Laser propulsion with a high specific impulse using a thin film propellant*

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A new laser propulsion scheme with a high specific impulse is proposed in this paper. An extremely thin polyimide film is used as the propellant to eliminate thermal diffusion and sputter from the target material. It is found that a high specific impulse of 1520 s can be achieved at 10^{11}-W/cm^2 laser intensity because of economic use of the propellant. The influences of the laser intensity and the ablation area on the specific impulse are also studied in the experiment.

Keywords: laser plasma, propulsion, polyimide

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1. Introduction

Driving spacecraft using laser ablation was first proposed by Kantrowitz in 1972 as an alternative to chemical combustion rockets.[1−3] This has attracted attention all over the world because of its high payload efficiency and potential low cost. Since the first proposal for laser propulsion,[1] many experiments on the momentum coupling between the laser and the target have been performed with various materials and laser systems.[4−13] When a solid target is irradiated by a high intensity laser pulse, a high speed plasma plume is produced. Pakhomov *et al.*[9,10] measured the velocity of the plasma plume produced by a 10^{13}-W/cm^2 intensity laser pulse irradiating a solid target by using the time of flight (TOF) method. More than 10^5-m/s blow-off velocity was detected. This corresponds to a specific impulse $> 10^4$ s, which is important for determining the propulsion efficiency of air- and spacecraft.[14] However, not all the material ablated from the solid target escapes with such a high velocity. Most of the target material is just sputtered or vaporized due to the mechanical shock and the thermal conduction.[8] Thus the real specific impulse measured by force measurements is much less than that measured by the TOF method.[9]

In order to avoid the problem of sputter and thermal conduction, and enhance the specific impulse to approach the theoretical limit, we consider in this paper an indirect laser-driven propulsion method based on the ablation of thin films. The thickness of the film is comparable to the ablation depth of the laser pulse, so that all of the propellant can be heated efficiently. Laser pulses irradiating on the film will produce two plasma plumes, in opposite directions. The momentum carried by the plasma plume in the forward direction to the vehicle can be transferred to the latter by simple collisions. In the experiment, the momentum of the plasma plume can be measured by a simple pendulum.

2. Experimental setup

Our experimental setup is located in a vacuum chamber at 5 Pa. The target is a piece of thin polyimide (PI, $C_{33}H_{24}N_2O_5$) film with 3-μm thickness, which is attached directly to an aluminum substrate, as shown in Fig. 1. A hole in the substrate allows the

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plasma plume to pass forward. A 7-ns, 850-mJ laser pulse at 532-nm wavelength from an Nd:YAG laser is focused on the PI film by a convex lens of 125-mm focal length. The diameter of the focal spot on the PI film is the same as that of the hole, so that the film is efficiently ablated. A single pendulum, which is made of an Al frame covered with a piece of optical glass, is hung behind the aluminum substrate to measure the thrust generated by the laser ablated plasma. The glass serves as the surface of the pendulum to avoid the effect of penetrated laser ablating on the pendulum, as shown in Fig. 1(c).

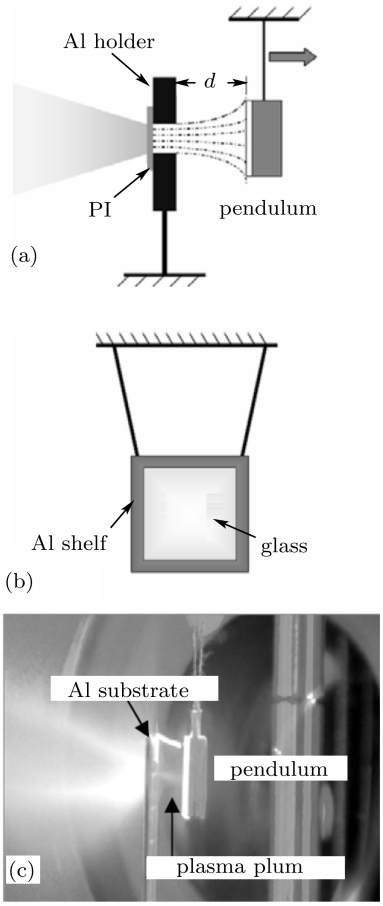


Fig. 1. (a) Schematic diagram of experimental setup, (b) the pendulum, (c) photo of the experimental setup.

The motion of the pendulum is recorded by a video camera. From the maximum height of the pendulum swinging, the momentum M of the latter can be deduced. The effectively ablative mass is

$$m_{\rm a} = \pi D^2 \rho_{\rm s}, \tag{1}$$

where D is the diameter of the hole and $\rho_{\rm s}$ is the surface density of the PI film. Then the specific impulse is

$$I_{\rm sp} = \frac{M}{g \times m_{\rm a}}. \tag{2}$$

3. Experimental results and discussion

In order to avoid damage to the pendulum by the laser light penetrating the PI film, the distance d (see Fig. 1(a)) between the aluminum substrate and pendulum is greater than 11 mm. Test shots without the PI film were performed before every thrust measurement and it was verified that the pendulum does not move at all. This ensures that the thrust measured in our experiment is totally due to the ablated plasma. The exact laser energy used to drive the film propellant in front of the hole is measured by an energy meter placed behind the substrate in the absence of the film propellant. The corresponding laser energy and intensity of the focal spot for different ablation areas are listed in Table 1.

Table 1. The energy and intensities of the focal spot with different ablated areas.

Diameter of the hole /mm	0.3	0.5	0.7	1.0
Energy /mJ	567.9	678.9	689.4	718.5
Laser intensity /10^{10} W$\cdot$cm^{-2}	11.5	4.94	2.56	1.31

The specific impulse as a function of the ablated area is shown in Fig. 2. The maximum specific impulse of 1520 s is achieved with the minimum ablated area (0.3 mm diameter). This specific impulse is much higher than the general case of ablating a solid target.[15] We find that the specific impulse decreases with increasing ablated area. This can be explained as follows. First, the large ablation area (large-diameter hole) corresponds to the low aspect ratio, so that the plasma plume from the large ablated area cannot be collimated by the hole and has a larger divergence angle. Hence not all of the plasma can reach the surface of the pendulum. This will cause the specific impulse to decrease. Second, the laser energy used for the phase transformation and the ionization of propellant is proportional to the ablated area, but this part of the energy does not contribute to the plasmas' moment. Thus, the specific impulse is much smaller for large ablation areas.

The dependence of the momentum coupling coefficient on the ablated area is shown in Fig. 3. We see

that the coupling coefficient increases with the ablated area. This is in good agreement with the law of conservation of momentum, since the coupling coefficient is inversely proportional to the specific impulse.

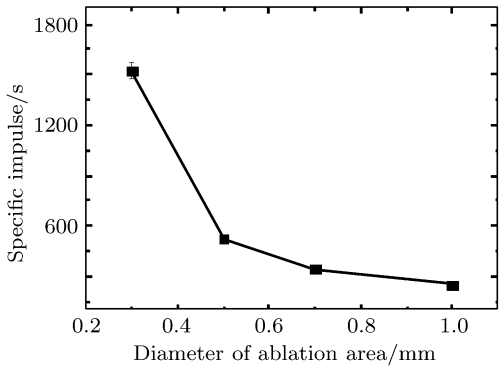


Fig. 2. Effect of the diameter of the ablation area on the specific impulse.

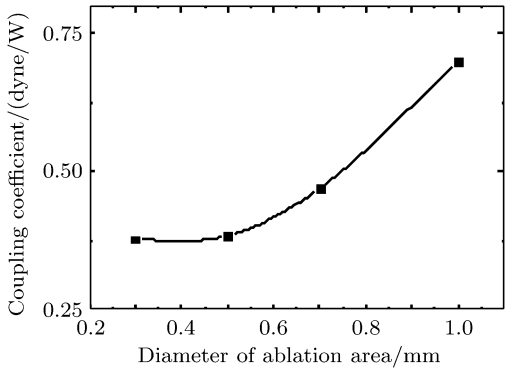


Fig. 3. The dependence of the coupling coefficient on the diameter of the hole.

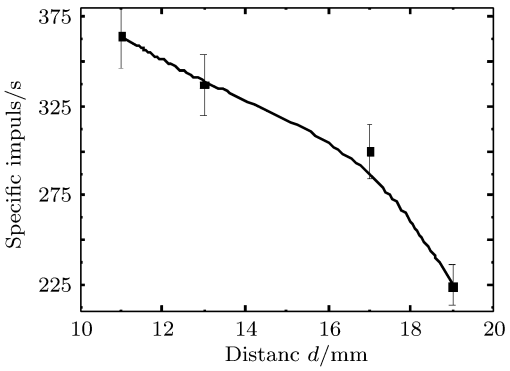


Fig. 4. The influence of the distance d on the specific impulse.

The influence of the distance d on the specific impulse is shown in Fig. 4. The diameter of the hole is fixed at 0.7 mm. The decrease in specific impulse is due to the fact that the portion of plasma jet reaching the surface of the pendulum decreases as the distance increases, i.e., better results in the experiment will be obtained if all of the plasmas plumes are collected by the pendulum.

Figure 5 presents the specific impulse and coupling coefficient as functions of the laser intensity. The laser intensity is changed by reducing the laser energy from 720 mJ to 240 mJ. The diameter of the hole is fixed at 0.7 mm. We see that the increasing trend of the specific impulse and the inverse relation between the specific impulse and the coupling coefficient reproduce our results in Figs 2 and 3. Thus, the laser intensity is an important parameter in this mode of laser propulsion. By simple calculation, it can be deduced that when the laser intensity exceeds 10^{12} W/cm^2 (laser pulse with maximum energy focus on 0.1 mm ablated area), the specific impulse of about 7200 s is obtained. However, for such small ablation areas, more precise target design is needed to obtain 'clean' results. The further increase in $I_{\rm sp}$ will be tested in the future.

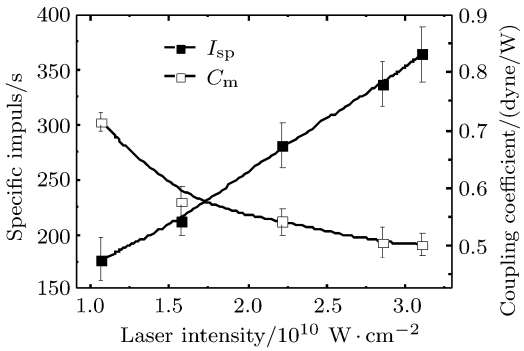


Fig. 5. The specific impulse and coupling coefficient for different laser intensities.

4. Conclusions

We have experimentally investigated laser-plasma propulsion based on the ablation of thin film targets. The momentum of the plasma plume was collected and measured by a pendulum. The extremely thin target can significantly reduce the thermal and mechanical damage to the target, and, in turn, the mass loss of the target. As a result, the specific impulse is greatly enhanced due to the economic use of the ablation mass. The effects of the ablated area and the laser intensity on the specific impulse are studied.

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