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Technical Notes

Miniature Microwave Discharge Ion Thruster Driven by 1 Watt Microwave Power

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Introduction

THE age of space exploration using self-propelled small spacecraft is approaching. In the past decade, research and development of small spacecraft have advanced extensively throughout the world. Numerous small spacecraft have been successfully launched and operated [1–8]. Small-spacecraft missions are increasingly used with widely varying applications. In recent years, planned small-spacecraft missions are increasingly in need of propulsive capability. Propulsion devices supply the spacecraft with attitude control, station-keeping, and orbit transfer functions. Furthermore, propulsion can support future spacecraft missions such as drag-free control from atmospheric or solar pressure, precise constellation flight for interferometer missions, and deorbiting maneuvers of end-of-life spacecraft into the atmosphere. The arrival of propulsion devices suitable for small spacecraft, namely, micropropulsion, is eagerly anticipated [9].

Ion thrusters [10] are promising propulsion devices intended for use not only with standard-sized spacecraft but also with small spacecraft. Their characteristics of high specific impulse (3000 s), high thrust efficiency (50%), usage of an inert propellant (xenon), and continuously controllable thrust meet the requirements for small-spacecraft missions. Several studies of miniature ion thrusters have been reported for plasma generators of several different types, namely, direct-current electron discharge [11,12], radio frequency discharge [13], and microwave discharge [14–17]. Among these types, microwave discharge ion thrusters have the following unique characteristics suitable for miniaturization. First, the discharge chamber generating the plasma has a simple structure because of its lack of an electron cathode. In this type, electrons are heated using electron cyclotron resonance (ECR); neither a discharge cathode generating primary electrons nor corresponding power supplies are needed. Second, the thruster performance is degraded only slightly by scaling down. In general, discharge loss is affected by the surface-to-volume ratio of plasma. In microwave discharge ion thrusters, however, the ECR heating zone is confined to the near-surface magnetic field, meaning that the surface-to-volume ratio is not sensitive to the system's scale. Using these advantages, Takao et al. [14], Yamamoto et al. [15,17], and Nakayama et al. [16] developed miniature ion thrusters driven by microwave discharges and showed good performance.

In spite of these benefits, however, miniature ion thrusters have not been used for small spacecraft yet. An important reason is the severe limitation of electrical power available on small spacecraft. In general, the electrical power generated in small spacecraft is about 1 W/kg. For example, the maximum usable power in a 10–50 kg small spacecraft was estimated at only 10–50 W. The miniature ion thrusters developed to date require a total power of at least 30 W. Low power limitations have made it difficult to use those ion thrusters on small spacecraft. On the other hand, mass limitations are not so severe problem as that of the electrical power. Nakayama et al. [16] estimated the total dry weight as approximately 4 kg for their miniature microwave discharge ion thruster. Additionally, this weight can be reduced father by decreasing the microwave power and discharge loss because the microwave power supply has a large fraction of its total weight attributable to the low energy conversion efficiency.

Our objective is a miniature ion thruster with a total power consumption of less than 10 W and a total dry weight of less than 2.0 kg. One such miniature ion thruster can propel a 10–20 kg small spacecraft, although several thrusters could propel larger spacecraft of 20–100 kg. Moreover, devices that produce minute and controllable thrust are useful for spacecraft that require precise control of both attitude and position. The major challenge to achieving this goal is to decrease the total required electrical power while maintaining high thruster performance. That is to say that power for generating plasma should be limited to only 1–2 W and the discharge loss should be suppressed to less than 500 W/A. To date, no ion thruster has been reported to operate at such low power applied to the plasma and at such a low discharge loss. As a first step toward this goal, we have developed a miniature ion thruster driven by 1 W of microwave power with a 250 W/A ion production cost and 37% mass utilization efficiency. In this paper, we present the characteristics and performance of a miniature microwave discharge-based ion thruster.

Experimental Setup and Method

Thruster Head

The new miniature ion thruster generates plasma by a microwave discharge using ECR heating. Generally, the most successful design of this type of thruster is the mu–ten ($\mu 10$) ion thruster developed at the Institute of Space and Astronautical Science of the Japan Aerospace Exploration Agency [18–20]. Four $\mu 10$ ion thrusters were installed on the asteroid explorer Hayabusa as the primary propulsion for the sample return program to the asteroid Itokawa [21]. We designated the miniature ion thruster developed for the present study as "mu–one" ($\mu 1$), which is the smallest ion thruster in the "μ" series of ion thrusters, with a 1-cm-class beam diameter and 1-W-class microwave power.

The $\mu 1$ ion thruster has a cylindrical discharge chamber with a 20 mm diameter. Figure 1 shows a schematic illustration of the $\mu 1$ ion thruster. Two annular permanent magnets are installed on the bottom of the chamber. The magnets form a maximum magnetic field of 0.30 T near the magnet surface and a minimum field of 0.05 T at the most distant point from the magnets. The resulting magnetic field also forms a magnetic bottle that inhibits electron loss. A two-grid ion accelerator system was placed across the downstream end of the discharge chamber. The grids are made of molybdenum by chemically etching 211 apertures within a 16-mm-diam region. The grid configuration was designed by Nakayama et al. for MINIT, their miniature microwave ion thruster [16]. Detailed grid geometries are presented in Table 1. The screen and accelerator grid voltages were

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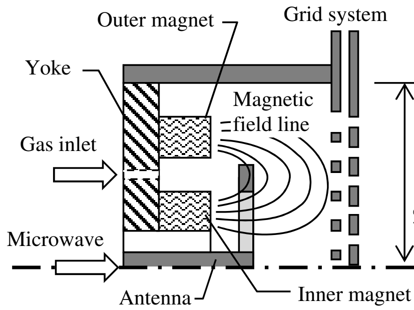

Fig. 1 Schematic illustration of the miniature microwave discharge ion thruster μ1.

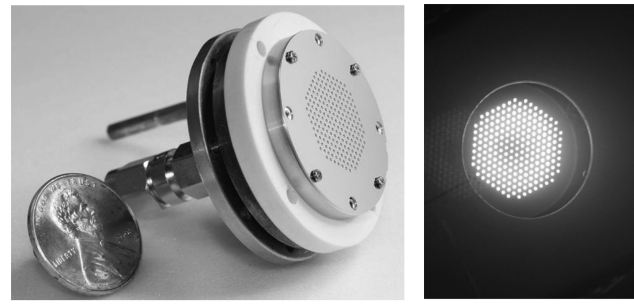

Fig. 2 Pictures of the μ1 and its operational view.

set to 1500 and −350 V, respectively. The typical recycling rate using this grid system was once every a few hours with 1.0 W of microwave power and a 14.6 μg/s mass flow rate. The emphasis of this study was to minimize the discharge loss associated with the μ1 thruster. To simplify the experiment, we did not use a neutralizer. Actually, in a preliminary experiment, we confirmed that the differences in ion beam current through the use of a filament neutralizer were less than 0.4% with typical operational conditions.

Microwave power with a frequency of 4.2 GHz was introduced into the chamber using an annular antenna extending from an inner conductive part of the microwave transmission cable. The electron cyclotron resonance of 4.2 GHz is given by the magnetic field strength of 0.15 T. The antenna configuration was matched to the plasma impedance. Details of the antenna configuration are presented elsewhere [22,23]. The microwave power line was isolated from ground potential by a dc block. Both the discharge chamber and dc block were set to a high positive voltage and were covered using a plasma screen connected to the ground potential.

The working gas (xenon) was fed through holes in the yoke plate and between the two magnet rings. A gas isolator was installed between the thruster and the gas feed system. The mass flow rate was controlled using a mass flow controller for xenon with a maximum flow rate of 1.0 sccm (98 μg/s for xenon) and an accuracy of ±1% with respect to the maximum flow rate.

The thruster head of μ1 has a mass of 65 g, with a 36 mm diameter and a 14 mm height. The μ1 used here is a laboratory model, designed specifically for the examination of its handling ability for the experiments. Hence, further miniaturization is attainable. Herein, the term “thruster head” is used to mean a plasma generator and ion accelerator. The plasma screen, dc block, gas isolator, and neutralizer are not included in the description given earlier. Miniaturizations of these components are under development. Images of the thruster head and its operational view are depicted in Fig. 2.

Vacuum Facilities

All the experiments were conducted in a 1.0-m-diam, 1.4-m-long vacuum chamber. The chamber is evacuated using a rotary pump of 1300 L/min and a turbo molecular pump of 800 L/s for N_2. The operating pressures during the experiment were between 4 and 8×10^{-3} Pa at 50 μg/s of xenon flow. The stainless steel chamber is used as the ground reference for all tests. The configuration of the thruster and vacuum chamber is depicted in Fig. 3.

Experimental Method

Performance of the ion thruster μ1 was evaluated using its ion beam current. Input microwave power was swept continuously between 0 and 5 W. First, the microwave power was set to around

Table 1 Grid geometry

	Thick, mm	Diam., mm	Gap, mm	No. of holes	Potential, V
Screen grid	0.20	0.72	0.25	211	1500
Accelerator grid	0.30	0.40			−350

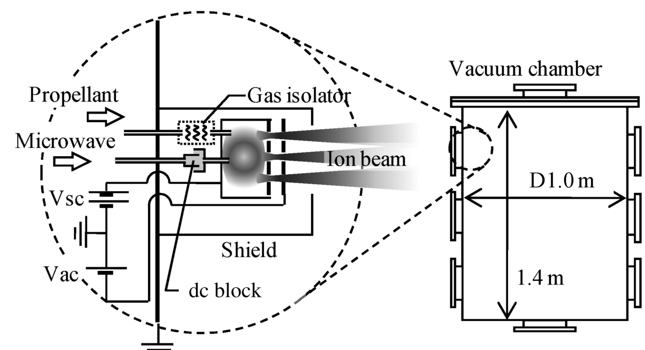

Fig. 3 Electrical schematic and configuration of the experiment.

0.1 W, then it was increased gradually up to 5.0 W, and finally decreased again to 0 W. The period of this round-trip sweeping took 20–40 s. During sweeping, the screen current, accelerator current, input microwave power, and reflected microwave power were recorded with a 200 Hz sampling rate. The swept power range was divided into 100 intervals, and data of 4000–8000 points were averaged over each interval. During power sweeping, the mass flow rate was fixed. The ion beam current was calculated by subtracting the accelerator current from the screen current. The accelerator current was less than 2.0% with respect to the beam current in the power region over 1.0 W and less than 10% in the power region below 1.0 W.

Input and reflected microwave powers are referred to herein as forward and backward powers, which are reported as values at the thruster head. Both powers were actually powers at the microwave power source. The measured values are then corrected by the transmission losses between the power source and the thruster head. The uncertainties of the input and the reflected power are within ±5%. Generally, when microwave power is put into the discharge chamber, some fraction of the power is absorbed by the plasma, some fraction is consumed by the skin-effect current on the inner walls (magnets surface, side wall, and grid surface), and another fraction is reflected back toward the power source. In our thruster, when no plasma is present in the discharge chamber, the input and reflected powers were equal, within a 2% difference, meaning that the microwave power loss on the inner walls was negligible. Therefore, we assumed that the difference between the input and reflected powers was equal to the net power absorbed by plasma.

Experimental Results and Discussion

Ion Beam Extraction

Ion beam extraction of 4.0 mA was achieved at an input microwave power of 1.0 W, which corresponds to 250 W/A discharge loss. This performance satisfied our initial target. The dependence of the ion beam on the input power is portrayed in Fig. 4. The ion beam current increased with input microwave power at all the mass flow rates that were studied. In the high-power region of more than 1.0 W, the beam current started to be saturated. This saturation trend was more significant at lower mass flow rates. The ion beam was extracted even

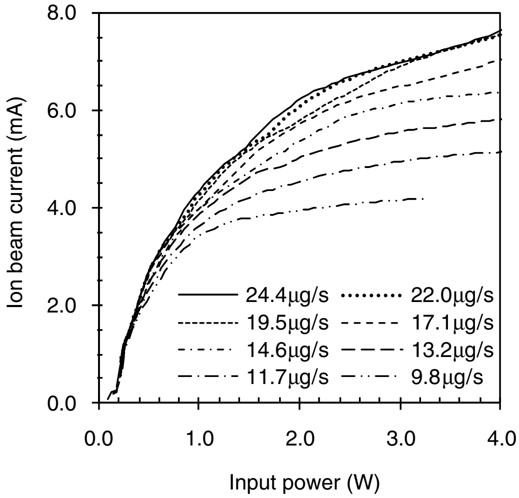

Fig. 4 Ion beam current dependence on input microwave power and mass flow rate.

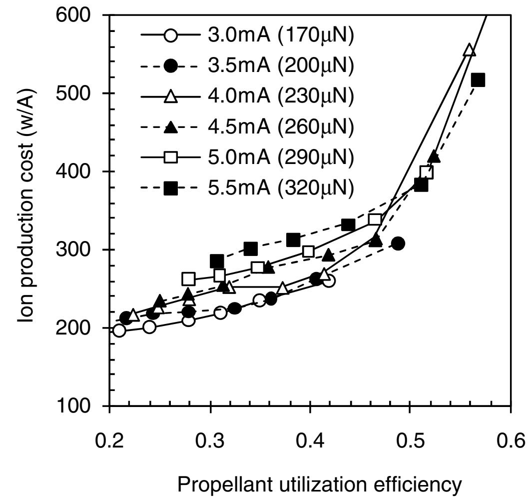

Fig. 6 Performance curves at constant beam current, changing the mass flow rate from 9.8 to 24.4 $\mu g/s$.

in the extremely low power range of 0.2–1.0 W. Below a power range of 0.2 W, the plasma was extinguished and no more beam current was measured. Minimal differences in beam current versus microwave input power traces were observed at flow rates greater than 17 $\mu g/s$. At lower flow rates, the differences were much more pronounced. At 1.0 W microwave power operation, the beam current varied between 3.3 and 4.2 mA, depending on the mass flow rate of 9.8–24.4 $\mu g/s$. Another important topic related to the low-power operation of a microwave discharge ion thruster is the ignition capability of the plasma. In our experiments, the plasma was ignited by inputting microwave power of 0.5–1.5 W. The power variation mainly depended on the mass flow rate.

Plasma Coupling

Net microwave power absorbed into the plasma was assumed to equal the difference between the input and reflected powers. Fractional absorption was defined as the net absorbed power over the input power, and its dependence on the input power is presented in Fig. 5. This fractional absorption is an indicator of coupling between microwave and plasma. In the wide power range from 0.2 to 5 W, fractional absorption was from 0.6 to 0.7. The mass flow rate did not affect the power absorption fraction, which suggests that the saturation of ion beam current in high-power regions is not caused by the degradation of the plasma coupling. A possible reason is the increase in the plasma losses to the inner walls. Moreover, the absorption of 0.7 means that a further improvement in discharge loss would be possible. The usage of a matching tuner increased the performance to 0.75. However, the tuner's increased size and weight to the system do not justify its use.

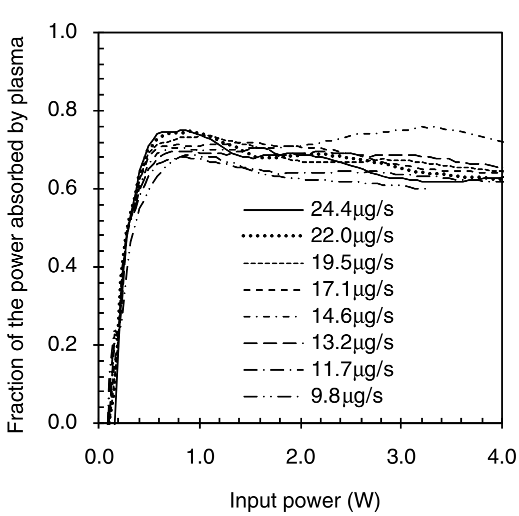

Fig. 5 Fractional absorption of the microwave power.

Thruster Performance

Performance curves of the μ1 ion thruster are presented at several constant ion beam currents in Fig. 6. The discharge loss was defined as the input microwave power over the ion beam current. Its mass utilization efficiency was calculated by the ion beam particle current and mass particle flow rate of propellant gas. The thrust portrayed in that figure was calculated by assuming a thrust coefficient of 0.90 (effects of beam divergence and doubly ionized particles). The discharge loss was 200–600 W/A; the mass utilization efficiency was 0.2–0.6. Near the knee of these curves, the discharge loss of 250 W/A and mass utilization efficiency of 37% were achieved at an ion beam current of 4.0 mA, corresponding to 230 μN of thrust. This discharge loss is as low as standard ion thrusters and the lowest ever in all developed miniature ion thrusters. In contrast to the good discharge loss, a mass utilization efficiency of nearly 40% is not too low considering the small size of the μ1. Effective plasma production is achieved by decreasing the fraction of the electrons that are directly lost to the walls without making an ionization collision. Generally, the electron confinement time is determined by the geometry of the system decreasing with thruster size. On the other hand, the mean free time for ionizing collisions is determined by the neutral gas density. More effective plasma production in a small system requires higher neutral density (i.e., a high mass flow rate) and decreased mass utilization efficiency.

Conclusions

To develop a 10-W-class miniature ion thruster for use with 10–50 kg spacecraft, we have developed the μ1, a new miniature microwave discharge ion thruster. Its design and development were conducted with the purpose of specifically examining low microwave power operation (0.2–5 W) with low discharge losses. Input microwaves were effectively coupled to the plasma with no tuning device. The following thruster performance was obtained: discharge loss of 250 W/A, mass utilization efficiency of 37%, and an estimated thrust of 230 μN at an input microwave power of 1.0 W and a xenon flow rate of 14.6 $\mu g/s$. The performance of the ion beam thruster satisfied our initial target, although miniaturization of the corresponding auxiliary subsystems (neutralizer, dc block, and gas isolator) is under development.

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