Research article

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Perfect metamaterial absorber improved laser-driven flyer

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Abstract: Laser driven flyer (LDF) can drive small particles to ultrahigh speed (several km/s) by feeding pulse laser light, and exhibits giant application prospect in both of the civilian and military regions, such as the ignition of missile and spacecraft and dynamic high-pressure loading. In this work, we demonstrate a high-performance LDF by using the perfect metamaterial absorber (PMA) to improve the energy utilization efficiency of light. The designed Ag nanopillar array in anodic aluminum oxide templates (APA-AAO) were skillfully fabricated *in-situ* on the flyer layer surface, which can greatly reduce the reflectivity from 93% of the pure Al foil flyers to about 5% of the APA-AAO enhanced flyers. Our systematically transient analysis reveals that this ultralow reflectivity, together with the well-formed metal structure on Al foil, greatly improve both of the electron temperature and sustaining time of plasma formed in the ablating layer, and further enhances the acceleration process at both of the initial detonation wave generation stage (0–10 ns) and the following thermal expansion stage (10–200 ns). The final speed of the flyer generated in the PMA-enhanced LDF approach to 1730 m/s, which is about 1.4 times larger than that (1250 m/s) of the pure Al foil flyers. The transient electron temperature, transient flyer shadowgraph, plasma sustaining time, velocity, and accelerated velocity have been investigated systematically in this work. This PMA enhanced LDF provides an effective method for obtaining high-speed microparticles, and opens up a new perspective and guidance for designing high-performance LDF.

1 Introduction

Laser-driven flyer (LDF) has attracted an intense research interest in the fields of ignition, detonation [1–3], dynamic high-pressure physics [4], and space scrap metal science [5]. The LDF device can support high-velocity flyer and tremendous impact pressure with a low-cost and simple installation compared with the traditionally driven mode, and owns giant application prospect in both of the civilian and military applications [6]. Especially in the ignition and detonation fields, LDF owns unique advantages of security, reliability and synchronism for the modern weapon system, such as missile, spacecraft, and ordnance, when comparing the traditional electron-based ignition and initiation method [7]. While the current miniaturization trend raises rigorous requirements, and a LDF of high-efficiency, small volume, and high-speed is urgently desired.

A typical LDF is generally composed by a dielectric window, an ablating layer, a flyer layer, and an accelerated chamber, where the ablating layer can absorb the incident laser pulse and generate extremely-high temperature and pressure plasma to drive the flyer [8]. The electron temperature and density of plasma formed in the ablating layer are two key parameters to evaluate the flyer performance in the initial driving process of the flyer [9]. To obtain a high velocity, all of the LDF parts, including the structure size and the applied materials, should be properly designed to form plasma of high temperature and density [10]. However, the currently-employed schemes cannot settle the issue of large light reflectivity from the ablating layer, which greatly restricts the LDF performance and the integration of LDF system due to the requirement of high power laser [11]. Although various materials, such as carbon, Ge, Ti, Zn and even the commercial-grade black lacquer paint, have been investigated as antireflection materials in the ablating layers, the enhanced absorptivity is still limited, and the velocity enhanced factor is usually located in the

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range of from 10 to 30%. In fact, importing these materials in the ablating layer will also bring some other issues, such as additional energy consumption, low electron temperature, and pressure plasma, due to the large heat capacity of these materials [12–15]. Applying energetic materials in the ablating layer, such as the mixture of Al and other metal oxides, is another effective scheme to greatly improve the flyer velocity, where the ablating layer, however, still owns a very high-reflectivity [15, 16].

In this work, we introduce perfect metamaterial absorber (PMA) to address the low-absorptivity of ablating layer and improve the performance of LDF. PMA is a kind of artificial structure devices, and can reach 100% absorptivity in the designed waveband through properly engineering the electric and magnetic resonators [17–21], which has inspired a great amount of novel applications, such as plasmonic sensor, seawater desalination, and infrared radiation detector [22–25]. When compared with the previously-reported antireflection schemes, the PMA-improved scheme only requires sculpturing a proper pattern on the top of ablating layer, which effectively avoids the introduction of the unmatched materials and also the related disadvantages into the LDF device. In this work, the Ag nanopillar array embedded in AAO template (APA-AAO) is carefully designed and *in-situ* fabricated on the ablating layer by the electrochemical deposition method. Both of the simulation and experiment results demonstrate that the APA-AAO LDF device owns an ultralow reflectivity of about 5% in the waveband from 200 to 1500 nm. This ultralow reflectivity, together with the matching materials, greatly improve the temperature and density of plasma generated in the ablating layer and the maximum velocity of flyers of about 40%, which is larger than that from all of the previously-reported enhancing schemes. This PMA-enhanced LDF opens up a new perspective and guidance for designing high performance LDF. The electromagnetic properties of APA-AAO, the generated plasma properties, the detail accelerated process and instantaneous morphology of the flyer have been systematically investigated.

2 Experiment section

2.1 Fabrication of the APA-AAO enhanced flyer

A 40 μm -thick Al foil was firstly used to prepare the APA-AAO enhanced flyer. The Al foil was washed with acetone and then pretreated using electro-polishing in an acidic solution (20 vol% HClO_4 mixed with 80 vol% $\text{CH}_3\text{CH}_2\text{OH}$) for 4 min under 8 V. AAO templates were

prepared on one side of the Al foil by using a two-step anodization approach in 0.3 mol/L $\text{H}_2\text{C}_2\text{O}_4$ solutions: First, the polished Al foil was anodized in 0.3 mol/L $\text{H}_2\text{C}_2\text{O}_4$ solutions for 1 h at 40 V. Then the Al foil was cleaned by a mixture solution of phosphoric and chromic acids to remove the formed alumina; Secondly, the Al foil was anodized again in a 0.3 mol/L $\text{H}_2\text{C}_2\text{O}_4$ solution to obtain the AAO template by controlling the anodization voltage and time. The voltage for AAO templates of sample A, B and C is 40, 50 and 70 V, respectively. Ag nanowires were finally deposited into AAO templates in the mixed solution of 0.05 mol/L AgNO_3 and 0.2 mol/L H_3BO_3 with an alternating current of 13 V and 50 Hz for 5 min. The well-prepared APA-AAO enhanced flyers were washed with deionized water for several times, and dried with N_2 gas.

2.2 Spectrum and morphology characterization of the APA-AAO enhanced ablating layer

The macroscopic appearance of the APA-AAO enhanced ablating layer was recorded by an Olympus 3000 Microscope with five-time object working on bright field mode. The reflection spectra were measured by the UV-VIS-NIR spectrophotometer (SolidSpec-3700, Shimadzu, Japan) with a step of 1 nm in the waveband of from 200 to 1500 nm. The microscopic surface and sectional morphologies of the fabricated APA-AAO were analyzed by the Zeiss-Ultra-55 scanning electron microscope. To obtain a well-formed sectional morphology, the APA-AAO was firstly immersed in liquid nitrogen for 2 min, and then taken out and broken through the sample center.

2.3 Transient velocity and shadow characterization of the flying flyer

The transient velocity of the flyer flying in the accelerated chamber and the transient shadow photograph of the flyer flying out of the accelerated chamber were measured by the photonic Doppler velocimetry (PDV) and the time-resolved shadow photograph system, respectively. To measure the transient velocity with PDV system, a single laser pulse from the Q-switched Nd:YAG laser (1064 nm wavelength, 8 ns pulse) transmitted through the glass window and was focused on the ablating layer surface. A detection light from a continuous laser was illuminated on the flying flyer in the accelerated chamber through an optical fiber, and the signal light was collected by the same optical fiber, which was connected to a detector and oscilloscope with

the help of a circulator. And the transient velocity can be extracted by analyzing the Doppler information of the signal light; When the flyer was flying out of the accelerated chamber, a femtosecond laser with wavelength of 800 nm was used to illuminate the flying flyer from one side, and a CCD camera was placed on the opposite side to record the shadow of the flyer. To avoid the influence of background light, a bandpass filter was placed before the CCD camera. In all of these transient measurements, a delay generator (Stanford DG 645) was used to sequentially trigger the related laser and detection parts, such as the pulse laser, oscilloscope, and CCD camera.

2.4 Laser-induced breakdown spectrum characterization of plasma generated in the ablating layer

The plasma in the ablating layer was generated by a Q-switched Nd:YAG laser, which was working at the wavelength of 1064 nm with pulse time of 8 ns, and the same with that used in the transient velocity measurement process. The radiated light from the generated plasma was measured with a spectrometer of from 200 to 800 nm and intensified charge-coupled device (ICCD), where the measured spectra was the so-called laser-induced breakdown spectra (LIBS). The pulse laser and the ICCD were triggered by a delay generator (Stanford DG 645). The laser-induced breakdown spectra collection software and the related library software were supported by Sophi Ltd. (Germany). The transient temperature of the plasma can be

tracted through analyzing the LIBS, and will be discussed in detail in the main text.

2.5 Optical absorption simulation of the APA-AAO layer

The simulations were carried out with the finite-difference time-domain (FDTD) method. A plane wave with the wavelength from 300 to 1500 nm was used as source to illuminate the APA-AAO structure. The perfectly matched layer was used as boundary conditions in the illumination direction, and the periodic boundary conditions were used in the lateral direction. The reflection spectra were recorded by a monitor placed in the reflection space. The structure parameters, including the Ag nanopillar diameter D , the height h , and the lattice period P , were extracted from the SEM images of APA-AAO, and the thickness of the aluminum substrate was assumed to be infinite in simulation. The optical constants of silver and aluminum are taken from the previously measured values [26], and the refractive index of Al_2O_3 is set as 1.6.

3 Results and discussions

3.1 Design of APA-AAO enhanced LDF device

The schematic diagram of the designed APA-AAO enhanced LDF device is shown in Figure 1(a), which is combined by a dielectric window, an APA-AAO-modified ablating layer, a dielectric adiabatic layer, a flyer layer and

Figure 1: (a) The architecture of the APA-AAO enhanced LDF, include a dielectric window (light green), the ablating layer (black and green), the flyer layer (yellow), and an accelerated chamber (blue). The ablating and flyer layers are fabricated by the method shown in (b), and then the dielectric window and the accelerated chamber are placed closely on the top and bottom sides respectively to form an integrated flyer; (b) The pretreatment and fabrication procedures of the APA-AAO absorber, include the pretreatment of Al foil, fabrication of AAO templates by a two-step anodization approach, and the electrochemical deposition of Ag in AAO templates.

an accelerated chamber. In general, plasma of high pressure and temperature can be generated immediately when a beam of pulse laser passes through the dielectric window and illuminates on the ablating layer. This hot plasma will strike the metal flyer layer to form flyers, and drive the formed flyers to fly with high speed in the accelerated chamber. In this process, the dielectric window forbids the high-pressure plasma diffusing to the laser beam side, and the accelerated chamber provides a shear force for the formation of the flyer and an effective accelerated space at the same time. In addition, the adiabatic layer placed between the ablating layer and the flyer layer can well prevent the heat transporting to the flyer layer and improve the integrity of the formed metal flyers. In order to obtain a high performance LDF, all of these functional layers should be well considered, including the thermal capacity, tenacity, structure parameters, and so on.

When PMA is introduced in the ablating layer to improve the absorbance of LDF, the following requirements also should be met to improve the performance of LDF: (1) PMA should work at the working wavelength of the excited pulse laser, which is about 1064 nm in this work and also for the common commercial pulse laser. This generally indicates that the PMA should own the characteristic size of smaller than 1064 nm, and is still a challenge for the current micro/nano fabrication techniques; (2) the fabricated PMA sample size should be larger than 1 mm² to match the inner size of the accelerated chamber; (3) the PMA should own low fabrication cost; and (4) the absorbed energy should be dissipated uniform in the ablating layer to generate enough plasma to drive the flyer. Certainly, the PMA also should not contain organic materials. The organic materials will generate lots of different components, such as H₂O, C, and CO₂, upon the injection of pulse laser, result in the formation of very complex plasma at different time-delayed stages, and decrease the final speed of flyers. Considering these factors mentioned above, most of the reported PMA are not suitable for applications in LDF. In particular, the top metal layer of the metal–insulator–metal type PMA absorbs most of the incident light [27, 28], but the layer thickness is too thin (mostly smaller than 100 nm) to support enough plasma to drive flyer. And the one-dimensional and three-dimensional photonic crystal based PMA are also not suitable for application in LDF due to the similar reasons.

In this work, the APA-AAO is applied to improve the performance of LDF. The APA-AAO is very similar to the two-dimensional photonic crystal except for the random arrangement, which shows large absorbance of about 95% at 1064 nm, uniform energy dissipation in APA, and enough metal materials for the generation of high temperature and pressure plasma. In addition, the APA-AAO of

large area can be easily achieved by the low-cost *in-situ* electrochemistry method. As shown in Figure 1, the APA-AAO is used directly as the ablating layer, and the Al₂O₃ layer formed under the APA-AAO layer in the electrochemistry process is used as the adiabatic layer to protect the flyer. The sapphire and Al are chosen as the materials of the dielectric window and the flyer layer due to their good optical transparency and malleability, respectively. The thickness of the window and the flyer layer are 4 mm and 30 μm, respectively. The accelerated chamber with a 1 mm diameter and 0.6 mm length hole inside is fabricated by stainless steel. The detail device performance and discussions can be seen in the following parts.

3.2 Preparation and characterization of APA-AAO nanostructures

Figure 1(b) shows the main fabrication process of the APA-AAO samples. In briefly, the AAO templates used in this work were synthesized by a two-step anodization method [29], and the deposition of Ag pillar array is performed by alternating current deposition [30]. The detail fabrication process can found in the Experimental Section. After that, the APA-AAO nanostructures are well formed in the ablating layer. In fact, the ablating layer, the adiabatic layer and the flyer layer are well formed at the same time due to the ingenious design of the fabrication technique. Figure 2(a–c) show the cross-section SEM images of the obtained AAO templates, where the thickness, i.e. the ablating layer, is about 4 μm, and the average hole diameters are about 50, 70, and 100 nm for Sample A, B, and C, respectively. The fill factor of Ag in the AAO temple for samples A and B are more than 90%, but it is less than 40% for sample C. Intuitively, a high fill factor is desired for that it can enlarge the pressure of the plasma formed in the ablating layer and improve the flyer velocity.

The APA-AAO enhanced LDF show an extremely-low reflectivity. As shown in Figure 2(d–f), the fabricated Sample A and B are totally black, while Sample C shows a light grey color, indicating that the Sample A and B should own a larger absorbance than that of the Sample C. The accurate absorbance spectra are shown in Figure 2(g). All of the APA-AAO enhanced samples own a large absorbance (>~80%) in a broad waveband of from 200 to 1500 nm, which is far larger than that from Al foil samples (as shown by the black curve in Figure 2(g)). Especially, at the wavelength of 1064 nm, the Sample A, B and C own an absorbance of about 79, 95 and 92% respectively, while the Al foil just owns an absorbance of only 10%, indicating that the APA-AAO nanostructures formed in LDF can greatly

Figure 2: (a–c) The cross-section SEM images of APA-AAO samples A, B, and C, respectively, where the hole diameters are 50, 70, and 100 nm respectively; (d–f) The microscopic appearance images of APA-AAO Sample A, B, and C; (g) The measured reflection spectra of the Al foil (black), the APA-AAO Sample A (red), B (green), and C (purple).

enhance the absorbance of the ablating layer. Although the measurement for the absorption spectra is under linear conditions (i.e. low-power light illumination), we believe that the consideration of reflection here is still reasonable in LDF, where a pulse laser with high-power is used. We also note that a fluctuation phenomenon is observed in the reflection spectra of Sample A and B, which should be attributed to the standing wave effect that formed in Ag nanopillar array and will be discussed in the next section.

3.3 Electromagnetic properties of APA-AAO nanostructures

To have an unambiguous understanding of the electromagnetic properties of APA-AAO nanostructures in LDF, we perform a systematic numerical investigation on the reflection spectra, the electric and energy consumption distributions. As shown in Figure 3(a), a fluctuation phenomenon in reflectance is confirmed in the waveband from about 500 to 1500 nm, and this meets well with the experiment results shown in Figure 2(g). This fluctuation phenomenon is caused by the standing wave modes that formed in APA-AAO nanostructures as shown in Figure 3(b), and can be explained by the effective medium theory as indicated by our previous work [31]. When we change the structure parameters of APA-AAO, the fluctuation phenomenon in

reflectance shows an obvious change. Especially for Sample C, the coexistence of standing wave modes in both of the air/ Al_2O_3 medium and the Ag/ Al_2O_3 medium leads to a complex fluctuation phenomenon in the reflection spectrum as shown in Figure 2(g). However, we observe an obvious difference between the simulated and measured spectra, and this should be attributed to the irregular APA-AAO nanostructures that cannot be duplicated in simulations.

The standing wave modes that formed in APA-AAO nanostructures can greatly change the electric field distribution and further affect the energy consumption distribution and the performance of LDF. As shown in Figure 3(c), (f) and (i), a similar standing wave mode is observed in the energy consumption distribution images. Obviously, the plasma will be created firstly from these high energy consumption regions. Thus, the standing wave modes in APA-AAO nanostructures, which can form complex space beat-frequency modes, are a key influence factor for the generation of plasma in LDF. As indicated by Figure 3(c), (f) and (i), a uniform energy consumption distribution is observed in the entire APA, i.e. the ablating layer. And the plasma will be firstly created from the entire Ag nanopillar surface in the APA-AAO enhanced samples, and then generated from the inner Ag pillars through continuously absorbing the laser energy and transmitting it to the inner Ag pillars. For the APA-AAO used in this work, the energy transmission distance to the inner Ag

Figure 3: The simulated reflection spectra of the APA-AAO samples with the same structure parameters of the Sample A (a), B (d), and C (g), respectively; (b), (e), and (h) The electric-field distribution at excited wavelength of 1064 nm with respect to the left reflection spectra; (c), (f), and (i) The electromagnetic energy consumption distribution extracted from the electromagnetic field distribution shown left. The inset dashed line indicates the Ag pillar and the Al foil material area, and the left area is the material of Al_2O_3 .

pillars is smaller than 50 nm, which greatly facilitate the generation of plasma in short time. While in the Al foil samples, the plasma is firstly created from the Al foil surface, and then further absorbs the laser energy and transmits the energy to the Al materials under the generated plasma. In this case, the energy transmission distance is larger than 1 μm . The longer energy transmission distance will require more time to generate enough plasma, waste more energy to the surrounding materials and decrease the temperature and pressure of the created plasma. Thus, we can expect that the APA-AAO can bring large light-

absorbance and high energy transmission speed to the entire ablating layer, and finally improve the flyer speed.

3.4 Laser-induced plasma temperature in the ablating layer

The electron temperature is one of the critical parameter to characterize the plasma generated process in the ablating layer under high-power laser illumination. A higher electron temperature indicates a larger plasma pressure, and

Figure 4: (a, b) LIBS spectra in the wavelength ranges of 200–500 nm for Al foil and Sample B. (c) The calculated electron temperature in plasma in terms of the peak intensity profile via the Boltzmann plot method.

thus a higher flyer speed can be anticipated. The transient electron temperature can be qualitatively studied by measuring and analyzing the atomic emission spectra with the laser-induced breakdown spectroscopy (LIBS) technique. Figure 4(a) and (b) show the LIBS spectra of pure Al foil and Sample B, where the detail measured process can be found in the Experiment Section. Some clear atomic emission peaks located in the waveband of from 200 to 500 nm are observed at 28 ns after the illumination of a short-pulse laser beam. And the peaks at 308.2, 309.3, 394.3, and 396.2 nm are corresponding to the aluminum atomic lines, respectively. All of the peak intensities undergo an initial increasing and final dropping process in the following 1500 ns, indicating that the reaction in the ablating layer approaches the end in about 1500 ns.

The electron temperature in plasma can be estimated in terms of the corresponding peak intensity profile via the Boltzmann plot method [32].

$$\ln\left(\frac{I_1}{I_2}\right) = \ln\left(\frac{A_1 g_1 \lambda_2}{A_2 g_2 \lambda_1}\right) + \frac{1}{KT(E_2 - E_1)}$$

where I_1 and I_2 are the emission intensities of the specified emission lines, A_1 and A_2 are the transition probability of electrons located on the specified energy levels, g_1 and g_2 are the statistical weight of electrons located on the specified upper levels, λ_1 and λ_2 are the emission wavelengths, and E_1 and E_2 are the emission energy.

Figure 4(c) shows the calculated electron temperature of aluminum, where the related parameters used in this work is shown in Table 1. It seems that all of the APA-AAO enhanced flyers own lower electron temperature at the beginning 828 ns when compared with that of the pure Al foil flyer, although a higher electron temperature is expected due to the larger absorbance of the APA-AAO

Table 1: Spectroscopic parameters of aluminum atomic lines used in the Boltzmann plot method.

Peak wavelength (nm)	A_i (10^8 s^{-1})	E_i (cm^{-1})	g_i
308.2	0.63	32,435.45	4
309.3	0.74	32,436.79	6
394.3	0.49	25,347.75	2
396.2	0.98	25,347.75	2

enhanced flyers. It should be noted that the pointer Al atoms in the APA-AAO enhanced flyers come from the metallic oxide Al_2O_3 . The Al_2O_3 owns a large thermal capacity and can greatly increase the energy threshold value for generating plasma and decrease the electron temperature, which is a disadvantage for high performance LDF. However, the mixture of Al_2O_3 and Ag shows a longer plasma holding time when compared with that of the Al foil samples. As shown in Figure 4(c), the plasma temperature of Al foil samples decreases to about 7200 K at the time of before 1200 ns, while the APA-AAO enhanced samples can keep the plasma temperature of above 7100 K to the time of near 1600 ns. Especially for Sample B, a maximum electron temperature of about 8310 K is observed at about 1128 ns, which is even higher than that of about 8190 K at 828 ns for the Al foil samples. These results clearly demonstrate that the incorporated APA-AAO can effectively improve the electron temperature and the holding time of the plasma generated in the ablating layer.

3.5 The flyer velocity in the accelerated chamber

The flyer velocity is the most important factor to estimate the performance of LDF. Because the accelerated process of

Figure 5: (a) The velocity measurement schematic diagram of the APA-AAO enhanced flyers, where a photonic Doppler velocimetry method is used. The detection light signal is collected by an optical fiber located on the end of the accelerated chamber and then transferred to the oscillograph for further analysis; (b) and (c) the measured velocity and accelerated velocity of the flyers from the Al foil sample (green), Sample A (red), B (blue), and C (yellow) at different times.

the flyer is an ultrafast process, we employ two kinds of high temporal resolution methods to record the flyer speed at different flying stages. One is the photonic Doppler velocimetry method [33], which is used to measure the velocity of flyer in the accelerated chamber (as shown in Figure 5(a)); the other is the time-resolved shadowgraph system, which is used to record the flyer flying out of the accelerated chamber (as shown in Figure 6(a)). The detail detected process can be got from the Experiment Section. Figure 5(b) and (c) shows the transient velocity and the transient accelerated velocity of the flyers in the accelerated chamber. At the beginning of 30 ns (the pink region), the flyer velocity increases sharply from 0 m/s to larger than 1000 m/s. And the maximum accelerated velocity can reach to above 10,000 m/s. Then the flyer velocity increases slowly in the time range of from 30 to about 200 ns, and keep unchanged when the time exceeds 200 ns. The final flyer velocity of the APA-AAO enhanced Sample A, B, and C is 1510, 1730, and 1285 m/s, respectively, which is about 1.2, 1.4, and 1.04 times larger than the velocity of the pure Al samples (about 1250 m/s). Thus, we achieve a maximum enhancement of 40% by using the APA-AAO to enhance the absorption efficiency of LDF.

In general, the whole accelerated process can be mainly divided into four different processes according to the accelerated curves shown in Figure 5(c). All of the samples show a chaotic accelerated process at the beginning 20 ns, where the accelerated speed increases and decreases sharply and randomly in this period. When excluding the possible influence from the photonic Doppler velocimetry system and seeing the time-resolved shadow photograph shown in Figure 6, this phenomenon indicates that many small flyers with different speed, not one large flyer with one speed, are generated during this

Figure 6: (a) The time-resolved shadow photograph measurement schematic diagram. A detection laser beam parallel to the bottom side of the accelerated chamber is used to illuminate the flyer out of the accelerated chamber, and the shadow is recorded by a high-speed CCD camera; (b) the measured time-resolved shadowgraphs of the flyer from the Al foil sample, Sample A, B, and C at different time steps. The times and the scale bar are denoted by the red and white characters, respectively. Time-resolved shadowgraphs of laser-ablated flyer plates at different time steps.

period. The different flyers with different speeds results in the randomly accelerated phenomenon. In the following 30 ns, the accelerated speed decreases quickly to about 1000 m/s^2 , indicating the end of the plasma generating process. In the period from 50 to 200 ns, it is the tenderly-adiabatic expanding process that drives the flyers to a higher speed, but the accelerated speed decreases to near zero slowly. When the time exceeds 200 ns, the speed of flyers keeps unchanged. Because the detail accelerated process of a flyer is highly related to the generation process of plasma formed in the ablating layer, and more information about the plasma and the flyer, can be extracted from the detail accelerated curves.

When comparing the detail accelerated curves between the pure Al foil samples and the APA-AAO enhanced samples, we can find that the accelerated speed of the pure Al foil samples drops quickly than that of the pure Al foil samples in the period of about from 20 to 50 ns. This is the main reason for the lowest ranking of the final speed obtained in the Al foil samples, which further indicates that the mixture of Al_2O_3 and Ag can give a longer plasma generating and holding time to drive the flyers. Certainly, the larger initial accelerated speed from the APA-AAO enhanced samples is another reason to decrease the final speed ranking of the Al foil samples. In addition, we note that Sample C shows a lower speed at the beginning 200 ns when compared with that of the pure Al foil sample. This should be attributed to the low fill factor of Ag in the AAO templates, where the pressure created by the Ag plasma will release to the sapphire window side, and there is not enough pressure to maintain the accelerated speed of the flyers at beginning. We also note that all of the accelerated processes happen in the accelerated chamber. In another word, the speed of flyers is kept unchanged before the flyers go out of the accelerated chamber.

3.6 The transient flying state of flyers out of the accelerated chamber

When the flyers are flying out of the accelerated chamber, their shadowgraphs are recorded by a high-speed CCD camera. As shown in Figure 6(a), a beam of illumination laser is placed on the left of the flying path and the flyer shadowgraphs are recorded by the high-speed CCD camera placed on the right side and shown in Figure 6(b). The flyers were observed at the exit of the accelerated chamber at about 580 ns after the illumination of laser. We can see that all of the flyers are formed by many small particles, which become more incompact with the increasement of flying time. The flyer particles from the pure Al foil samples

almost own the same speed and flying direction due to the integrally accelerated process. While for the flyer particles from the Sample A, B, and C, a large speed difference is observed between different flyer particles, and some low-speed flyer particles even deviate from the direction of the accelerated chamber. These flyer particles with low speed and small directionality are not beneficial for practical applications. However, these disadvantages can be overcome by contacting the targets (i.e. explosive) with the accelerated chamber, where the flying state of the flyer particles can be well controlled by the accelerated chamber.

In addition to the high-speed flyer, the LDF also can create a kind of detonation wave with speed of up to about Mach 8 in air, which is highly-desired in the region of high-pressure science. As shown in Figure 6(b), the dark grey line denotes the wave-front of the detonation wave. It is clear that the detonation wave owns larger speed than of the flyers. However, its speed decreases quicker than that of the flyers, and some of the flyer particles catch up with the wave-front of the detonation wave at about 2000 ns. In addition, we see two different wave-fronts in the transient shadowgraphs of Sample B at 586 ns and Sample C at 562 ns. This phenomenon should be attributed to the interval ionized process between Ag and Al_2O_3 and the low fill factor of Ag in AAO template. It should be noted that all of the shadow graphs shown in the same row in Figure 6(b) is collected from different samples at different times due to the limitation of the measuring technology. Thus, the transient shadow graphs in the same row show four flyer states in different LDF processes.

3.7 Repeatability and optimization of APA-AAO enhanced flyers

Finally, we investigate the surface morphology of the flyer layer after illuminated by pulse laser and the repeatability of the APA-AAO enhanced LDF. Figure 7 shows the surface morphology of the flyer layer after illuminated by the pulse laser. A round hole is clearly formed in the ablating layer (Side A) and the flyer layer (Side B) in all of the investigated samples. All of the circles in the flyer layer side own a similar size, indicating that the total mass of flyers from the purl Al foil sample and Sample A, B, and C should be nearly the same. In addition to the hole, a black half-ring is also observed in the pure Al foil sample, which should be originated from the high reflectivity of Al foil and the twice ablation effect. In other word, the APA-AAO structure perfectly avoids this disadvantage phenomenon, and increases the laser energy utilization efficiency.

Figure 7: Surface morphology of the flyers after illuminated by pulse laser.

(a) The schematic diagram of the flyer surface denoted by Side A and B; (b) the micrographs of the top and bottom surface of the flyers from the Al foil sample, Sample A, B, and C.

Table 2: Parameter summary of the APA-AAO enhanced LDF.

	Sample A	Sample B	Sample C	Pure Al foil-sample
Hole diameter (nm)	45–55	65–75	100–110	/
Hole depth (μm)	4	4	4	/
Hole distance (nm)	95 ± 15	125 ± 25	175 ± 25	/
Ag pillar height (μm)	3.8 μm	3.8 μm	1.6 μm	/
Ag fill factor	95%	95%	40%	/
Flyer velocity (m/s)	1552.0 ± 20.4	1804.2 ± 64.8	1315.0 ± 93.2	1170.0 ± 60.9

All of these discussions demonstrate that the APA-AAO nanostructures can effectively reduce the reflectivity of the ablating layer and improve the flyer velocity. To confirm the repeatability of the APA-AAO enhanced LDF, all of the experiments have been carried out for at least 20 times, and the results are summarized in Table 2. In fact, we have done a lot of works to optimize the structure parameters of the flyers, include the laser beam size, the thickness of the flyer layer, the diameter and height of the accelerated chamber. These experiments confirm that the APA-AAO enhanced flyers own a higher velocity than that from the pure Al foil flyers, indicating that using PMA to reduce the reflectivity of the ablating layer is an effective method to improve the performance of LDF. Under the optimized conditions, we can achieve about 50% enhancement of velocity, as shown in Table 2.

4 Conclusion

In this work, we experimentally demonstrate a kind of high performance PMA-enhanced LDF. The APA-AAO working as PMA has been successfully fabricated *in-situ* on the surface of the ablating layer by employing the electrochemistry synthesis technique, which can greatly improve the absorption efficiency of the ablating layer from about 7 to 95% at the wavelength of 1064 nm. The transient characterizations, include the photonic Doppler velocimetry

method, LIBS and the time-resolved shadowgraph method, reveal that the APA-AAO of high absorptivity can effectively improve the temperature and density of plasma, and results in a final flyer speed of 40%-enhancement. And our results further reveal that the APA-AAO enhanced LDF owns four different accelerated processes, which is highly related the plasma generation process, and demonstrate that the APA-AAO structure can improve the plasma holding time and further facilitate the improvement of the final speed of flyers. The PMA enhanced LDF scheme proposed here can effectively improve the performance of LDF visa simply patterning the ablating layer, and provides new guidance for designing high performance LDF. It can be expectative that by combining the PMA enhanced LDF scheme and other schemes (such as using energetic materials), we can further increase the flyer velocity, reduce the inputting laser energy, and improve the miniature laser and the integration of LDF system.

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