A Fundamental Study of a Photon-driven Microthruster through Interaction of Ultraviolet Photons and Polymers

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Abstract: The objective of this study is to develop a microthruster, utilizing a reaction force of the molecular flow generated through dissociation of molecular bonds of polymer targets by irradiation of ultraviolet (uv) photons, namely photochemical reactions. The uv-photons, carrying higher photon energies, can directly dissociate the molecular bonds having lower bonding energies than the photon energies. In this study, the uv-photons from light emitting diodes were irradiated to two types of solid polymer targets, nylon and polyvinyl chloride (PVC), to investigate each mass consumption rates. Furthermore, thrusts caused through the photo-dissociations of each polymer targets were measured using a torsional pendulum thrust stand. The results showed that PVC target was capable of generating higher thrusts in lower propellant mass consumption rates than nylon target.

Nomenclature

c	=	speed of light
d	=	separation of electrodes
E	=	photon energy
F	=	force
h	=	Planck's constant
l	=	length of a side of an electrode
V	=	voltage
ε	=	dielectric constant
λ	=	wavelength of light

I. Introduction

Micro-spacecraft segments of the satellite[1], which has a wet mass less than 100 kg, have been considered in the aerospace community since the early 1980s and have gained increased attention ever since. One benefit is the substantial reduction in the overall life-cycle cost by making satellites less costly to construct, due to fewer components and the potential for mass production techniques. Furthermore, the significance in reducing launch masses has attracted growing interests in regard to a decrease in mission cost and an increase in launch rate[1]. In recent years, a number of private sectors planning use of outer space for their activities have focused on these advantages. The micro-spacecraft segments of the satellite launch industry have been growing rapidly for this reason. 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, the launch rate rapidly rose up to 92 satellites in 2013. Annual number of launches has been exceeding 100 from 2014, which included some of more practical missions. Projections based on announced and future plans of developers and programs indicate as many as 3000 microsatellites will require launches from 2016 through 2022[2,3].

Under these activities, the strong demands have arisen for the development of micro-propulsion devices that enable

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micro-spacecraft to perform more advanced missions. These devices will be required to deliver very low thrust values and low impulse bits and may feature engine masses and sizes orders of magnitude smaller than available with current thruster hardware. The benefit of using electric propulsion (EP) for the reduction of spacecraft mass will likely be even more significant for mass limited micro-spacecraft missions[4,5]. Various potential EP systems for micro-spacecraft applications have been proposed and are under significant development for primary and attitude control applications. However, further mass reduction and miniaturization of the propulsion components including new technologies are strongly required. Although use of EP can be one of the strong candidates for the micro-spacecraft, simple miniaturization of conventional EP components is not as physically simple due to high-voltage or high-current requirements, etc.

For these severe requirements of micro-spacecraft, we propose a novel, compact, lightweight, and low-power (low-voltage) propulsion system. This system employs an interaction of ultraviolet light-emitting diodes (uv-LEDs) and polymer targets.

Since the invention of the first LED in 1927, the first visible LEDs in 1962, and the first blue LEDs in 1972, the significant improvements in photon energies (shortening wavelengths) and luminous efficiencies of LEDs have been made. Recently, the first high-brightness blue LED was demonstrated by Dr. Shuji Nakamura of Nichia Corporation in 1994. After that, uv-LEDs employing semiconductor structures using aluminum gallium nitride (AlGaN) or Indium gallium nitride (InGaN) were demonstrated. As development of uv-LEDs and its manufacturing technologies have made a significant progress in recent years, further improvement in the efficiency and further cost reduction can be expected in near future[6]. In general, the uv-LEDs are significantly compact and lightweight than previous uv-light sources such as mercury lamps and excimer lasers. In addition, it is not usually necessary to drive them with high-voltage power supplies and with time delays for warming up during operation.

The mechanism of thrust generation of uv-photon propulsion technique proposed in this paper differs from those of conventional light propulsion concepts for spacecraft, such as laser ablation propulsion (LAP) and photon rockets (or lightsails)[7]. In the LAP, an intense laser beam strikes a condensed-matter surface (solid or liquid) and produces a jet of high temperature vapor or plasma, and just as in a chemical rocket, thrust is produced by the resulting reaction force on the surface. The lightsail utilizes the momentum of photons to produce a thrust directly through reflecting photon beams by pellicle mirror. Unlike the previous light propulsion mechanisms described above, our uv-photon propulsion mainly employs photochemical reactions, or photo-dissociations, induced by a large energy of individual photons, instead of thermal dissociations or radiation pressure. In this case, given higher energies from the uv-photons, the intermolecular bonds of the polymer target will directly be disconnected and exhausted from the surface. At the same time, the thrust is induced as a reaction force. These photochemical phenomena induced by uv-rays have been applied in various fields, such as surface modification and optical cleaning in industry[8].

Table 1. List of bonding energies and dissociation wavelengths for typical bonds.

Molecular bond	Bonding energy [kJ/mol]	Dissociation wavelength [nm]
C-N	266.5	448.9
C-Cl	321.9	371.6
C-C	352.9	339.0
N-H	384.7	311.0
C-H	408.6	292.8
H-Cl	426.6	280.4

Relations of typical molecular bonds and their bonding energies including corresponding dissociation wavelengths of photons, λ, are listed in Table 1. In this table, photon energies, E, are calculated from the following relation,

$$E = hc/\lambda \tag{1}$$

, where h is Planck's constant, and c is the speed of light. Depending on the wavelengths, or photon energies, of the uv-photons, some organic compounds, or molecular bonds, can be directly dissociated.

In this study, firstly, mass consumption rates of polymer targets caused through photo-dissociation of surfaces by uv-photons from the LEDs were measured to verify photochemical reactions (photo-dissociation) occurring on polymer surfaces. Secondly, measurement of thrusts by a torsion pendulum thrust stand capable for sub-micro-newton thrust ranges was conducted.

II. Experimental Procedure

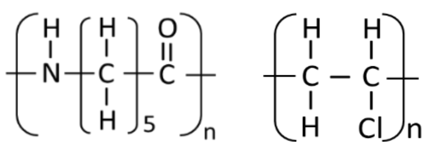
A. Mass consumption rate measurement

Firstly, mass consumption rates of polymer targets caused by uv-photons from LEDs were measured. In this study, a uv-LED (Nichia Corporation, NC4U133B (T)) of peak wavelength of 365 nm was employed. Specifications of the LED are listed in Table 2. Considering the wavelength of 365 nm, or photon energy, and bonding energies of molecular bonds, nylon with C-N bonds and polyvinyl chloride (PVC) with C-Cl bonds were selected for target materials. As shown in Table 1, the uv-photons of wavelength of 365nm emitted from the LED, carrying higher energy than bonding energies of C-N and C-Cl bonds, are capable enough to dissociate these molecular bonds. Constitutional formulas of nylon and PVC are shown in Fig. 1. A schematic of experimental setup is shown in Fig. 2. As shown in this figure, the measurement was conducted in a vacuum chamber kept at 10^{-3} Pa and a distance of uv-LED and target was 4 mm. The uv-LED was fixed to an aluminum heat sink in order to prevent degradation of its light emitting performance caused by heat generations during long-time drive of the LED in a vacuum environment.

Table 2. Specifications of uv-LED employed in this study.

Forward current [mA]	500
Forward voltage [V]	15.4
Radiant flux [mW]	2040
Peak wavelength [nm]	365
Spectrum half width [nm]	9.0

To measure the mass consumption rates of the targets during uv-irradiation, uv-photons emitted from the LED were irradiated on the targets for 6 hours continuously. Using an electronic balance of the minimum resolution of 0.1 mg, mass reductions of the targets before and after uv-irradiation were measured to estimate mass consumption rates.



(a)Nylon6 (b)PVC

Figure 1. Constitutional formulas of polymer targets.

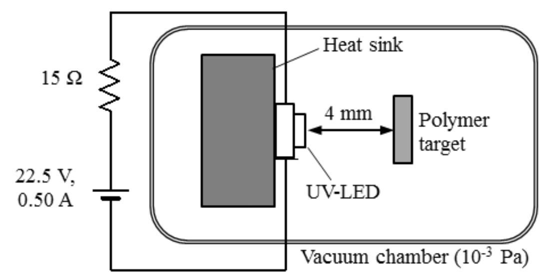


Figure 2. Schematic of experimental setup for mass consumption rate measurement.

B. Thrust measurement

An experimental setup for thrust measurement is shown in Fig. 3. A thrust stand consists of a horizontal torsion pendulum was installed on a vibration isolator with rubber cushions in a vacuum chamber. The vacuum chamber was kept at 10^{-3} Pa during thrust measurement. Displacement of the pendulum arm was measured by a laser displacement sensor (LDS) with the resolution of 0.1 μm. A propellant target was fixed on an edge of the pendulum arm. Photons of a uv-LED were irradiated to the target surface with a separation of 4mm. In order to make fine adjustment of the neutral position of the arm, an end of the flex pivot of the pendulum was connected to a rotary stage with an actuator.

A calibration of the thrust stand was conducted using an electrostatic actuator consist of square copper plates. An electrostatic force F was generated

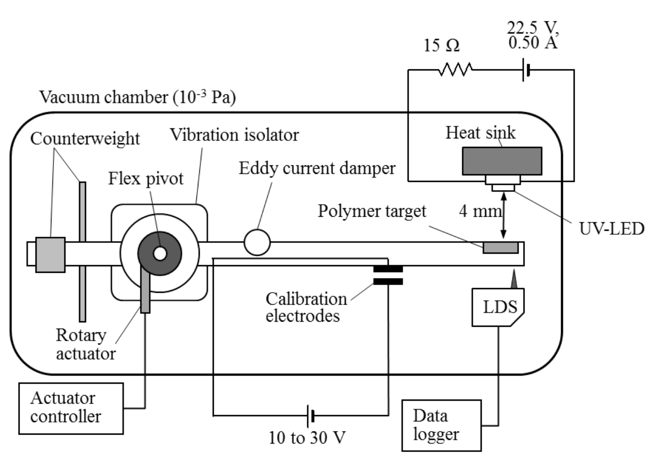


Figure 3. Schematic of experimental setup for thrust measurement. *Viewed from above.*

when a voltage *V* was applied to two parallel square plate electrodes. In this case, the electrostatic force considering fringing effect is determined by the following equation,

$$F = \frac{1}{2}\varepsilon_0 \left(l + \frac{3}{8}d\right)^2 \left(\frac{V}{d}\right)^2 \tag{2}$$

, where ε, dielectric constant, *l*, a length of a side of the electrode, and *d*, a separation of the electrodes.

The thrust generated through an interaction of uv-photons and target was calculated from the relation between the displacement and the electrostatic force estimated from the theoretical equation (2).

III. Experimental Results

A. Results of mass consumption measurement

Results of mass consumption rate measurement are listed in Table 3. After irradiation of uv-photons for 6 hours in vacuum, mass reductions of nylon target and PVC target were 9.8 mg and 3.5 mg, respectively. From these results, mass consumption rates for nylon and PVC targets were 0.45 μg/s and 0.16 μg/s, respectively. On the other hand, from the results of a preliminary experiment conducted to survey mass reductions caused by the outgassing of each polymer targets, it was verified that each target mass decrements induced simply by being exposed to a vacuum environment for 6 hours were about 0.04% of their initial masses. Considering this effect, mass reductions of nylon target and PVC target induced by irradiation of uv-LED were estimated to be 9.3 mg and 2.9 mg, respectively.

According to the above results, it is confirmed that the mass reduction largely caused by photochemical dissociations is taking place on the target surfaces by irradiation of uv-photons, then intermolecular bonds with the targets are disconnected and the molecules are discharged. It is also confirmed that the mass consumption rate of PVC target was about one third of that of nylon target.

Table 3. Results of mass consumption rate measurements.

Target material	Nylon	PVC
Initial mass [mg]	1178.2	1376.5
Final mass [mg]	1168.4	1373.0
Decrement [mg]	9.8	3.5
Estimated mass consumption rate [μg/s]	0.45	0.16

B. Results of thrust measurement

Typical waveform of the thrust stand displacement is shown in Fig. 4. In this figure, it can be seen that a thrust force was detected in a duration of irradiation of uv-photons on the target surface for 4 s.

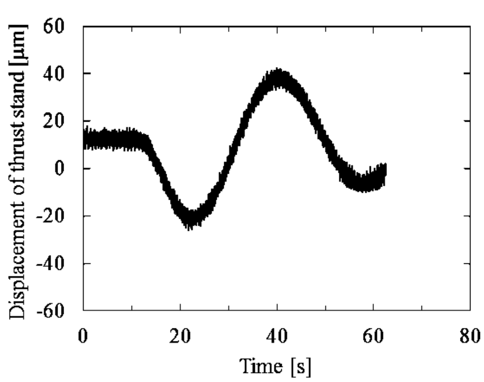


Figure 4. Thrust waveform with nylon target. *Uv-LED was irradiated to the target surface between 10 s and 14 s.*

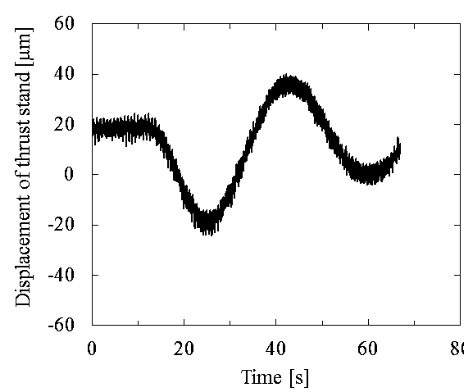


Figure 5. Calibration waveform with electrostatic actuator. *Applied voltage = 30 V.*

Examples of results of calibration by an electrostatic actuator are shown in Figs. 5 and 6. Results of calibrated thrusts calculated from the calibration are listed in Table 4. From this table, it was confirmed that the thrusts were 0.103±0.037 μN and 0.414±0.046 μN, for nylon and PVC targets, respectively. Considering resolution of the LDS, variations of the electrode separation and applied voltages, the accuracy of the thrust calibration was within ±5 nN.

From Table 4, it can be seen that generated thrusts tend to become lower with the repetition of LED irradiation in both case. One of several causes for this phenomenon could be that the exhausted substances from targets adhered to the LED surface and caused lowering of uv-light intensity. Another possible cause is that adsorbed impurities on the target surfaces were discharged from target materials, and increased thrusts in the early stages of uv-irradiation. From these results, cleaning of the target surface before irradiation of uv-LED may be effective to obtain stable thrusts.

The specific impulses estimated from the mass consumption rates and the thrusts for nylon target were estimated to be 14 to 37 s, while those for PVC targets were 230 to 320 s. In addition, the coupling coefficients (thrust-to-radiant flux ratios) were 29 to 83 μN/kW for nylon target and 176 to 245 μN/kW for PVC target.

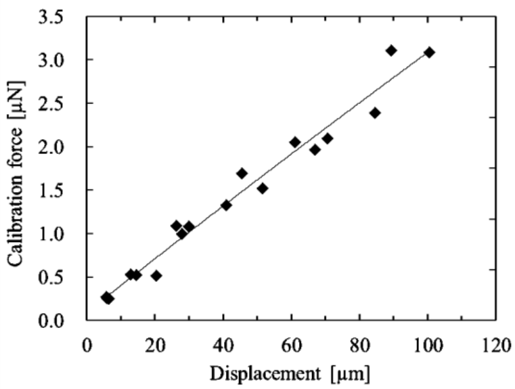


Figure 6. Calibration curve of thrust stand.
R^2 = 0.97.

Table 4. Calibrated thrusts of polymer targets.

Number of measurement	Thrust of nylon [μN]	Thrust of PVC [μN]
1	0.162	0.504
2	0.166	0.463
3	0.136	0.445
4	0.116	0.415
5	0.079	0.392
6	0.083	0.387
7	0.084	0.404
8	0.075	0.358
9	0.067	0.358
10	0.063	-

On the other hand, a thrust, F_{photon}, induced only by photon pressure of light of power P (= 2040m W) is expressed as,

$$F_{\text{photon}} = P/c = 6.80\ \text{nN} \tag{3}$$

The thrusts measured in this experiment were larger at least in two orders of magnitude than the photon pressure of the uv-photons.

IV. Conclusion

In this study, a fundamental investigation on use of interaction of uv-LEDs and polymer targets for micropropulsion thruster was conducted. The following conclusions were obtained;

1) By irradiating uv-photons to nylon and PVC targets continuously, mass reduction primarily caused by photochemical reactions were observed on each target surface.

2) By measuring the thrust by using the torsional pendulum thrust stand, it was confirmed that nylon and PVC targets can both generate thrust in durations of irradiation of uv-photons.

3) In the case of using PVC as a propellant, the mass consumption rate and the thrust were about one third and 4 times of that of nylon, respectively.

From these results, specific impulse and coupling coefficient of PVC were considered to be superior to those of nylon. In addition, the thrusts produced by photo-dissociation were larger in two orders of magnitude than the photon pressure of the uv-photons.

The differences between thrust, or specific impulses, of nylon and PVC are supposed to be related to the gas species exhausted from target surfaces and its exhaust speed, or vapor pressure. One of our future works will include an investigation on correlations of thrust performances and target properties through photochemical reactions for various polymers.

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