Thermal analysis of diode-laser coupled fiber-tip heat source for high-temperature generation Innovative or Advanced Electric Propulsion Concepts

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Abstract: In this research, fabrication of a prototype of a laser thermal microthruster with a diode-laser coupled fiber-tip heat source was conducted, and operational tests including thrust measurement with a thrust stand were additionally conducted. From the figure, it was shown that as laser power increased, the thrust increased. With laser powers of 11.3 ~ 25.3 W using water as propellant, generation of thrusts of 400 ~ 1400 μN was confirmed.

I.Introduction

In recent years, a strong attention to research and development of micro-spacecraft is rapidly increasing in universities and companies, since they require much shorter period in fabrication with much cheaper cost than conventional spacecraft [1-7]. However, most of them have been lacking onboard propulsion systems due to their mass-, power-, and size-limited requirements. Because of the lack of primary and attitude control propulsion systems, their mission potentials are limited. To achieve more diverse and advanced missions, small-sized propulsion systems, or micropropulsion systems, have been under significant development in universities and companies in these years [1-4]. Since the mass, size and power are limited for the micropropulsion systems, simple miniaturization through simply employing and miniaturizing conventional propulsion systems cannot be acceptable for practical utilization of the spacecraft. Therefore, significant development of novel electric propulsion techniques has been conducted for electrothermal, electrostatic, and electromagnetic regimes, including laser acceleration regimes.

Authors have been focused on the onboard laser micropropulsion systems [8]. Among them, in this paper, a fiber-coupled laser thermal micropropulsion system is extracted, which employs a medical (surgical) treatment system. With this system, a high temperature “hot spot” (over 3000 K) can be generated within sub-milliseconds on a tip of an optical fiber coupled with a low power laser diode (LD) of only seral watts.

Since the structure of the heat source generator consisting only of a LD coupled fiber can be very simple, compact, and lightweight, a thruster employing this technique can be significantly small.

In this paper, fabrication of a prototype of the thruster and its preliminary thrust performance tests with a thrust stand are conducted and some results are presented.

A. A Fiber-tip Heat Source Coupled with a Laser Diode

A high-temperature micro-heat source made from a fiber-tip heat source coupled with a low-power laser-diode can generate a thin high-temperature layer with a diameter of that of the fiber. Currently, the LD-coupled fiber-tip heat source is used as a novel high-temperature heat source for skin surgery applications [9,10].

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Before its operation, a tip of the optical fiber is treated as follows. Figure 2 shows how the fiber tip is processed using titanium dioxide powder. Coherent light from the LD source is directed through the fiber as the tip is pressed into the TiO2 powder. The laser beam from the fiber is absorbed by the TiO2 in the powder granules and the heat generated there partly fuse the fiber tip, which then resolidifies with a coating of Ti containing material over it.

From the SEM and EPMA analysis, it is shown that the heat generated in the fiber tip burns the primary coating on the fiber exterior with stripping off the clad and exposing the core.10)A portion of the tip is melted portion in the tip due to high temperature exceeding the material melting point. A Ti layer is distributed to a depth of about 0.1 mm beneath the surface of the fiber tip, for a fiber of 0.4 mm in diameter, LD power of 6 W, wavelength of 908 nm.

Figure 3 shows temporal variation of fiber-tip temperature estimated with two-color radiation thermometry analysis [10] The fine heat source on the fiber-tip was found to be capable of elevating temperatures as high as 3100 K. Typical temperatures for 80, 110, 140, and 170 ms after excitation laser pulse was triggered were measured to be 2540, 2710, 2940 and 3110 K, respectively, for a fiber of 0.4 mm in diameter, LD power of 6 W, wavelength of 908 nm.

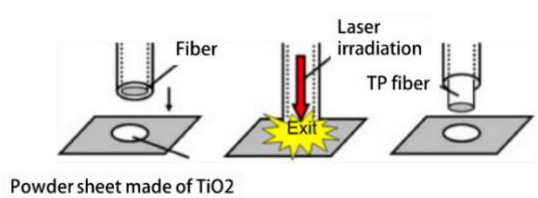


Figure 1. Conceptual drawing of fiber tip processing with TiO_2 powder

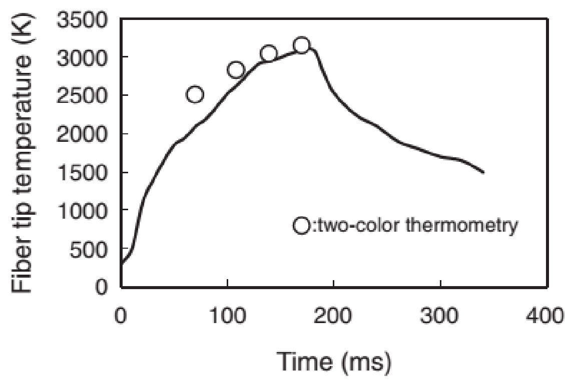


Figure 2. Results of fiber-tip temperature [10]
Solid curve shows full temporal behavior after the infrared radiation intensity of the pump laser had been calibrated with a two-color radiation thermometry at a time of 170 ms, assuming the fiber-tip to have a blackbody radiation spectral distribution. Also, round plots other than one at 170 ms indicate analysis with the two-color radiation thermometry at times of 80, 110, and 140 ms.

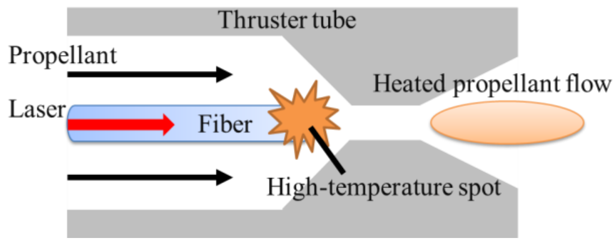
B. Novel Laser-thermal Microthruster Concept using LD-coupled Fiber-tip Heat Source

In this study, to characterize the temperature generation and to understand its physical mechanism, characteristics of high-temperature generation mechanism of the LD-coupled fiber-tip heat source for novel laser-thermal microthruster applications were investigated.

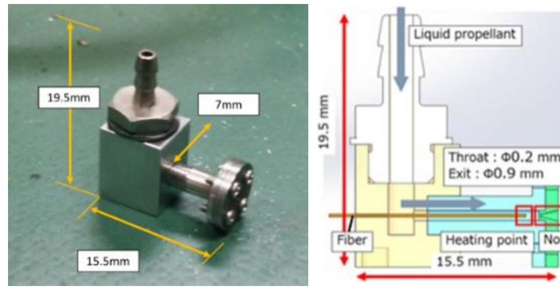
A schematic illustration and a photo of a novel laser-thermal microthruster concept using LD-coupled fiber-tip heat source were shown in Figs.3 (a) and (b). As shown in this illustration, the fiber is simply installed coaxially in a thruster tube in which liquid propellant is fed. Since the structure of the thruster head is very simple, it can be miniaturized as small as possible, depending on the diameters of a tube and a fiber. To heat the propellant flow, the laser power output from the fiber tip must be absorbed by the tip (and then transferred to the propellant). Then, the heated propellant gas is exhausted through an exhaust nozzle aerodynamically accelerating the propellant and generating a thrust as a reaction force.

As shown in Fig.3 (b), sizes of the thruster are 19.5 mm in height, 15.5 mm in length, and 7 mm in widsurfaceyth. Throat and exit diameters are 0.2 mm and 0.9 mm, respectively.

The propellant is supplied from the tube at the top of the thruster, and the laser enters the thruster through an optical fiber from the rear hole. The laser oscillator used in this study is a laser diode (Jenoptik:JOLD-30-CPXF-1L) to which a fiber with a diameter of 0.6 mm was coupled, and water was used as a liquid propellant, because it is handy, or safe and easy, to handle and to obtain.



(a)Schematic illustration of a novel laser-thermal microthruster concept using LD-coupled fiber-tip heat source.



(b) Photo of thruster.

Figure 3 Novel laser-thermal microthruster concept using LD-coupled fiber-tip heat source.

II.Experimental

Figure 4 shows a photo and an illustration of thrust measurement system. In this study, a continuous wave (cw) mode of laser irradiation is selected. To drive the laser, a DC power supply (UNITAC, NELD-15) is utilized.

Thrust measurement is performed using a thrust stand installed in a vacuum chamber. The thrusters are connected to the stand via the thruster holder.

Displacement of a pendulum is measured using a laser displacement sensor (KEYENCE:LB-040) and recorded with a data logger (HIOKI:LR8431). An electrostatic actuator consisting of two copper plates is used for calibration. Liquid propellant, water, is fed to the thruster head with a syringe pump, in which pumping speed of the syringe is adjusted with an actuator (SIGMAKOKI: SOM-C25E) and controller (SIGMAKOKI: OMEC-2-BG), and then, a flow rate of the propellant can be controlled. Table 1 shows operational conditions of the laser during the experiment.

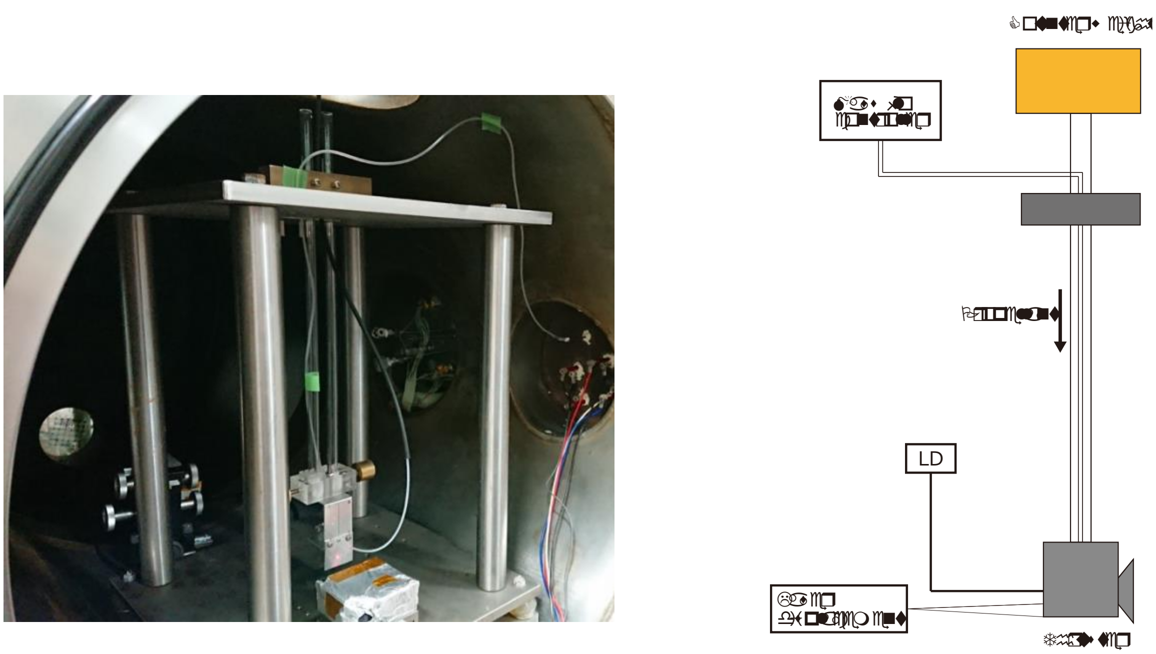


Figure 4 Thrust stand and measurement system.

III.Results and Discussion

A typical waveform of temporal changes of displacement of the thrust stand, or thrusts, is shown in Fig.5. It is shown that displacement starts to occur around 20 seconds after the start of laser output and propellant supply. Moreover, values of the thrust is relatively stable during operation. In addition, it can also be seen that the generation of thrust has stopped when the output of the laser and the supply of the propellant are stopped at around 90 seconds. A photo of the thruster in operation is shown in Fig.6, where a thruster and a water vapor plume are shown. From the figures, it is shown that the propellant is heated and vaporized by the output of the laser, and then the thrust can be generated.

Variations of the thrusts versus laser powers are shown in Fig.7. From the figure, it is shown that as laser power increases, the thrust tends to increase as well. This is presumably because the amount of propellant that can be vaporized increases as the power of the laser increases. With laser powers of 11.3 ~ 25.3 W using water as propellant, generation of thrusts of 400 ~ 1400 μN was confirmed. Moreover, some scatters of the values of the thrust can be seen at identical conditions. It is necessary to repeat some more tests to investigate the cause of this variation.

Table 1 Condition of thrust measurement experiment

Laser output[W]	10 ~ 26
Water mass flow rate[mg/s]	3.98 ~ 9.83
Liquid propellant	Water

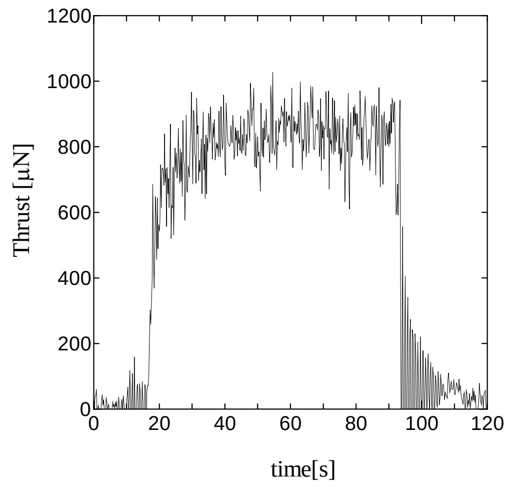


Figure 5 Temporal changes of thrusts.

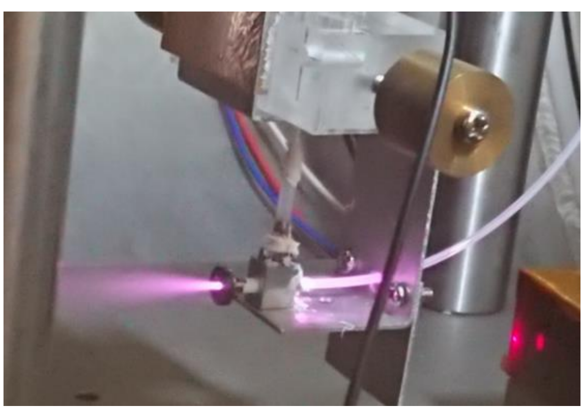


Figure 6 Photo of thruster in operation.

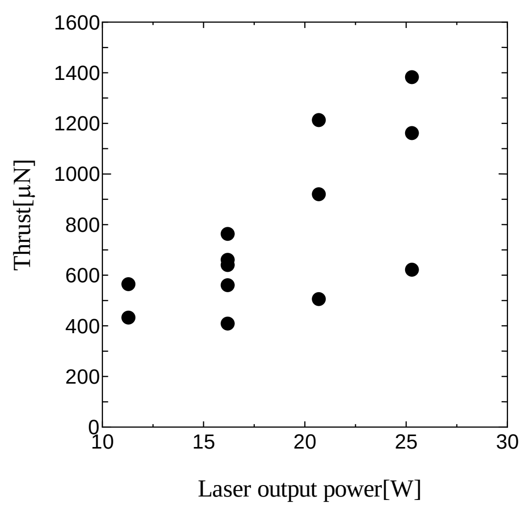


Figure 7 Variation of thrust for various laser powers.

IV.Conclusion

In this research, fabrication of a prototype of a laser thermal microthruster with a diode-laser coupled fiber-tip heat source was conducted, and operational tests including thrust measurement with a thrust stand were additionally conducted.

From the figure, it was shown that as laser power increased, the thrust increased. With laser powers of 11.3 ~ 25.3 W using water as propellant, generation of thrusts of 400 ~ 1400 μN was confirmed.

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