Thrust Performances of a Very Low-Power Micro-Arcjet

Hotaka Ashiya, Tsuyoshi Noda*, Hideyuki Horisawa* and Itsuro Kimura***
**Department of Aerospace Engineering, Tokai University*
1117 Kitakaname, Hiratsuka-shi, Kanagawa, 259-1292 Japan.
***Professor Emeritus, University of Tokyo, and Nara Textile Inc.*
4-19-4 Nakahara, Isogo-ku, Yokohama, 235-0036 Japan.

E-Mail: horisawa@tokai.ac.jp

Keywords: Micro-Arcjet, Very Low-Power Arcjet, Micropropulsion.

Abstract

In this study, microfabrication of a micro-arcjet nozzle with Fifth-harmonic generation Nd:YAG pulses (wavelength 213 nm) and its thrust performance tests were conducted. A micro-arcjet nozzle was machined in a 1.2 mm thick quartz plate. Sizes of the nozzle were 0.44 mm in width of the nozzle exit and constrictor diameter of 0.1 mm. For an anode, a thin film of Au (~ 100 nm thick) was deposited by DC discharge PVD in vacuum on divergent part of the nozzle. As for a cathode, an Au film was also coated on inner wall surface. In operational tests, a stable discharge was observed for mass flow of 1.0 mg/sec, discharge current of 6 mA, discharge voltage of 600 V, or 3.6 W input power (specific power of 3.6 MW/kg). In this case, plenum pressure of the discharge chamber was 80 kPa. With 3.6 W input power, thrust obtained was 1.4 mN giving specific impulse of 138 sec with thrust efficiency of 24 %.

1. Introduction

The current trend towards smaller spacecraft, which is not only mass limited but also power limited, has produced a strong interest in development of micropropulsion devices [1-3]. The significance in reducing launch masses has attracted growing interests in regard to reduction of mission costs and increase of launch rates. Although in the past, many very small spacecraft have lacked propulsion systems altogether, future microspacecraft will require significant propulsion capability in order 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 microspacecraft missions [1-3]. Feasibility studies of microspacecrafts are currently under development for the mass less than 100 kg with an available power level for propulsion of less than 100 watts. Various potential propulsion systems for microspacecraft applications, such as ion thrusters, field emission thrusters, PPT, vaporizing liquid thrusters, resistojets, microwave arcjets, pulsed arcjets, etc., have been proposed and are under significant development for primary and attitude control applications [1-3].

As for low power DC arcjets operational at power levels down to about 300 watts, several investigations have been conducted on their use for north-south stationkeeping (NSSK) on geosynchronous satellites [4-7]. However, there has been little focus on the study of DC arcjets operational at very low power levels, i.e., less than 100 watts [8-11], for microspacecraft propulsion devices, relating not only to the thrust performance but to fundamentals of the very low power DC discharges as well. The structural simplicity of an arcjet may be favorable for both size and mass reduction of the thruster; also, further reduction of the input electrical power, to less than 100 watts for example, may be effective for reducing the mass of the power supplies. In addition, very low power operation of arcjets, especially at reduced specific power levels with lower temperature of the propellant which is heated through the discharge, will elongate the life of electrodes and reduce the electrode losses and frozen flow losses, resulting in higher thrust efficiency. Although the specific impulse achievable during operation will be reduced at low specific power levels, it will be recovered to some extent through the achievement of loss reduction.

The objective of this study is to investigate the fundamentals of discharge characteristics and the performance of very low power DC arcjets with electrical input power levels ranging from approximately 1 ~ 10 watts in order to ascertain the effective operational condition which possibly results in higher thrust performance. In this study, the conditions for stable operation and diagnostics of an internal flow of the arcjets, temperature measurements of plasma in a discharge chamber were conducted. Also, thrust performance, such as thrust, specific impulse and thrust efficiency of a very low-power arcjet, was evaluated.

Moreover, microfabrication of a micro-arcjet nozzle with Fifth-harmonic generation Nd:YAG pulses were conducted. Investigations of the conditions for stable operation at less than 10 watts and evaluation of thrust performances were carried out with the newly developed thruster.

2. Very Low-Power Arcjet

2.1 Experimental

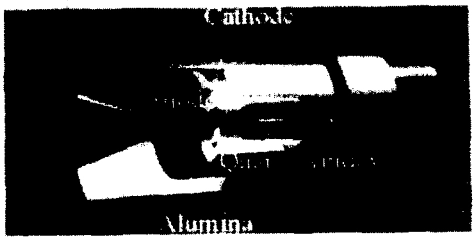
A cross-sectional schematic of an arcjet thruster used in this study is shown in Fig.1(a). In general, an arcjet nozzle consists of a metallic material, and serves a dual function as an anode and an arc column constrictor, except for a divergent section. In this study, a ceramic material with low heat conductivity for a convergent section and the following part of the constrictor in a nozzle was used to reduce electrode losses.

Sizes of the thruster are 41 mm in length, 17 mm in diameter (maximum), constrictor diameter of 0.3 mm (or 0.5 mm), and anode-cathode gap of 0.5 mm. A photo of the thruster is given in Fig.1(b). The inner thruster body consists of a clear-quartz tube to diagnose internal behaviors of the discharging plasma measuring spontaneous emissions from the plasma with the color CCD camera and the multichannel spectrum analyzer.

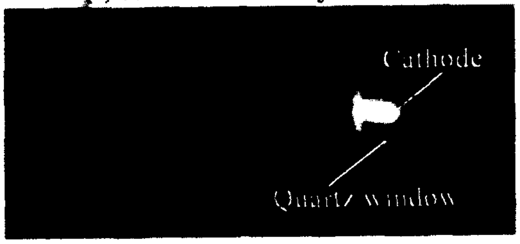
For the ceramic material, the alumina (Al_2O_3) was used for a part of the constrictor to allow the arc column to penetrate further downstream of the constrictor, or to maintain the high-voltage mode discharges, and possibly reduce the electrode losses. The cathode used in the tests was made from a tungsten rod 0.5 mm in diameter with a conical tip angle of 15 degrees. Nitrogen gas was used as a propellant, and the feed pressure was measured upstream of the plenum. In this study, in order to establish stable discharges at very low current levels ranging from 1 ~ 10 mA, a high-voltage power supply with high ballast resistance was used.

A thrust performance test was conducted in a vacuum vessel. A calibrated cantilever-type thrust stand consisting of quartz plates (Fig.2) was used for the measurement. The specific impulse: *Isp* and the thrust efficiency: *?* are calculated using the values of *T* : total thrust, *Tc* : thrust of cold gas jet, m: mass flow rate, and *Pin*: electrical input power[11].

Spectroscopic measurements were also conducted to evaluate the effects of variations in the mass flow rate and discharge current on heavy particle, or molecular nitrogen, temperature of the heated propellant. In order to evaluate the gas temperature, the wavelength (300 ~ 800 nm) and spectrum intensity of the spontaneous emission of the gas on a central axis of the discharge chamber were measured using a multichannel spectrum analyzer. Based on spectroscopic theories, the spontaneous emission spectrum resulting from electronic transitions of nitrogen molecules (1st Positive System, $?^3?_g - A^3?_u^+$) was calculated for a given set of conditions [11-13]. Here, the parameters assumed for computing each theoretical spectrum were the number density of the gas, the vibrational temperature (T_{vib}) and the rotational temperature (T_{rot}). The temperatures (T_{vib} and T_{rot}) of the gas were found by selecting a set of parameters which makes the calculated spectrum fit well to the measured spectrum[11].



(a) Schematic of an arcjet thruster.



(b) Photo of an arcjet thruster in operation.

Fig.1 Schematics of an arcjet thruster.

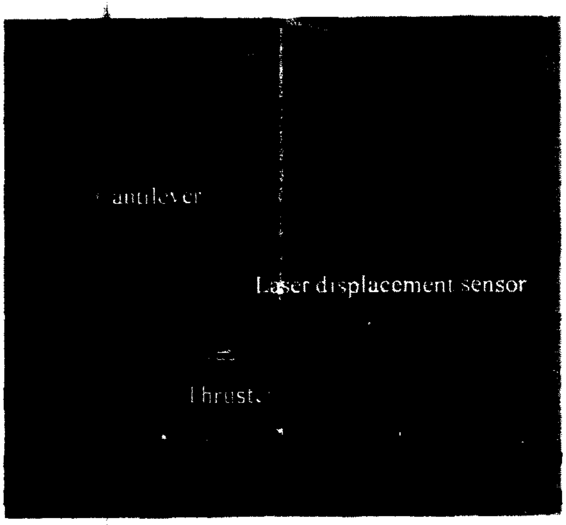


Fig.2 Schematic of a thrust performance test.

2.2 Thrust performance and heavy particle temperature

Fig.3 shows the plots of specific impulse versus arcjet input power (~ 5 W). It must be noted that the specific impulse shows linear increases even with very low power levels of ~ 5 W. For a higher mass flow rate case, slightly lager specific impulse is obtained. Values of the specific impulse in these cases are much lower than expected probably due to the significant radiative heat loss through a quartz window.

Plots of heavy particle temperatures of the plasma in a discharge chamber versus arcjet input power, for various mass flow rate cases are shown in Fig.4. Under the experimental conditions, it was observed that the rotational temperature (*T*rot) and the vibrational temperature (*T*vib) of the nitrogen gas in the discharge chamber estimated through the spectroscopic measurements are found in nonequilibrium in most cases. In Fig.4, it is shown that the vibrational temperature is almost constant with increasing arcjet input power for each mass flow case but significantly rises with decreasing the mass flow rate. On the other hand, the rotational temperature is almost constant with the mass flow rate but significantly increases with the current. Also it can be seen that the difference between vibrational temperature and rotational temperature, or the degree of thermal nonequilibration, becomes smaller with higher current and higher mass flow cases. For example, in a higher mass flow case with higher input power (e.g. 2.08 mg/sec, 7 W), *T*vib ~ *T*rot ~ 2,000 K, and almost in thermal equilibrium. While in a lower mass flow case with lower input power (e.g. 0.62 mg/sec, 1 W), *T*vib ~ 2,500 K, *T*rot ~ 1,200 K, and in higher thermal nonequilibrium.

3. Micro-Arcjet

3.1 Microfabrication of a micro-arcjet nozzle

In microfabrication of an arcjet-nozzle, an ultra-violet short-pulse laser with the pulse duration of ~ 5 nsec was utilized to minimize thermal influences of the laser pulse. As the ultra-violet laser beam oscillator, a fifth harmonic generation wave (Fifth-HG: ? = 213 nm) of a Qswitched Nd:YAG laser (NEW WAVE RESERCH, Tempest-10) was used. The specification of the laser system is given in Table 1. In this system, a combination of KTP (for SHG), BBO (for THG) and BBO (for Fifth-HG) nonlinear crystals was used for UV generation. The laser pulses were focused with a focusing lens (*f* = 40 mm) and irradiated onto a workpiece surface in air under an atmospheric pressure (Fig.5). A scanning electron microscope (SEM, JOEL JSM5410LV) and a laser microscope (KEYENCE, VK-8500) were used for detailed surface observations and measurements.

For micromachining of nozzles, an X-Y stage was utilized to scan focused laser beams, on which a workpiece was attached. Motion of the X-Y stage was controlled with a PC and a stage controller.

From our previous study, it was found that depth of a removed area on which laser pulses were irradiated could be controlled with number of pulse shots.[14]

Fig.6 shows a SEM image of a sapphire micro-nozzle. Fig.7 shows a laser-microscope image of the nozzle. Sizes of the nozzle are 240 ? m in width for the nozzle exit and 520 ? m in depth to its throat. In this case, average laser pulse fluence was 5.6 J/cm^2 for a beam spot of 40 ? m in diameter on a workpeace surface. A focusing point is 10 ? m below the surface. Feed speed of the X-Y stage was set 100 ? m/sec.

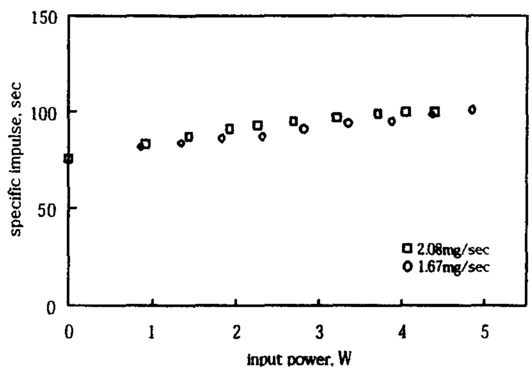


Fig.3 Input power vs specific impulse.

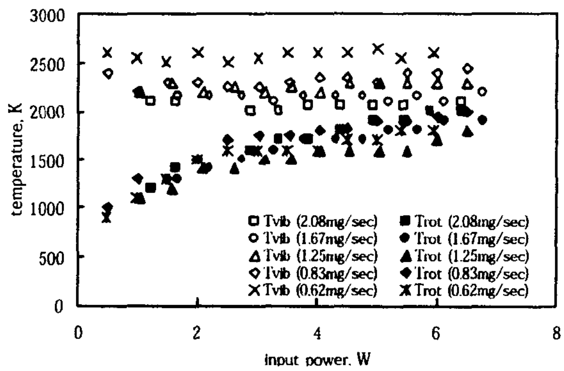


Fig.4 Input power vs heavy particle temperature.

Table 1 Specifications of NEW WAVE RESEARCH Nd:YAG Laser: Tempest-10.

	Wavelength [nm]	Maximum energy [mJ/pulse]	Pulse width [nsec]
Fundamental	1064	200	
Second-HG	532	100	
Third-HG	355	50	3 ~ 5
Fourth-HG	266	30	
Fifth-HG	213	7	

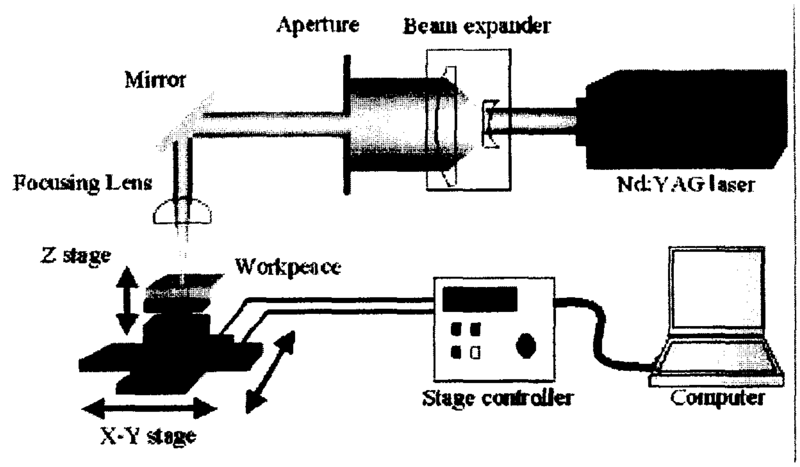


Fig.5 Schematics of laser microfabrication of an arcjet-nozzle.

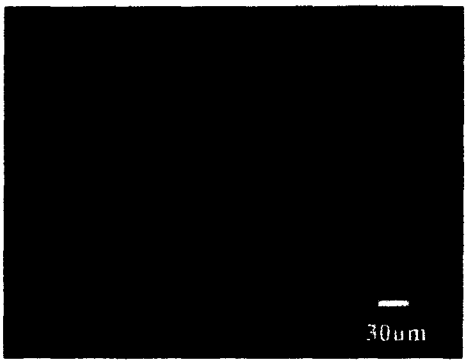


Fig.6 SEM image of a micro-nozzle.

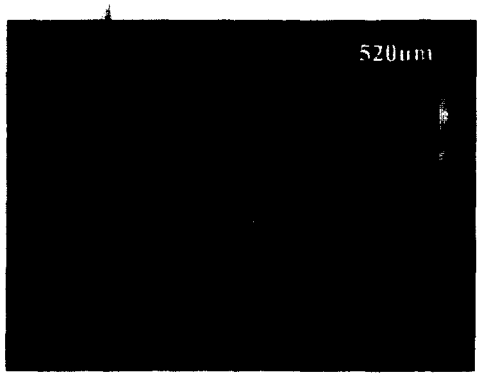


Fig.7 Laser-microscope image of a micro-nozzle.

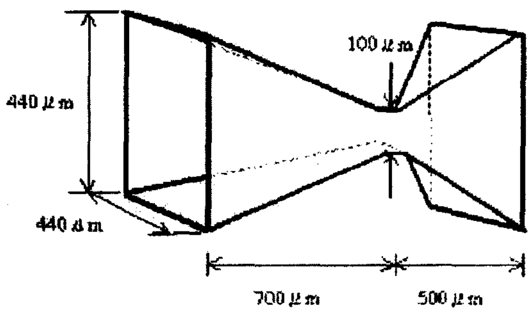


Fig.8 Schematic of a micro-arcjet nozzle.

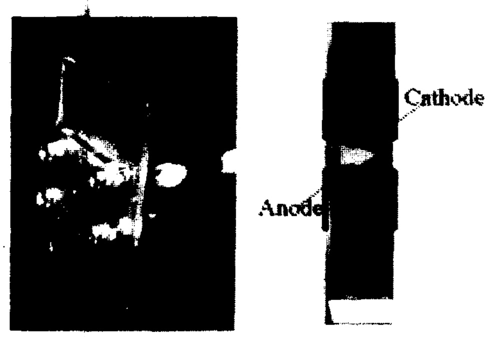


Fig.9 Photo and schematic of micro-arcjet (type1).

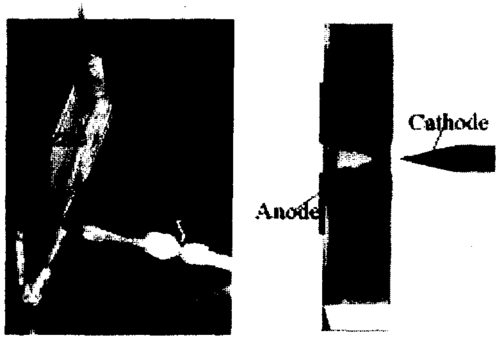


Fig.10 Photo and schematic of micro-arcjet. (type2).

3.2 Micro-Arcjet

Figure 8 shows a schematic illustration of a micro-arcjet nozzle machined in a 1.2 mm thick quartz plate. Sizes of the nozzle are 0.44 mm in widths of the nozzle exit and constrictor diameter of 0.1 mm. For an anode, a thin film of Au (~ 100 nm thick) was deposited by DC discharge PVD in vacuum on divergent part of the nozzle. As for a cathode, an Au film was also coated on inner wall surface for type 1 (Fig.9). In addition, a tungsten rod of 0.5 mm in diameter with 10-degree tip was also tested for type 2 (Fig.10). In all the tests, nitrogen gas was used as a propellant.

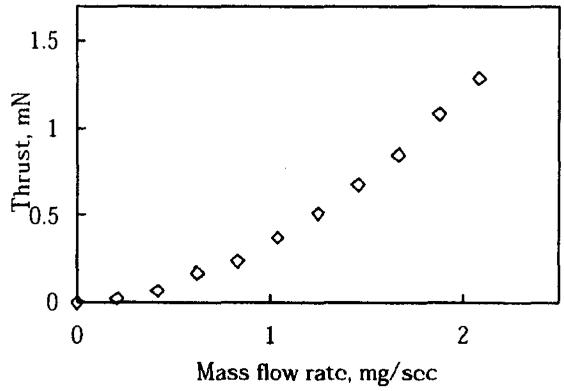


Fig.11 Cold-gas thrust (at 0 W) versus mass flow rate.

Fig.12 Photo of a micro-arcjet (type1) in operation.

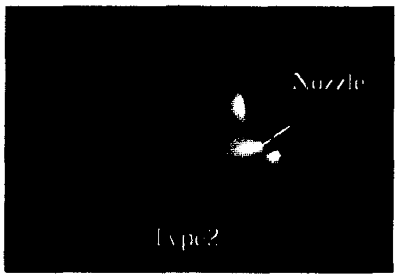


Fig.13 Photo of a micro-arcjet (type2) in operation.

Table 2 Thrust performance of a micro-arcjet.

Propellant : N_2 (@ 1.0 mg/sec)	Thrust [mN]	Specific impulse [sec]	Thrust efficiency
0 W	0.4	39.7	-
3.6 W	1.4	138.1	0.24

3.3 Results and discussion

Fig.11 shows plots of cold-gas thrust (with 0 W input power) versus mass flow rate for a type 1 micro-thruster. The cold-gas thrust varies from 0.02 to 1.3 mN, or specific impulse ~ 63 sec for propellant (N_2) mass flow rate of 0.2 to 2 mg/sec.

Photos of discharging plasma plumes exhausted from micro-arcjet nozzles taken by a color CCD camera (30 frames/sec, 30 msec/frame) are shown in Figs.12 (type1) and 13 (type2), respectively.

As shown in Fig.12 for type1, a stable discharge was observed for mass flow of 1.0 mg/sec, discharge current of 6 mA, discharge voltage of 600 V, or 3.6 W input power (specific power of 3.6 MW/kg). In this case, plenum pressure of the discharge chamber was 80 kPa. From results of Fig.4, it can be presumed that estimated maximum rotational temperature of the plenum is about 1,500 K in this case.

Thrust performances of this case operation are listed in Table 1. With 3.6 W input power, thrust could be increased up to 1.4 mN giving specific impulse of 138 sec. Thrust efficiency in this case is 24 %.

Although a similar tendency was observed in type2 operation, misalignment of a cathode tip to a nozzle axis was inevitable because of their very small sizes.

4. Conclusions

In this study, microfabrication of a micro-arcjet nozzle with Fifth-harmonic generation Nd:YAG pulses (wavelength 213 nm) and its thrust performance tests were conducted. A micro-arcjet nozzle was machined in a 1.2 mm thick quartz plate. Sizes of the nozzle were 0.44 mm in width of the nozzle exit and constrictor diameter of 0.1 mm. For an anode, a thin film of Au (~ 100 nm thick) was deposited by DC discharge PVD in vacuum on divergent part of the nozzle. As for a cathode, an Au film was also coated on inner wall surface. In operational tests, a stable discharge was observed for mass flow of 1.0 mg/sec, discharge current of 6 mA, discharge voltage of 600 V, or 3.6 W input power (specific power of 3.6 MW/kg). In this case, plenum pressure of the discharge chamber was 80 kPa. With 3.6 W input power, thrust obtained was 1.4 mN giving specific impulse of 138 sec with thrust efficiency of 24 %.

References

1) Myers, R.M., Oleson, S.R., Curren, F.M., and Schneider, S.J., "Small Satellite Propulsion Options," AIAA Paper 94-2997, June 1994.
2) Mueller, J., "Thruster Options for Microspacecraft: A Review and Evaluation of Existing Hardware and Emerging Technologies," AIAA Paper 97-3058, July 1997.

3) Micci, M. M., and Ketsdever, A.D. eds.: Micropropulsion for Small Spacecraft, Progress in Astronautics and Aeronautics Vol.187, American Institute of Aeronautics and Astronautics, 2000.
4) Curran, F.M., and Sarmiento, C.J., "Low Power Arcjet Performance Characterization", AIAA Paper 90-2578, July 1990.
5) Martinez-Sanchez, M., and Pollard, J.E., "Spacecraft Electric Propulsion-An Overview", Journal of Propulsion and Power, Vol.14, No.5, 1998, pp.688-699.
6) Sankovic, J.M., "Ultra-low-power Arcjet Thruster Performance", Proceeding of the 1993 JANNAF Propulsion Meeting, Vol.V, CPIA, Nov. 1993, pp.371-386.
7) Sankovic, J.M., and Jacobson, D.T., "Performance of a Miniaturized Arcjet", AIAA Paper 95-2822, July 1995.
8) Horisawa, H., and Kimura, I., "Influence of Constrictor Size on Thrust Performance of a Very Low Power Arcjet," AIAA Paper 98-3633, July 1998.
9) Horisawa, H., and Kimura, I., "Optimization of Arc Constrictor Sizes in Low Power Arcjet Thrusters," AIAA Paper 97-3202, July 1997.
10) Horisawa, H. and Kimura, I.: Studies of Very Low Power Arcjets, Chap.6 in Micropropulsion for Small Spacecraft (Micci, M.M., and Ketsdever, A.D. eds.), Progress in Astronautics and Aeronautics Vol.187, pp.185-197, American Institute of Aeronautics and Astronautics, 2000.
11) Horisawa, H., Ashiya, H. and Kimura, I.: Discharge Characteristics of a Very Low-Power Arcjet, IEPC 03-0078, 2003.
12) Arnold, J. O., Whiting, E. E., and Lyle, G. C., "Line by Line Calculation of Spectra from Diatomic Molecules and Atoms Assuming a Voigt Line Profile," Journal of Quant. Spectrosc. Radiat. Transfer., Vol. 9, 1969, pp.775-798.
13) Pearse, R. W. B., and Gaydon, A. G., The Identification of Molecular Spectra (4th Edition), Chapman and Hall, 1976, pp.217-219.
14) Emura, H., Horisawa, H. and Yasunaga N.: Microfabrication of Sapphire with Fifth Harmonic Generation YAG Laser Pulses, Advances in Applied Plasma Science, Vol.4, 2003, pp.349-354.