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Technical Notes

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Dual Propulsive Mode Microthruster Using a Diode Laser

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Introduction

MICROSPACECRAFT have increasingly attracted the interest of researchers in recent years. The research is motivated by the need to reduce in the cost of developing and launching spacecraft and to improve in the mission capability and redundancy using microspacecraft constellations. Although several laboratory and flight models of 1–10 kg class microspacecraft have been developed, most of them do not have propulsion systems.[1–3] To enable future microspacecraft missions, such as formation flying, a small propulsion system suitable for microspacecraft, namely, a microthruster, is needed.[4]

One of the most important requirements in the microthruster is the capability to generate both lower range thrust and higher range thrust. For instance, microspacecraft require lower thrust for attitude controls and higher thrust for slew maneuvers. In the case of formation flying,[4] microspacecraft need lower thrust for the constellation controls and higher thrust for the rearrangement of their formation patterns. In particular, formation flying inevitably requires propulsive capability, although attitude control is accomplished by passive systems such as momentum wheels and magnetic torqueres. To limit the weight and size of microspacecraft, it is essential to satisfy the requirement of lower and higher range thrusts with the same propulsion system. To our knowledge, there is as yet no single propulsion system that can supply such a wide range of thrust for the 1–10 kg class microspacecraft.

A diode laser ablation microthruster and digital microthruster array seem to be promising candidates for the 1–10 kg class microspacecraft. The diode laser ablation microthruster[5] uses laser beams to irradiate the surface of a polymer propellant, and the heated and evaporated propellant is ejected from the surface (laser ablation). The compactness of diode lasers, which weigh 1–2 g and require less than 5 V, is suitable for microthrusters. The thrust can be widely and precisely adjusted by varying the laser pulse width, although only a low thrust ($<50\ \mu$N) can be generated. The thrust efficiency and propellant use are gradually increased with increasing power density. On the other hand, a digital microthruster array[6,7] consists of an array of small thrust chambers filled with solid propellant; it produces the thrust by firing individual propellants. (Each can be used once.) The thrust can be quite high (0.1–10 mN) depending on the size of the chamber, but the thrust is predetermined and uncontrollable. Although other microchemical and microelectric propulsion systems have been proposed, they have been unsuitable for microspacecraft less than 10 kg due to their large and heavy fuel tanks and high voltage power sources, respectively.

In this study, a novel type of microthruster enabling multiple propulsive tasks is proposed, and its feasibility is demonstrated through fundamental tests. The microspacecraft envisioned here has a weight of less than 10 kg and characteristic length of 10–20 cm. In such microspacecraft, the space allowed for the propulsion system would be strictly limited, typically less than 0.5–1.0 kg and dimensions of 5–10 cm including a power source. Compactness is the most important feature of these systems, rather than thrust performance, because there are almost no electric or chemical propulsion systems that can be applied to such a small size.

Our microthruster has dual propulsive modes using a diode laser. Its propellant consists of polymeric and pyrotechnic material. When the laser beam irradiates the surface of the polymer propellant, the laser ablation jet generates low thrust, the laser ablation mode. The thrust is controlled by the laser pulse width, and fine adjustment of the thrust is enabled. When the laser irradiates and ignites the pyrotechnic material, which is loaded in the arrayed small holes, higher thrust is generated by the solid propellant, the laser ignition mode. The thrust is controlled by the mass of the loaded pyrotechnic material, and it is predetermined during the thruster design process. Figure 1 shows a conceptual diagram of the two modes. In the laser ablation mode, the laser beam provides energy to the ablation jet, and in the laser ignition mode, it plays the role of an ignitor of the solid propellant. The two modes can be easily interchanged by changing the location irradiated by laser beam. The greatest benefits of our thruster are compactness and wide thrust range. We believe that compactness is the most important feature for the microthruster,

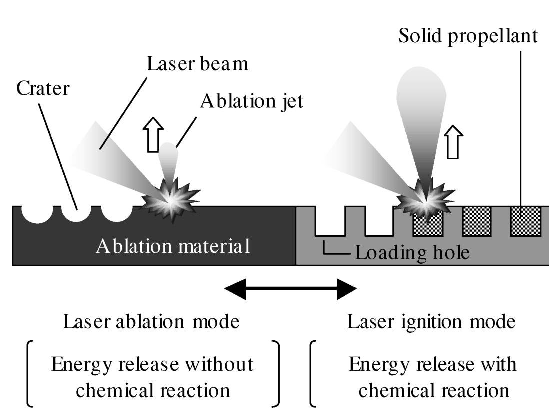

Fig. 1 Laser ablation mode and laser ignition mode.

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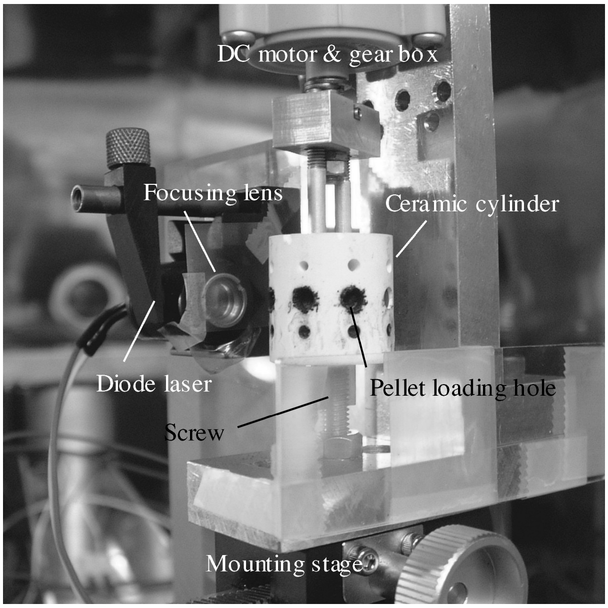

Fig. 2 Test thruster.

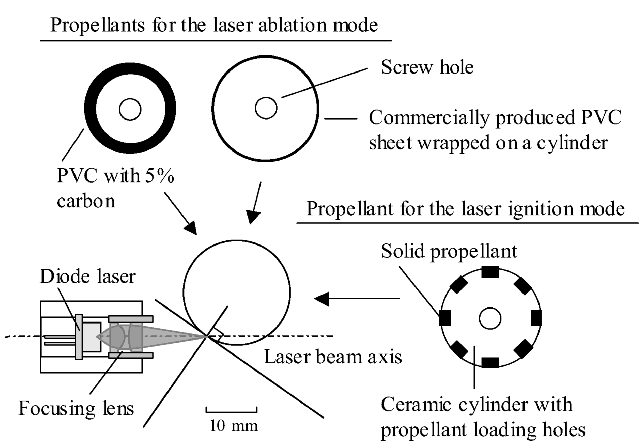

Fig. 3 Top view of test thruster and propellants.

and to our knowledge, there is no thruster that can supply thrust over the four orders of magnitude using a single propulsion system and can be installed in a 1–10 kg microspacecraft.

Experimental Setup and Procedure

Figure 2 shows a test thruster that consists of an optical assembly, propellant, propellant rotation system, and mounting stage. The optical assembly employs a 250-mW diode laser with a wavelength of 980 nm and a focal length of 14 mm, a beam waist size of 1.0×0.05 mm, and a maximum power density of 5 MW/m^2. Polymer or pyrotechnic propellants were installed on a cylinder, which was installed on a screw fixed on the mounting stage. The laser optical assembly was aligned such that the laser beam was focused on the surface of the cylindrical propellant with a certain angle of incidence (Fig. 3). After every shot, the cylinder was rotated upward (or downward) by the screw pitch. (The dc motor and gearbox were installed above the cylindrical propellant.) The advantages of the cylindrical propellant feeding system are that the entire surface of the cylinder can be used for the propellant and it is easier to load with solid propellant than in a tape feeding system. A transparent wall was installed between the optical assembly and the propellant to protect a focus lens. Lens fouling could be a crucial problem for thrusters using lasers. Although no quantitative investigation was performed in this experimental program, we present several ideas to protect the optical system: use of an optical system with long focal length, use of a movable protection wall or tape, or application of transmission mode.[5]

Two varieties of polyvinylchloride (PVC) were utilized as propellants for the laser ablation mode: a custom-ordered PVC (18-mm-diam cylinder) that included 5% carbon additives and a commercially produced black PVC (0.2-mm-thick sheet), which was wrapped around a 20-mm-diam cylinder. PVC was used as the propellant because it displayed the best performance among several polymers in a previous study.[8]

Three varieties of pyrotechnics were prepared for the laser ignition mode experiments: a composite propellant, a double-base propellant, and pelleted boron/potassium nitrate (B/KNO_3). These pyrotechnics were loaded into the holes on the ceramic cylinder. The composite and double-base propellants were cut to the appropriate size and pressed into the 2.0-mm-diam, 1.0-mm-long holes. Pelleted B/KNO_3 cylinders of 3.2 mm diameter and 2.0 mm long weighing 0.03 g were installed in holes of the corresponding size.

Experiments in the laser ablation mode were performed in a 1.1-m-diam, 1.8-m-long vacuum chamber. The base pressures were between 2 and 5×10^{-5} torr. The impulses generated by the test thruster were measured using a thrust stand, which is a horizontally swinging torsional balance with a 40-cm-long arm.[9] A thruster was installed on the arm of the thrust stand, and the reaction force of the thrust was measured in terms of the displacement of the arm. Calibration of the thrust stand was performed by striking a force transducer attached to the thrust stand with impact pendulum. The resolution of the thrust stand measurement was $\pm 1.0\ \mu\mathrm{N \cdot s}$ (Newton second) and the accuracy of the calibration was $\pm 2\%$. Experiments on the laser ignition mode were performed in a 0.9-m^3 vacuum chamber with the base pressures being between 1.4 and 3.0×10^{-4} torr. The thrust stand used to measure the impulse was similar to that used in experiments in the laser ablation mode. It does not possess a dumper; the resolution was ± 2 mN $\cdot$ s.

In the experiments on the laser ablation mode, to evaluate the specific impulse, the mass ablated by each laser irradiation Δm was estimated from the pressure increase in the vacuum chamber ΔP using the equation $\Delta m = C \Delta P$, where C is the proportionality constant. The proportionally constant C was determined by the averaged ablated mass as determined from the difference in the weight of the propellant before and after the 1550 shots experiments, divided by the averaged pressure increase during the experiment. The weight difference of the propellant was 29.4 mg after 1550 shots, and the uncertainty of the weight measurement was at most $\pm 5\%$. The accuracy of individual pressure measurements was $\pm 15\%$. The specific impulse was evaluated from impulse and ablated mass over 20 shots; measurement accuracy was better than $\pm 10\%$.

Results and Discussion

Laser Ablation Mode

The laser beam focused on the surface of the propellants evaporated the PVC and formed a crater. Light emission from the ablation point was observed during the laser irradiation. (The wavelength of the laser beam, 980 nm, lies in the infrared region and is invisible.) The plume of the ablation jet was highly rarefied and was not observed, but it is believed that the plume was directed normal to the ablation surface, on the basis of our past study[8] as well as a number of other studies[10,11] on the laser ablation plume.

Impulses generated by the laser ablation jet were measured, varying the laser pulse width from 50 to 800 ms. Figure 4 shows the result of the experiment using two ablation materials; each symbol indicates the impulse generated in an individual shot. Both the propellants exhibited a linear dependence of impulse on the laser pulse width, that is, laser incident energy. The custom-ordered PVC (material A) has a momentum coupling coefficient C_m of $152 \pm 4\ \mu\mathrm{N \cdot s/J}$ and a specific impulse of 104 ± 7 s, and commercially produced PVC (material B) has C_m of $42 \pm 5\ \mu\mathrm{N \cdot s/J}$ and a specific impulse of 137 ± 13 s. The mass ablated by each laser shot ranged from 1 to 40 μg and was also proportional to the pulse width, indicating that the exhaust velocity was constant. Although improvement of specific impulse is not our objective, it could be increased up to around 300 s by increasing the power density.[5]

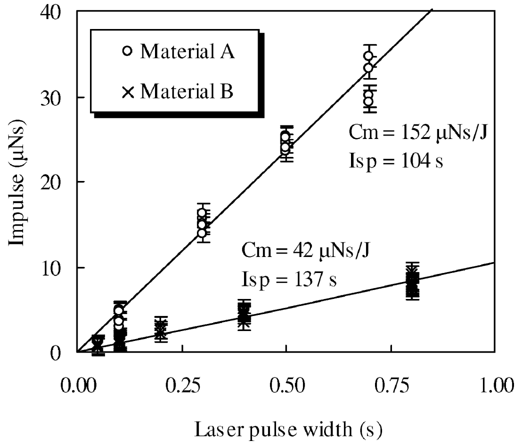

Fig. 4 Impulse dependence on laser pulse width in laser ablation mode.

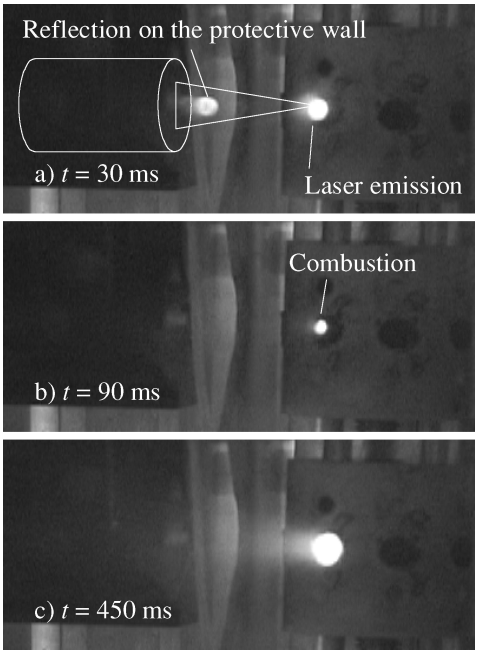

Fig. 5 Laser ignited combustion of a B/KNO_3 pellet.

The good proportionality between the impulse and laser pulse width indicates that the laser ablation mode would enable the pulse width to control very low impulse on the order of micro-Newton seconds. Because the momentum coupling coefficients differ across the ablation materials, an appropriate ablation material should be selected depending on the required impulse resolution.

Laser Ignition Mode

In the atmosphere, all pyrotechnics were successfully ignited by irradiation from a diode laser. However, in vacuum, composite and double-base propellants were not ignited. Only B/KNO_3 was successfully ignited under a background pressure of $1.4–3.0 \times 10^{-4}$ torr. Generally, the combustion speed of pyrotechnics decreases with a decrease in the background pressure, and few have a threshold pressure for self-combustion.[12]

Figure 5 shows images of the laser ignition of a B/KNO_3 pellet. Initially, the laser beam irradiates the pellet (Fig. 5a). The pellet then undergoes combustion at the focal point of the laser beam (Fig. 5b). The combustion front spreads over the surface of the pellet and steady combustion lasts from 300 to 700 ms (Fig. 5c). Thereafter the combustion becomes weak and terminates at approximately 1000 ms.

Several researchers have studied the laser ignition of chemical propellants, although most of them have conducted the experiments in the atmosphere.[12–14] They observed that the ignition depends on a thermal mechanism and the incident laser energy and the laser power density control the ignition threshold. They also noticed that the laser energy required for the ignition decreases as the laser power is increased.

The ignition threshold of B/KNO_3 was investigated against the laser pulse width; the results are shown in Table 1. At laser pulses shorter than 50 ms, no propellant was ignited. Between 50 and 150 ms, the propellants were ignited only after several attempts. When the laser pulse width exceeded 150 ms (38 mJ), all of the propellants were successfully ignited. The ignition threshold of our solid propellant was, therefore, about 100 ms. The uncertainty of the ignition around the threshold was caused by slight differences in the experimental conditions, surface position of propellants, and so on, and depends on the alignment accuracy of the optical system. A pulse width of 1000 ms (250 mJ) would be enough for spacecraft applications. These results indicate that the laser ignition mode can easily coexist with the laser ablation mode because the energy required for ignition was lower than or comparable to that for laser ablation.

Table 2 indicates performance in the laser ignition mode using B/KNO_3 propellant in vacuum. The averaged impulse was 11 ± 2 mN · s and the specific impulse, which was calculated using the weight of the pellet, was 36 ± 7 s. The theoretical value of the specific impulse of B/KNO_3 in vacuum is estimated to be higher than 100 s. This discrepancy probably arose because the propellant and the nozzle were not optimized in shape.

Table 1 Laser ignition with varying laser pulse width

Laser pulse width, ms	Number of ignitions	Number of trials
50	1	6
75	3	7
100	6	8
200	14	14

Table 2 Performance in laser ignition mode

Parameter	Value
Impulse	11 ± 2 mN · s
Specific impulse	36 ± 7 s
Laser pulse width	150 ms
(Energy)	(38 mJ)

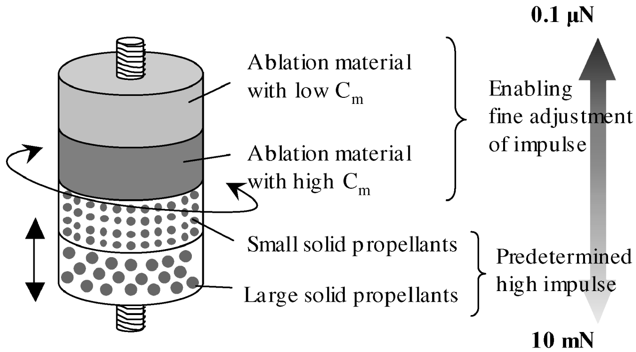

Fig. 6 Dual propulsive modes microthruster.

Dual Propulsive Mode

The experiments described here have shown that dual operational modes, laser ablation of polymer propellants and laser ignition of solid propellants, can be achieved using the same laser optical assembly. The two modes of operation generated impulses over the four orders of magnitude, impulses of 1–40 μN · s in the laser ablation mode and 10 mN · s in the laser ignition mode. Figure 6 shows a conceptual diagram of a dual propulsive mode microthruster. The propellant is fabricated from several kinds of materials, namely, ablation material with low and high C_m and solid propellant of small and large size. It is reoriented to the fixed laser optical assembly to provide the appropriate material and vary the propulsive mode according to the required thrust level. This single propulsion system, thus, performs multiple propulsive tasks with a single propulsion system.

Conclusions

A dual propulsive mode microthruster using a diode laser was proposed for 1–10 kg class microspacecraft, and the concept was discussed in detail. Experiments on the dual modes, laser ablation and laser ignition, were conducted using a single optical system. In the laser ablation mode, the impulse generated by the laser ablation from a diode laser could be finely controlled between 1 and 40 $\mu N \cdot s$ by varying the pulse width, and the momentum coupling coefficient differed across ablation materials. In the laser ignition mode, solid propellant pellets were successfully ignited by the diode laser beam with power comparable to that employed in the laser ablation mode, and the averaged impulse was 11 $mN \cdot s$. These results ensure the feasibility of a dual propulsive mode microthruster providing thrust over four orders of magnitude (1 μN–10 mN) using a single propulsion system.

Acknowledgments

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