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Taper-tube Concentrator of Millimeter-wave Beam for Microwave Rocket

ー マイクロ波ロケットのテーパー管型ミリ波ビームコンセントレーターー

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Introduction

Due to high in vehicle transportation to space cost, number of launches has been decreased. One of the low cost launchers, Microwave Rocket is regarded as beamed energy propulsion that utilizes the beam source on the ground to generate thrust. In this study, Microwave Rocket's proposed by the University of Tokyo was carried out. Its thrust generation is achieved similar to detonation engine in which air breathing system was also introduced. Thus, there is no need for on-board propellant, and complicated engine components e.g. turbo pump in which higher payload ratio can be achieved. 1 MW-class gyrotron developed by Japan Atomic Energy Agency (JAEA) is expected to be used as high-power millimeter wave beam source.

Microwave Rocket Beam Transmission System

170 GHz gyrotron, Microwave Rocket's expected beam source located on the ground, transmits high-power millimeter wave, however its beam power density decreases along the propagation distance. Due to its Gaussian beam output characteristic. In order to increase beam Rayleigh length, function of wavelength and beam waist, beam transmission mirror system was developed. It comprises of set of mirror designed to expanded beam waist of gyrotron output and transmits it to Microwave Rocket. It achieved in expanding beam waist from 20.4 mm to 120 mm. As a result, taper-tube concentrator was needed to receive expanded beam and guide it into the thruster.

In general, taper-wave guide in mode theory, to expand 40.8 mm beam diameter to 240 mm, length of taper-tube approximately greater than 7 m long is required. Microwave Rocket, on the other hand, requires shorter taper-tube. Thus the development of taper-tube for Microwave Rocket was studied.

Taper-tube Concentrator Designed by Ray tracing

Ray tracing method recognizes the wave as rays of light and traces each ray individually. Wave effect is neglected in this method, however since the diameter of taper-tube for Microwave Rocket is expected to be much larger than the wavelength ray tracing was used to determine and design taper-tube geometry.

Designed inlet and exit diameter was 250 mm and 56 mm respectively, while taper-tube length was 470 mm. Ray tracing shows that at this design point, no beam is reflected back toward the upstream direction.

Low-power Measurement

To validate the design method, low-power test was conducted due to difficulties in conducting experiment using gyrotron. Thus, beam source was solid state amplifier 94 GHz transmitter (~415mW) attached with horn antenna. It oscillates millimeter wave and parabolic mirror was deployed as collimator to collimate the beam after the transmitter. Receiver was fixed on two dimensional moving stages on the far field with slot antenna. Fig.1 shows measurement schematic.

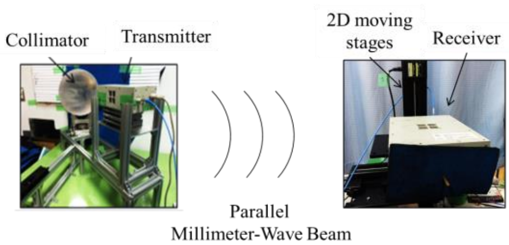

Fig.1 Low-power measurement schematic.

Incident beam was measured and integrated power was 3.63 mW while beam diameter was estimated and approximately 150 mm.

Beam Power Transmission Measurement

Taper-tube geometry for low-power test was different with one using gyrotron due to the difference in incident beam diameter was used to determined taper-tube inlet size. As a result, with the similar approach, taper-tube length, inlet, and exit diameter were 160 mm, 180 mm, and 65 mm respectively. Shapes of taper-tube were conical taper-tube.

At downstream of taper-tube, ray tracing indicated that there are 3 beam output i.e. 0, 1, 2-reflection beam which refer to the number of reflection between rays and taper-tube wall before they leave at the exit. This is shown in Fig.2.

Then, receiver was used to measure each beam output power density at downstream of taper-tube and comparison with simulation was conducted.

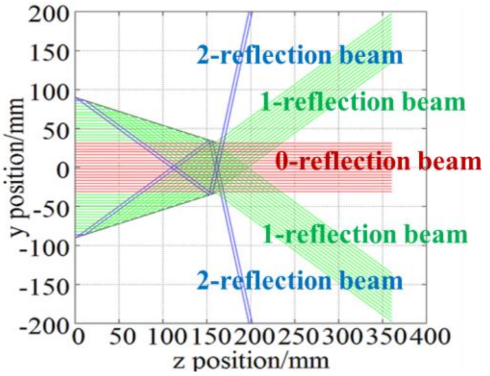

Fig.2 Ray tracing result on beam output.

Beam Power Density Transmission

Beam power density profile was measured and it shows qualitatively good agreement with simulation result as shown in Fig.3. It is noted that receiver alignment was changed corresponding to each beam output. Slot antenna at the receiver was set up and aligned with direction of each beam output since angle of reflection of each beam with respect to center axis was different depending on number of reflections occurred inside taper-tube. The result in table 1 shows integrated beam power fraction of each beam output compare to ray tracing simulation result.

Total power of conical taper-tube in the simulation result was less than that of incident beam (3.63 mW) since not the entire incident beam entered the taper-tube inlet as inlet size was slightly smaller than that of entire incident beam. However, 3.44 mW of integrated power was used as incident beam power in the simulation.

Experimental results show that transmission efficiency (η_t) was 92.0 ±15.9%. And it is defined as in Eq.1.

$$\eta_t = \frac{\text{Total beam output}}{\text{Incident beam power}} \quad (1)$$

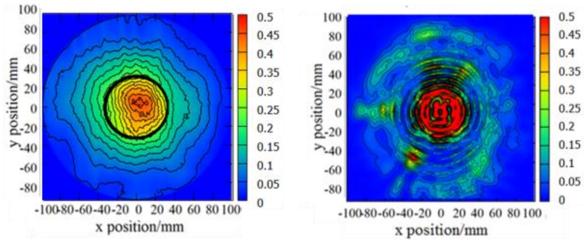

Fig.3 Comparison of power density profile between simulation (left) and experimental (right) result.

Table 1 Power transmission of conical taper-tube

Beam output	**Experiment**	**Simulation**
0-reflection/mW	1.13 ± 0.1	1.17
1-reflection/mW	1.94 ± 0.4	2.12
2-reflection/mW	0.095 ± 0.05	0.15
Total/mW	3.17± 0.87 (92.0 ±15.9%)	3.44 (100%)

Microwave Rocket Experiment

Experiment on Microwave Rocket with taper-tube using gyrotron was carried out. Gyrotron transmitted power of 638 kW and it is expanded before go through taper-tube concentrator and then inside the thruster.

As a result, plasma ignition was observed and ionization front propagation was estimated using high-speed video camera capturing frames through acrylic window attached with the thruster. Supersonic speed of ionization front propagation velocity inside the thruster was obtain around 560 m/s

Conclusion

Ray tracing simulation method shows good agreements with low-power measurement results. And high power transmission (92.0 ±15.9%) was achieved using taper-tube design by ray tracing. Experimental result using gyrotron shows that pulse detonation was achieved using conical taper-tube on Microwave Rocket. Plasma was ignited with ionization front propagation velocity of 560 m/s.