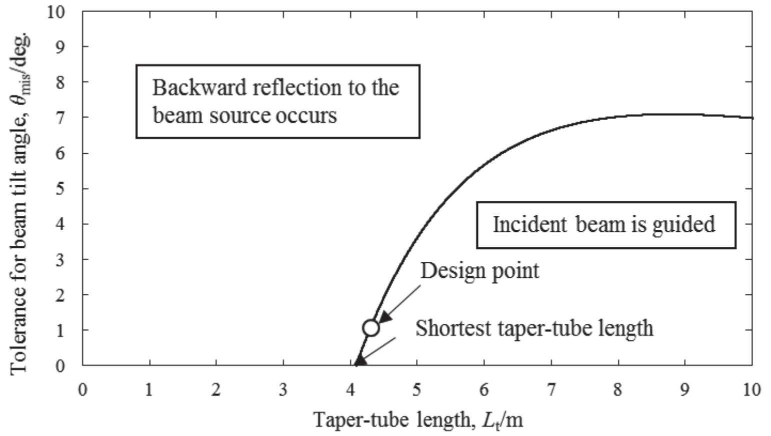

Figure 3 Relationship between tolerance for incident-beam tilt angle and the length of the tapered-tube receiver.

III. Demonstration of the millimeter-wave wireless power transfer at low power level

The millimeter-wave wireless power transfer was demonstrated at low power level using a small size tapered-tube receiver. Figure 4 shows setup of the demonstration. A Gaussian profile beam whose frequency was 94 GHz was injected into the tapered-tube receiver. The tapered-tube receiver was designed as same way described in section II. $D_{\rm in}$ was 180 mm, $D_{\rm out}$ was 65 mm, and $L_{\rm t}$ was 160 mm. $D_{\rm out}/\lambda$ was set at 20, which is enough to utilize the ray-tracing method. The measurement system had a slot antenna and two-dimensional beam power density profile was measured using the x-y stage.

Figure 5 shows the incident beam power density profile. Beam power fraction injecting into the tapered-tube receiver was estimated to be 3.09 mW. Figure 6 shows a measured beam power density profile at a distance of 80 mm from the tapered-tube receiver exit and a two-dimensional ray-tracing result for the small size tapered-tube receiver. Transmitted beam power through the tapered-tube receiver was estimated to be 2.76 mW±0.06 mW. A ratio of the transmitted beam power fraction to the injecting beam power fraction, $\eta_{\rm trans}$ was deduced to be 0.89±0.02.

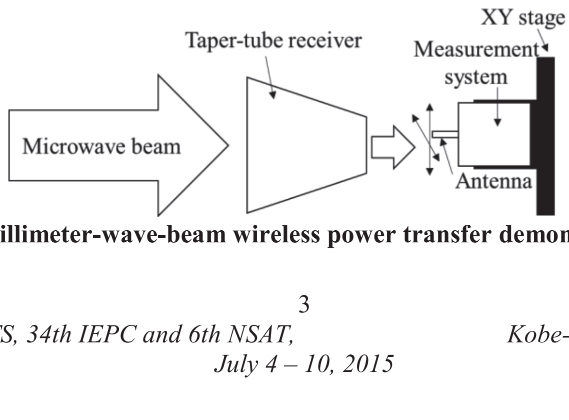

Figure 4 Millimeter-wave-beam wireless power transfer demonstration setup.

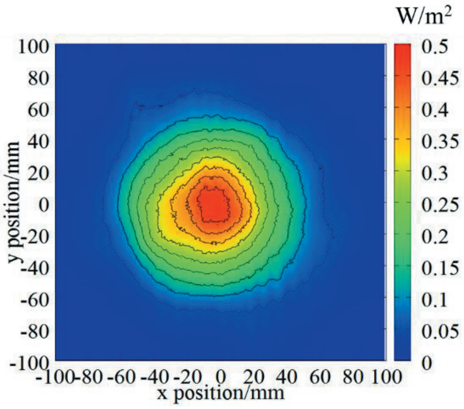

Figure 5 Beam power density profile of the incident beam.

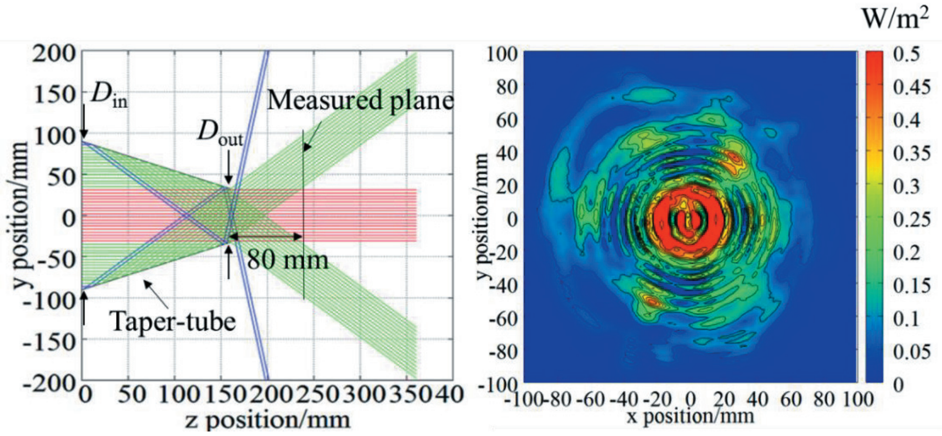

Figure 6 Two-dimensional ray-tracing result and measured beam power density profile at a distance of 80 mm from the tapered-tube receiver exit

IV. Conclusion

Tapered-tube millimeter-wave receiver was designed using the ray-tracing method. The large-bore diameter, the small-bore diameter and the length of the tapered-tube were designed to be 8.4 m, 4m and 4.3 m, respectively. Tolerance for incident beam tilt angle respect to the tapered-tube receiver axis was set at 1 deg. and the beam power fraction injecting into the tapered-tube receiver was estimated to be 0.87.

Millimeter-wave wireless power transfer was demonstrated at low power level to investigate its feasibility. Beam power density profile was measured and transmitted beam power fraction of 0.89 was obtained. Eventually, overall transfer efficiency of the wireless power transfer system was estimated by $\eta_{in}\times\eta_{trans}$ to be 0.77.

Acknowledgments

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