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Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes should not exceed 2500 words (where a figure or table counts as 200 words). Following informal review by the Editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Photonic Laser Propulsion: Proof-of-Concept Demonstration

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Introduction

THE propulsion concept of photonic propulsion (i.e., the direct transfer of the momentum of photons to a spacecraft that emits them) has been around since the beginning of the 20th century [1]. According to special relativity, the largest velocity of any kind of rocket exhaust particles is the velocity of light, $c = 2.99 \times 10^8$ m/s. Photons are the propellant with the largest specific impulse $I_{sp} = 3.06 \times 10^7$ s, but with the smallest thrust-to-power ratio $T/P = 3.34 \times 10^{-9}$ N/W. Photonic propulsion is highly inefficient in thrust generation at a given power. Thus, the applications proposed for its implementation require high-power photon beams and extremely large space platforms, with power generation from large solar collectors [2], nuclear power generators [3], or from antimatter power generators [4]. Implementation of these large complex systems is many decades away.

One approach to enhance practicality of photonic propulsion involves overcoming its inherent inefficiency through amplification of photon momentum transfer. This may be accomplished by bouncing or trapping photons between two high-reflectance (HR) mirrors that form an optical cavity between two space platforms. There have been two types of optical cavities considered for this purpose: 1) passive resonant optical cavities and 2) nonresonant optical cavities. In a passive resonant optical cavity, a laser beam is injected into the cavity. Because the passive resonant optical cavity requires a high-power single-frequency laser (which is itself inefficient) for efficient power injection into the cavity, and because the passive resonant optical cavity is highly sensitive to small changes in cavity length [5] and deterioration in mirror quality, it is impractical for photonic propulsion. The sensitivity to cavity length was exemplified in a gravitational detection system with a high Q passive optical cavity, in which even a 1-nm perturbation in cavity length thwarted the resonance condition and canceled the force exerted on mirrors [6].

The nonresonant optical cavity approach [7,8], as in Herriot cells, requires tightly focused laser beam spots on each mirror to avoid the beam interference that may result in optical resonance in the cavity. However, as the cavity length and the number of laser beam reflections increase, the laser beam focal spot diameter projected on mirrors increases, which requires extremely large mirrors to avoid beam interferences. Once the laser beam spots start to interfere, the nonresonant cavity becomes the passive resonant cavity that is impractical for photonic propulsion. An attempt to demonstrate an amplified photonic propulsion concept based on the nonresonant optical cavity was performed by Gray et al. [9]. They reported measurement of an amplified photon thrust of ~0.4 μN using a 300-W continuous-wave Nd:YAG laser and a photon thrust amplification factor of ~2.6. The much-lower-than-expected performance probably resulted from the previously mentioned technical difficulties. Therefore, the previously proposed photonic propulsion concepts seemed to be impractical, and the search for a new viable photonic propulsion concept continues.

Photonic laser propulsion (PLP) is a new and innovative photonic propulsion concept [10,11] that is based on forming an active resonant optical cavity between two space platforms. The laser gain medium is located in the optical cavity, in contrast to the passive resonant cavity concept, in which the laser gain medium is located outside of the optical cavity. In PLP, the photon thrust F_T produced on each mirror is given by

$$F_T = \frac{2PRS}{c} \tag{1}$$

where P is the extracavity laser output power through the output coupler (OC) mirror, R is the OC mirror reflectance ($R \sim 1$), and S is the apparent photon thrust amplification factor, defined as the ratio of the intracavity laser power to the extracavity laser power P. S is given approximately by

$$S = \frac{1}{1 - R} \tag{2}$$

One important near-term application of PLP is in flight control of a formation of spacecraft with the distance accuracy of nanometers, such as has been applied in photon tether formation flight (PTFF), with the maximum baseline distances greater than 10 km [10,11]. PTFF is stabilized by photonic laser thrusters (PLTs), subscale PLP engines, and tethers. PTFF is contamination-free with a high power-to-thrust conversion efficiency. It provides ample mass savings, which enables various types of extremely large-aperture spaceborne observation platforms. If other technical issues such as thermal limitation, optical absorption, and saturation of the laser gain media are neglected, one may estimate that a 10-W PLT with a 0.999998 reflectance OC mirror would produce $F_T \sim 33.5$ mN, which is sufficient for a wide range of formation flying missions [10,11].

Another interesting far-term PLP application [12] is in deep-space rapid-turnaround probing missions. When the mass of the mother platform (launching spacecraft) is much greater than the mass of the daughter platform (launched spacecraft), the launched spacecraft maximum velocity V_{max} with PLP, which is much smaller than c, is given by

$$V_{max} = \sqrt{\frac{2F_T L}{M}} \tag{3}$$

where L is the distance of the acceleration and M is the mass of the launched spacecraft. For example, if the scattering and absorption of the optical systems are negligible, with a 10-MW laser system, 0.999998 reflectance mirrors, $M = 1$ kg, $L = 1000$ km, and $V_{max} \sim 180$ km/s. At this velocity, the PLP spacecraft would transit the 100 million kilometers to Mars in less than a week.

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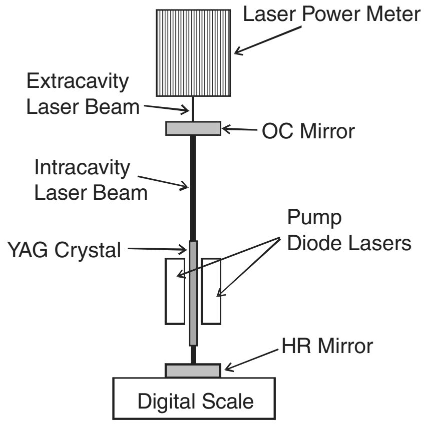

Fig. 1 Schematic diagram of prototype PLT demonstration setup.

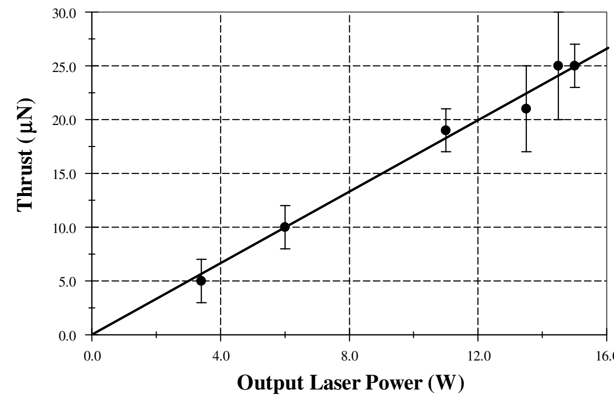

Fig. 2 Photon thrust data obtained with an output coupler mirror with a reflectance of 0.996.

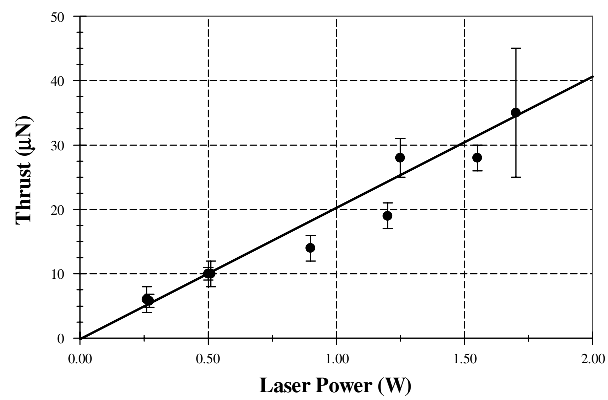

Fig. 3 Photon thrust data obtained with an output coupler mirror with a reflectance of 0.99967.

PLT Demonstration Results

Results of the first demonstration of a subscale PLP engine, PLT, are reported in this Note. Significant thrust was produced by a small laboratory-scale PLT and measured in a laboratory environment. Originally, it was assumed that the operational principle of PLT would be similar to that of the passive resonant optical cavity, which is highly sensitive to the change in the cavity length. Thus, PLT was assumed to be useful only for static applications, such as PTFF. However, during the test prototype operation, it was discovered that PLT is highly stable against perturbations in optical cavity parameters. This discovery enables the expansion of PLT applications to wide ranges of dynamic propulsion applications, including PLP, as mentioned previously.

The schematic diagram of the PLT demonstration setup is illustrated in Fig. 1. The present prototype PLT consisted of a concave HR mirror, a diode-pumped solid-state (DPSS) laser gain medium, and a flat OC mirror. The laser amplification was achieved in a Nd:YAG crystal with a 3-mm diameter, a 6-cm length, and a 0.6-% dopant density. The Nd:YAG crystal was optically pumped by laser diodes with a wavelength of 808 nm in a side-pumping configuration. The photon thrust was determined by measuring the difference between the weights of the HR mirror with the laser on and off with the use of a digital laboratory scale. The scale had a maximum weighing capacity of 80 g and an accuracy of 0.1 mg, which is equivalent to 0.98 μN, according to the manufacturer's calibration. The weight of the HR mirrors was approximately 10 g. The laser power through the OC mirror, which is the extracavity laser output power P, was measured with the use of a laser power meter with an accuracy of $\pm 2.5\%$. The concave HR mirrors had $R > 0.997$ according to the manufacturer's specification. The HR mirrors with radii of curvature of 50 and 100 cm were used. The photon thrust was measured as a function of the PLT cavity length, which was varied between 12.6 and 30 cm. At a fixed input power for the pump laser diodes, the measured photon thrust was nearly insensitive to the changes in the radius of curvature of HR mirrors and the PLT cavity length.

Fig. 2 shows the experimental results of photon thrust measured as a function of the extracavity laser power P with $R = 0.990 \pm 0.005$ according to the manufacturer's specification. The standard deviation of multiple measurements was ~ 2 μN, which is slightly larger than the repeatability of the scale specified by the manufacturer, ~ 1.5 μN, indicating that the error in the thrust measurement is dominated by the repeatability of the digital scale. The data with larger error bars at the power level near 14 W were obtained under the condition in which the HR mirror and the scale pan had been heated by the absorption of the laser energy into a contaminant on the mirror. This resulted in thermal drift in the scale and error accumulation in the measurement. After correction, the standard deviation decreased, as shown in the data point at 15 W. The best fit to the Fig. 2 data produced a thrust-to-power ratio $T/P = 1.67 \pm 0.05$ μN/W; the photon thrust enhancement factor is $S = 249 \pm 8$. From Eq. (2), the true OC mirror reflectance was estimated to be 0.9960 ± 0.0002.

The extracavity laser power P depends on the reflectance of the OC mirror, R. In the setup of this demonstration, P was maximized with $R \sim 0.8$. The value of P obtained with $R \sim 0.996$ was about a factor of 2 smaller than that obtained with $R \sim 0.8$. This decrease results from the fact that transmission of the OC mirror becomes smaller than the absorption and scattering in the Nd:YAG crystals and surfaces of the crystal and mirrors. If there was no effect from the absorption and scattering, the maximum thrust obtainable in the current PLT with $R \sim 0.996$ is estimated to be ~ 50 μN.

Figure 3 shows the experimental results of the photon thrust measured as a function of the extracavity power P with $R > 0.997$ according to the manufacturer's specification. The best fit of Fig. 3 data resulted in a thrust-to-power ratio $T/P = 20 \pm 1$ μN/W, an apparent photon thrust amplification factor $S = 2990 \pm 150$, and a true OC mirror reflectance $R = 0.99967 \pm 0.00002$.

Conclusions

In this demonstration setup, P was maximized with $R \sim 0.8$, and P obtained with $R \sim 0.99967$ was about a factor of 10 smaller than that with $R \sim 0.8$. Therefore, if there was no effect of the absorption and scattering, the maximum obtainable thrust in the current PLT with $R \sim 0.99967$ is estimated to be ~ 350 μN. The maximum photon thrust, 35 μN, observed in the present PLT was obtained at a pump diode laser power a factor of 2 smaller than that of the maximum pump diode laser power limited by the crystal heating. If there was no heating effect, it was estimated that the current PLT with $R \sim 0.99967$ is estimated to generate ~ 70 μN, and additionally, if there was no effect from the absorption and scattering, its maximum obtainable thrust is estimated to be ~ 700 μN.

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References

[1] Tsander, K., "From a Scientific Heritage," NASA Technical Translation TTF-541, 1967.

[2] Forward, R. L., "Solar Photon Thruster," *Journal of Spacecraft and Rockets*, Vol. 27, No. 4, 1990, pp. 411–416.

[3] Gulevich, A. V., Ivanov, E. A., Kukharchuk, O. F., Poupko V. Y., and Zrodnikov, A. V., "Application of Nuclear Photon Engines for Deep-Space Exploration," *Space Technology and Applications International Forum*, AIP Conference Proceedings, Vol. 552, American Inst. of Physics, Melville, NY, 2001, pp. 957–962.

[4] Wickman, J. H., "Technology Assessment of Photon Propulsion: How Close Are We?," AIAA/SAE/ASME Conference, AIAA Paper 81-1532, 1981.

[5] Fowles, G. R., *Introduction to Modern Optics*, Holt, Rinvehart and Winston, New York, 1975, Chap. 4.

[6] Sheard, B. S., Gray, M. B., Mow-Lowry, C. M, McClelland, D. E., and Whitcomb, S. E., "Observation and Characterization of an Optical Spring," *Physical Review A*, Vol. 69, No. 5, 2004, Paper 051801(R). doi:10.1103/PhysRevA.69.051801

[7] Meyer, T. R., Pryor, W. R., McKay, C. P., and McKenna, P. M., "Laser Elevator: Momentum Transfer Using an Optical Resonator," *Journal of Spacecraft and Rockets*, Vol. 39, No. 2, 2002, pp. 258–266.

[8] Metzger, R. A., and Landis, G., "Multi-Bounce Laser-Based Sails," *Space Technology and Applications International Forum*, AIP Conference Proceedings, Vol. 552, American Inst. of Physics, Melville, NY, 11–15 Feb. 2001, pp. 397–401.

[9] Gray, P. A., Carruth, M. R., Jr., and Edwards, D. L., "Photon Flux Amplification for Enhancing Photonic Laser Propulsive Forces," 33rd Plasmadynamics and Lasers Conference, Maui, HI, AIAA Paper 2002-2177, 20–23 May 2002.

[10] Bae, Y. K., "A Contamination-Free Ultrahigh Precision Formation Flying Method for Micro-, Nano, and Pico-Satellites with Nanometer Accuracy," *Space Technology and Applications International Forum*, edited by M. S. El-Genk, AIP Conference Proceedings, Vol. 813, American Inst. of Physics, Melville, NY, 2006, pp. 1213–1223.

[11] Bae, Y. K., "Photon Tether Formation Flight (PTFF)," NASA Inst. for Advanced Concepts, Phase I Final Report, Apr. 2006, http://niac.usra.edu/files/studies/final_report/1047Bae.pdf [retrieved 10 Mar. 2007].

[12] Bae, Y. K., "Photonic Laser Propulsion (PLP): Photon Propulsion Using an Active Resonant Optical Cavity," AIAA Space 2007 Conference, AIAA Paper 2007-6131, 2007.

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