Design of Microwave Rocket Beamed Energy Propulsion Transmission Receiving System

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1. Introduction

Microwave Rocket beamed energy propulsion has been proposed as a potential candidate for an additional space launch system in the future. It is expected to be used during the atmospheric flight as Microwave Rocket propulsion system utilizes atmospheric air as a propellant. Hence, higher payload ratio could be achieved. Its propulsive energy is achieved by using millimeter wave beam in which transmitted from the beam source on the ground. Gyrotron is expected as a powerful beam source. It is originally developed for the purpose of plasma heating device for nuclear fusion and moreover, high power stable output 1MW class has already been achieved[1-3].

Fig.1 shows the engine cycle of Microwave Rocket as explained in the followings; first, millimeter wave is irradiated and transmitted from the ground through the rocket and when it reflects with the thrust wall the discharge of plasma is occurred. Then the ionization front of plasma and shockwave starts to propagate toward the incoming wave or upstream direction in which it absorbs the upstream wave itself. In the third step, both ionization front and shockwave reached the atmospheric air, or open-end of the thruster and expansion wave in contrast propagates toward the thrust wall again. This creates the pressure oscillation inside the thruster and apparently the pressure inside the thruster becomes low again where the atmospheric air outside of the thruster could flow into it. Then the process is repeated, and thrust is generated similar to the process of pulse detonation system[4].

As a result, simple structure of Microwave Rocket could be achieved which could realize the lower in production cost and higher payload ratio. Beam source, on the other hand, is on the ground where the maintenance is convenient and easy to be used as many times as possible.

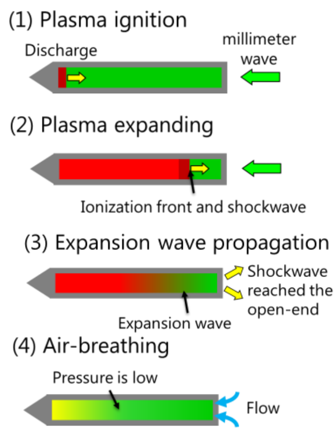


Fig.1 Engine cycle

Nakagawa *et al, 2004*[5] conducted Microwave Rocket experiment with single pulse engine cycle using conical nozzle and cylindrical tube as thruster. Its momentum coupling coefficient C_m, which is defined as a ratio of propulsive impulse to incident energy, was achieved at 395 N/MW while in 2009 Oda *et al*, conducted the experiment in multi-pulses operation and achieved some significant results[6]. Attempting to establish the Microwave Rocket long range launching system was investigated and in Fukunari *et al*, 2013[7] the experiment with Microwave Rocket transmission system which comprised of a transmission mirror system and a receiving system was conducted. Fig.2 shows the schematic of Microwave Rocket with transmission system. The transmission mirror is necessary for long range launching system as millimeter wave beam diverges with the traveling distance, however its divergence angle could be suppressed by an increasing in beam radius as shown in equation (1), which θ_D is a beam divergence angle, λ is a wavelength, and ω_0 is a beam waist.

Thus, the transmission mirror is designed for the purpose of expanding the beam radius and transmitting the expanded beam to the thruster in which the receiving system is equipped at the upstream of the thruster. Then the receiving system focuses the expanded beam and guides it into the thruster.

$$\theta_D = \frac{\lambda}{\pi \omega_0} \qquad (1)$$

In addition, the past experimental result in table 1 has shown that by obtaining the different millimeter wave beam profile, thruster generated different thrust value. The experiment was conducted, only thruster is used without any transmission mirror and receiving system, comparing the thrust impulse between 2 different cases; having Gaussian beam profile and Flat-top beam profile as an upstream before the beam goes into the thruster. According to the result it can be suggested that if Flat-top beam profile at the upstream of the thruster was achieved, Microwave Rocket could produce higher thrust compare to the Gaussian beam profile.

Consequently, this study aimed to optimize the design of Microwave Rocket receiving system, called taper tube in which it could create Flat-top beam profile. Mainly the shape of taper tube is focused. Small size of receiving taper tube system was experimented using low power millimeter wave source with frequency of 94GHz. Simulation was also conducted using Ray tracing method; tracing the rays that reflect inside the taper tube and monitoring the output at the taper exit, exactly at the position of the downstream of thruster.

2. Microwave Rocket transmission receiving system

Microwave Rocket is expected to receive expanded beam from the transmission mirror system on the ground, thus the receiving system is needed to guide the beam into the thruster. Moreover, the upstream beam profile before it enters the thruster has significant effect to the thrust generation and since flat-top beam profile is expected, this study emphasizes the shape of the receiving system as it could alter the beam profile.

Taper receiving system is simply a tapered tube in which upstream inlet size is decided base on the incident beam waist as well as the downstream exit size which is decided by the thruster size. Length and

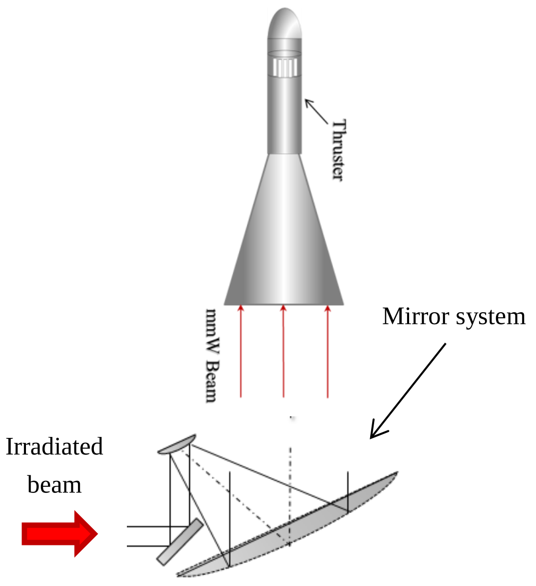


Fig. 2. Schematic of Microwave Rocket

Table 1 Beam profile comparison

	Gaussian	Flat-top
Peak power density	33 kW/cm^2	16 kw/cm^2
Ionization front propagation velocity	140 m/s	68 m/s
Thrust impulse	13.2 mNs	28.4 mNs

Yamaguchi *et al*, 2011[8]

tapered angle must be chosen to avoid the incident beam reflection into the direction of itself. Fig.3 shows the taper tube receiving system. It is designed for the purpose of simplicity, therefore lightweight and low cost of production could be realized. As a result, 4 shapes of tapered tube was simulated and experimented to investigate the beam profile after the beam passes through them.

3. Simulation and experimental results

Ray tracing simulation method was used to investigate the beam profile after it passed through the tapered tubes. Tapered tubes shapes were conical, square, hexagon, and octagon. They were calculated and had same upstream (inlet) and downstream (exit) size which are 250mm and 56 mm in diameter respectively. Meanwhile, besides the conical tapered tube, their inlet and exit were designed to fit inside the inlet and exit plane of conical tapered tubes. Thus all 3 tapers were having slightly lesser in both inlet and exit diameter compare to conical tapered tubes. Length was fixed at 470mm, exactly the same as the real tapered tube which is expected to be used in the experiment. Hundred thousands of rays were simulated with the basic principle of reflection inside tapered tubes. And the crossing points inside the tubes were assumed to create the higher power at those specific points. Ray tracing was chosen due to its simplicity and fast in calculation. Also since the tapered tube size was comparatively bigger than the wavelength of the millimeter wave beams such that the wave characteristic can be neglected.

Results were obtained and shows in Fig.4 which are the beam profile at each taper exit plane. Total flux energy is identical for each taper. Y and X axis represent the position of the tapered tubes whereas brighter color represents higher power output (unit in a.u). Fig. 5 shows the normalize power density at the taper exit cut through the center plane (y = 0) of each taper

Experiments were conducted using low power facility, with 94GHz using horn antenna as a wave source. Millimeter wave beam was oscillated and reflected with the collimation mirror in order to create the parallel beam. The size of the beam waist is different from which is expected to be used in the experiment using the gyrotron as a wave source. In case of using gyrotron, D/λ which is the ratio of taper exit diameter to wavelength, is approximately 33. However, due to the window time slot of using gyrotron is limited, the low power facility was used, and the results were expected to show the same beam profile with using the high power wave source. As a consequence, the experiment were conducted with small size of tapered tube corresponding to beam waist, and D/λ was equal to 17. Fig.6 shows the experimental apparatus. The beam at downstream was measured the signal by detector with slotted antenna using 2 dimensional stage moving in X and Y direction of the exit plane. Fig.7 shows the experimental results of each taper at the exit plane compare to the beam profile without any taper tubes.

4. Results and discussion

Simulation results obviously show the different beam profile of each taper. It can be stated that conical taper tube has highest peak value compare to others and the taper tube with some certain sharp angles could produce likely the flat-top beam profile. As can be seen from Fig.7, on the other hand, the experimental results contain fringe pattern and it is difficult to say that the beam profile shapes are consistent with the simulation results. However, the result from conical taper tube still has the highest peak value, and with the

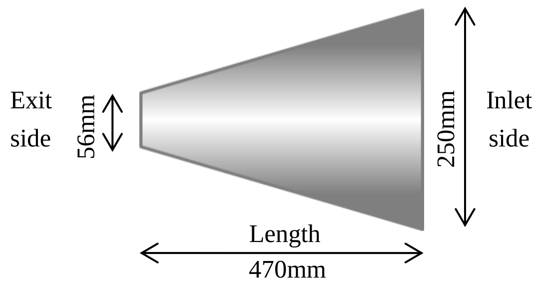
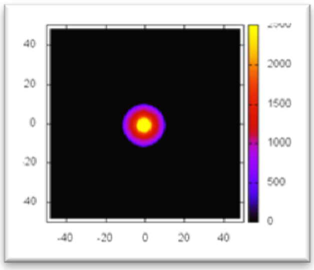
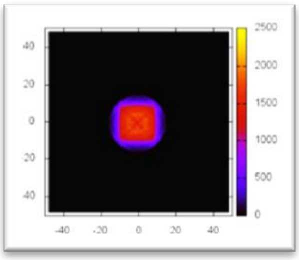


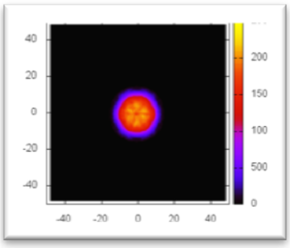
Fig.3 Microwave Rocket tapered tube



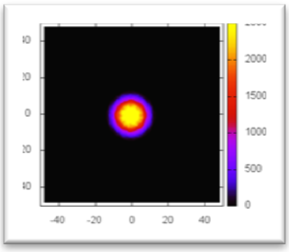
Conical



Square



Hexagon



Octagon

Fig.4 Ray tracing simulation results of each tapered tubes at tapered tubes exit.

observation it can be seen that other tapered tubes have less peak value of the beam profile. Nonetheless, experimental results show that the transformation of the beam profile using taper tube is achieved.

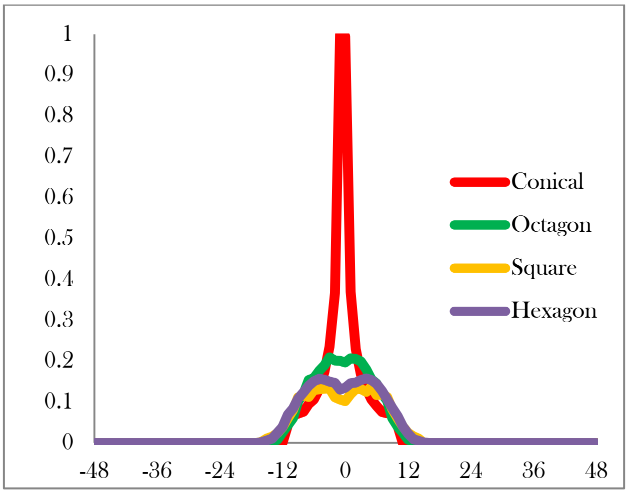


Fig.5 Power density of each tapers at the center plane (Y=0) of the results in Fig.4 y-axis: normalize power density. x-axis: position in x direction

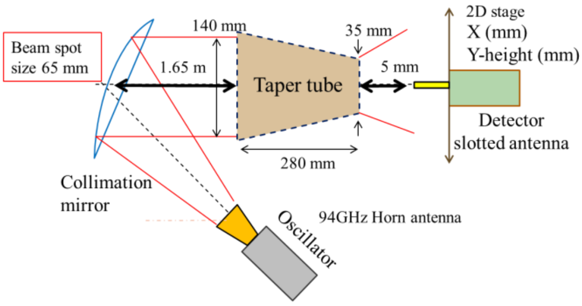
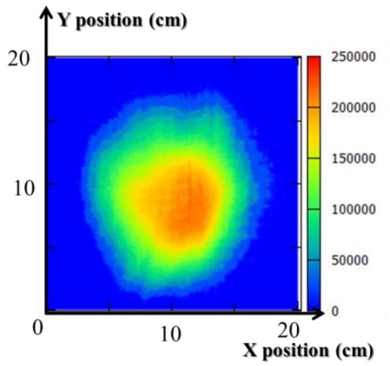
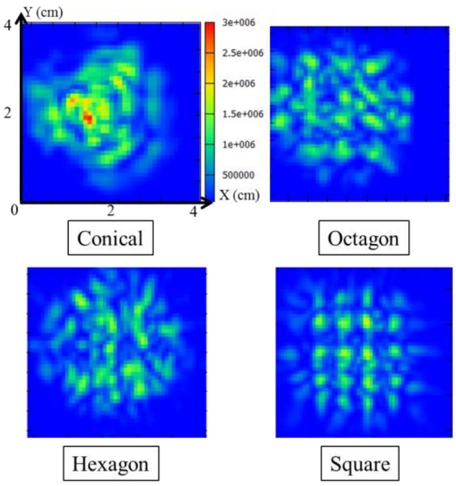


Fig.6 Experimental apparatus



Measured power density without any taper tube



Power density at each taper exit

D/ λ = 17

Fig.7 Experimental results

5. Conclusion

Taper tube was used as a wave guide changing the beam profile before and after the millimeter wave beam passes through. Calculation results using ray tracing method proves that the conical taper tube produce the highest peak value of the beam profile while other shapes have an influence on reducing the peak value. Although, experimental results are slightly agreed with the suggestion above yet, it cannot be said that both are consistence. Due to the different in D/ λ which could appeal the effect of wave characteristic, in the experiment, lower ratio was used and thus they have to be taken into account. The investigation on D/ λ = 33, on the other hand, with 94GHz as a beam source will be proposed.

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