A laser thermal microthruster with a novel laser-diode-coupled fiber-tip thermal source

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Yoshiki Fukuda[1], Keisuke Kondo[2], Tatsuro Shimojo[3] and Hideyuki Horisawa[4]
Tokai University, Kitakaname, Hiratsuka City, Kanagawa, 259-1292

Abstract: A study on a novel microthruster with a novel laser-diode-coupled fiber-tip heat source excited by a semiconductor laser was conducted. Fundamental phenomena of high-temperature generation of the fiber-tip heat source excited by a semiconductor laser were investigated. Measurement of absorption rates of the light irradiated on various absorbers mixed with water was conducted to optimize propellant mixtures.

Nomenclature

I	=	*intensity of the beam*
I_0	=	*intensity of an incident laser beam*
α	=	*absorbance*
x	=	*optical path length*

I. Introduction

Feasibility studies of micro-spacecraft are currently under significant development for a mass less than 100 kg with an available power level for propulsion of less than 100 watts.[1-4] The significance in reducing launch masses has attracted growing interests in regard to a decrease in mission cost and an increase in launch rate. The micro-spacecraft segments of the satellite launch industry have been growing rapidly in recent years. Development activity for a mass less than 50 kg range has been significantly exceeding that in the 50 ~ 100 kg range. In the smaller range alone, there were fewer than 15 satellites launched annually in 2000 to 2005, and 34 satellites in 2006. Then there were fewer than 30 launches annually during 2007 to 2011, and 34 satellites in 2012. The launch rate rapidly rose up to 92 satellites in 2013, and then 158 in 2014, which included some of more practical missions .[5,6]

Although, in the past, many very small spacecraft lacked propulsion systems, future micro-spacecraft will require significant propulsion capability to provide a high degree of maneuverability and capability. The benefit of using electric propulsion for the reduction of spacecraft mass will likely be even more significant for mass limited micro-spacecraft missions.[2-4]Various potential propulsion systems for micro-spacecraft applications, such as ion thrusters, field emission thrusters (FEEPs), colloid thrusters, pulsed plasma thrusters (PPTs), etc., have been proposed and are under significant development for primary and attitude control applications.[4]

On the other hand, small-sized onboard laser plasma thrusters are also under significant development with rapid evolutions of novel compact laser systems.[8] One of the advantages of the laser thrusters is that they can induce high specific impulses. In addition, the system can be very simple and small with significant controllability of the thrust.

[1] Graduate student, Department of aeronautics and astronautics, norakichi0301@gmail.com
[2] Graduate student, Department of aeronautics and astronautics.
[3] Undergraduate student, Department of aeronautics and astronautics.
[4] Professor, Department of aeronautics and astronautics, hideyuki.horisawa@gmail.com.

In this study, characteristics of high-temperature generation mechanism of a laser-diode (LD) coupled fiber-tip heat source for novel laser-thermal microthruster applications were investigated. The LD-coupled fiber-tip heat source can generate a high temperature spot, and is currently used as a novel high-temperature heat source for skin surgery applications.[9] However, detailed physical mechanism of the high temperature generation is still not well-known.[10] An objective of this study is to characterize the temperature generation and to understand its physical mechanism for the future application of microthrusters.

II. 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.

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 TiO_2 powder. The laser beam from the fiber is absorbed by the TiO_2 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 thermometryanalysis.[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.

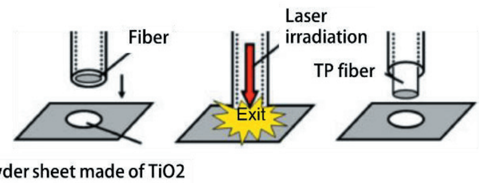

Figure 1. Conceptual drawing of fiber tip processing with TiO_2 powder

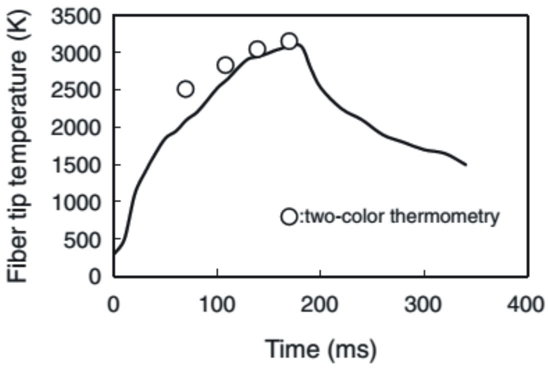

Figure 2. Results of fiber-tip temperature

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.

III. A 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 of a laser microthruster with the LD-coupled fiber-tip heat source is shown in Fig.3. As shown in this illustration, the fiber is simply installed

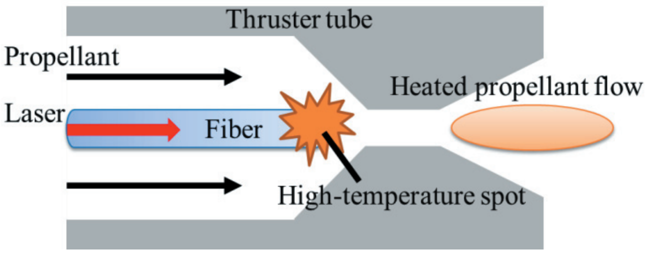

Figure 3. A schematic illustration of a laser microthruster with the LD-coupled fiber-tip heat source.

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 either by the tip (and then transferred to the propellant) or directly by the propellant with absorber additives. Then, the heated propellant gas is exhausted through an exhaust nozzle aerodynamically accelerating the propellant and generating a thrust as a reaction force.

IV. Experimental

As for a laser oscillator, a fiber coupled laser diode (JENOPTIK, JOLD-30-CPFX-1L), shown in Fig.4 and Table 1, was employed. In this study, a continuous wave (cw) mode of irradiation was selected. To drive the laser, a DC power supply (UNITAC, NELD-15) was utilized.

To enhance the absorption of the laser beam to a liquid propellant, black (TOYO ALD, TC-30) and red (TOYO ADL, RedMA) absorbers were employed considering the compatibility of the wavelength of the laser.

Since absorption rates of the laser beam to the liquid propellants are key factors in laser heating of the propellants, measurement of the absorption rates was conducted. A schematic illustration of the measurement is shown in Fig.5. A propellant (pure water) with an arbitrary concentration of an absorber was contained in a transparent container (10 mm in depth (horizontal)) to the laser wavelength. Variations of intensities of the laser beam passing through the propellants with various conditions in the container were monitored with a spectroscopic analyzer (STELLEMET, Black Comet).

In Beer-Lambert-Bouguer law, in general, relations of transmitted intensity of the beam I, intensity of an incident laser beam I_0, optical path length x, and absorbance α, are expressed as follows.

Figure 4. Fiber coupled laser diode.

Table 1. Specification of JOLD-30-CPFX-1L

Power	30 W (cw)
Wavelength	808 nm
Fiber core	0.6 mm
Voltage	2 V

$$I = I_0 e^{-\alpha x} \quad (1)$$

$$\alpha = -\frac{1}{x}\ln\frac{I}{I_0} \quad (2)$$

As can be seen from the relations of (1) and (2), the measurement of I for an arbitrary I_0 and fixed x enables determination of α.

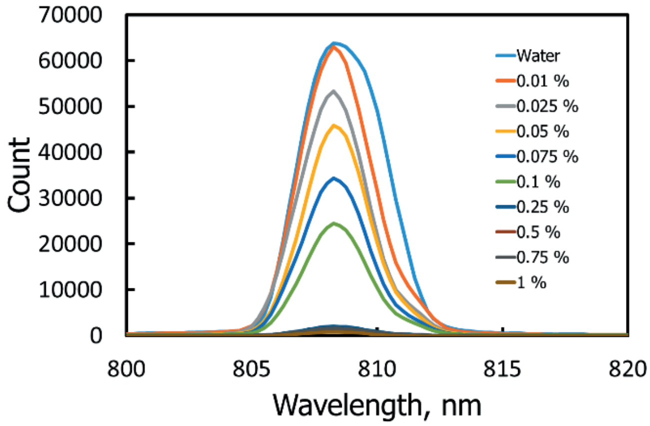

Figure 5. Measured spectra for various conditions.

Typical spectra for various conditions of concentrations are shown in Fig.5. The peak intensity of the spectra for a pure water case was regarded as I_0, and the peaks for various conditions as measured Is.

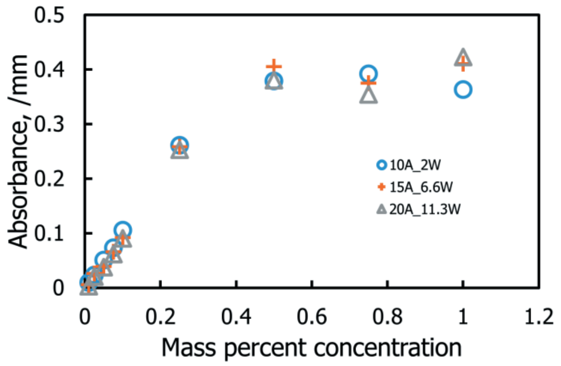

Figure 6. Measured spectra for various conditions (TC-30)

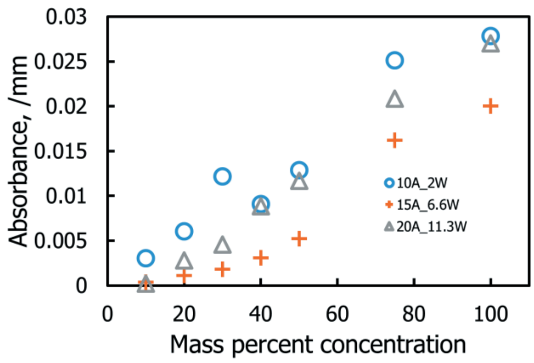

Figure 7. Measured spectra for various conditions (RedMA)

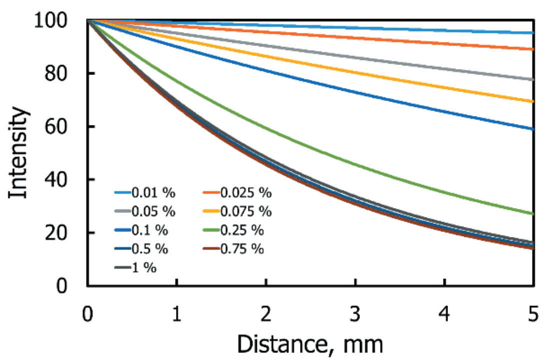

Figure 8. Relations of output intensities and distance (TC-30)

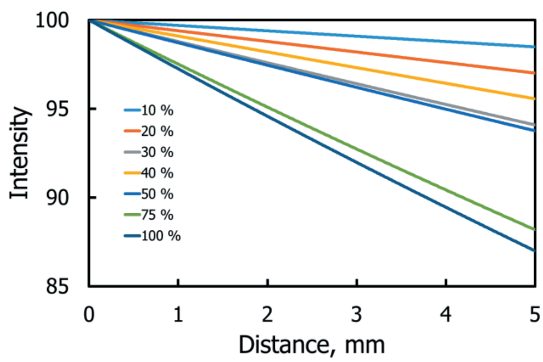

Figure 9. Relations of output intensities and distance (RedMA)

V. Results and Discussion

Measured absorbances for various conditions are shown in Figs.6 and 7 for TC-30 and RedMA, respectively. As seen in these figures, the absorbance increases with concentration of the propellant. However, in Fig.6 for TC-30, the absorbance is relatively flat with increase of concentration after that of 0.5wt%. This is probably because the concentration is too high for the propellant to maintain the Beer-Lambert-Bouguer law. Moreover, the absorbances of TC-30 are almost independent of laser power. On the other hand, those of RedMA changes with laser power.

Relations of output of intensities and distances, or x, are estimated and plotted for various concentrations in Figs.8 and 9 for TC-30 and RedMA, respectively. In Fig.8 for TC-30, the output intensity decays down to below 20% for concentrations of over 0.5wt%. On the other hand for RedMA, the decay, or absorption, is relatively small and probably not adequate for an absorber to the laser beam. Further measurement will be needed to investigate optimum conditions.

VI. Conclusion

In this study, characteristics of high-temperature generation mechanism of a laser-diode (LD) coupled fiber-tip heat source for novel laser-thermal microthruster applications were investigated. Since absorption rates of the laser beam to the liquid propellants are key factors in laser heating of the propellants, measurement of the absorption rates was conducted.

1) For TC-30, the absorbance is relatively flat with increase of concentration after that of 0.5wt%.
2) For TC-30, the output intensity decays down to below 20% for concentrations of over 0.5wt%. On the other hand for RedMA, the decay, or absorption, is relatively small and probably not adequate for an absorber to the laser beam.

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