Observation of radiation pressure induced deformation of high-reflective reflector

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Abstract
In this paper, radiation pressure induced deformation of a series of thin aluminum reflectors is analyzed theoretically and experimentally. Theory of quantum mechanics and material mechanics are applied in 2D simulations and exhibits good coordination with experiment results. The original laser source used in the experiment is Gauss-distributed and has been shaped and expanded, resulting in the flattened light to avoid over heating or even ablation of the irradiated reflector, which can also bring a major deformation. The aluminum reflectors are fabricated by a high precision machine tool into a thickness of 100, 200, 300 μm with a surface roughness of 8 nm in Ra, and then coated with high-reflective coatings and mounted on a thick 3D printing base made of polylactic acid (PLA). In the experimental process, a vacuum chamber is employed to distinguish the effect of thermal convection. The results show that radiation pressure induced deformation has an obvious negative correlation with the reflector thickness. The time-deformation curve of the reflector reaches 2.4 μm peak negative displacement at most the moment laser beam is acting when under vacuum circumstance, and soon raises up to over 12 μm positive displacement if the reflector is continuously irradiated. Subsequent analysis shows that such negative displacement is induced by radiation pressure and the positive displacement is caused by thermal expansion of the PLA base.

1. Introduction
Light photon is unique due to its wave-particle duality, which means photons can behave like waves, for example, electric-magnetic waves, as well as particles like atoms and molecules. People have observed its wave properties via diffraction and interference phenomena, and its particle properties can be demonstrated by photoelectric effect, Compton scattering. Meanwhile, one specific physical phenomena can certify both two properties of light photon, that is the effect of radiation pressure.

Radiation pressure refers to the pressure exerted by the light when the light is reflected, refracted or diffracted in the medium. As long as the propagation path, intensity or wave length [1] of the initial light is changed, there must be radiation pressure effect involved. The study of radiation pressure can be derived from 17DC when the great astronomer Kepler studied the trajectory of comet and found that the comet tail always pointed opposite to the Sun. With the foundation of Maxwell equations, radiation pressure can be theoretically deduced and precisely calculated. However, the experimental demonstration failed to be carried out because of multiple obstacles, including thermal effect and diffusion of the light source. The first successful experiment was designed by Russian physicist Lebedev in 1901 and conducted under high vacuum circumstance [2]. In the latest decades, with the advent and development of laser beam, both the experiments and application studies had achieved significant progresses. According to the size of the interacting object, radiation pressure can be categorized into micro and macro radiation pressure.

The research on micro radiation pressure includes capture, levitation, manipulation and acceleration of cells, micro particles, molecules or so by laser light [3]. Ashkin et al pioneered in experimental realization of
stable levitation of micro spheres ranging from dozens of nanometers to dozens of micrometers in different medium, including water, atmosphere and vacuum [4−6]. This radiation force could be further enhanced under resonant conditions, which had been proved recently by Maslov et al who observed giant optical forces as well as propelling velocities of dielectric micro sphere ranging from 15 to 20 um by use of resonant light forces [7, 8]. Radiation pressure can also be applied in non-contact precise manipulation of biomass and organics like DNA chain, which is called optical tweezers [9]. Radiation pressure functions like tweezers in process and it proves to be superior to magnetic tweezers or AFM method because of high resolution and negligible damage to the target [10]. Li et al further studied this mechanism and applied it in measurement of instantaneous velocity of a single Brownian particle in atmosphere and liquid circumstances [11, 12]. Another important application of radiation pressure is laser cooling. With multiple counter-propagating laser beams, the target particle will receive a force opposite to its direction due to Doppler effect, so that the particle motion is slowed, which means the temperature decreases [13, 14]. Further research which combined magnetic field and radiation pressure could cool the atom down to micro or even nano K [15]. Meanwhile, high power laser was used in the acceleration of nanoscale particles and proved successful. The acceleration process was classified into two types by incident laser intensity, including target normal sheath acceleration and radiation pressure acceleration. Henig et al conducted the experiment of irradiating a 5 nm thick DLC plate by \( 5 \times 10^{19} \text{ W cm}^{-2} \) circular polarized laser, and the energy of output plasma was over 30 MeV [16]. Kal irradiated the similar plate with \( 3 \times 10^{20} \text{ W cm}^{-2} \) high-power laser and measured the energy of output carbon plasma, which was 5−10 MeV [17].

As for the macro radiation pressure, the research focuses on the dynamic deformation on the surface as well as inside the macro object after the interaction, which is also called opto-dynamics. Precisely, opto-dynamics includes laser-induced mechanical motion [18], laser-induced shock waves and cavitation bubbles in fluids [19, 20], laser propulsion [21], a wide variety of laser material processes [22], laser-assisted medical applications and so on. Tomáš et al compared the irradiated object to an elastic body, and built up the laser induced wave analysis method under condition of non-relativistic conservation field [23, 24], and managed to measure the ultra sonic wave of the fused quartz with high reflective (HR) coating by PZT sensors irradiated by high power laser [25]. Astranšt et al irradiated the ultra-pure water with laser of radius of 104 um, and the momentum transmitted in process was precisely calculated by interference phenomena [26]. Similar experiment were conducted in 2015 when Sun et al applied the laser into directly irradiating the liquid surface and measured the variation of the radius of the reflected light spot, and successfully calculated the radiation pressure value, which helped to distinguish the condition of using Minkowski light momentum formula and Abraham light momentum formula [27]. Meanwhile, radiation pressure were also applied in aerospace field. Japan Aerospace Exploration Agency lunched the first solar sail spacecraft named IKAROS in 2010, which successfully unfolded, accelerated and sailed along its preset orbit [28]. The latest known macro radiation pressure levitation experiment were carried out by Zhang et al who demonstrated the experiment of levitation and propulsion of graphene bulk by laser of \( 10^{4} \text{ mW} \) [29].

In this paper, we presented an experiment that could be the solid proof of macro radiation pressure and helped to calculate the radiation pressure. In order to avoid over heating or even ablation of the irradiated part, beam shaping lens were used to expand the original spot radius \( R \) from 2 to 10 mm, which was the same size of the irradiated aluminum plate. The aluminum plate was attached to a 20 mm square base with the bottom side smoothed via high precision machining made of polylactic acid (PLA) plastics by 3D printing, which had benefits in shortening machine time as well as decreasing vibration when irradiated due to its elasticity. There was a 1 mm tall vertical holder in the middle of the PLA base so that the aluminum plate can be set perpendicular to the base. One side of the aluminum reflector was coated by HR coating, which consists of titanium oxide and silicon dioxide, which had 27 layers and each layer’s thickness was 266 nm. The coated side irradiated by the expanded beam was defined as front side, and the back side was measured by an interferometer. We conducted the experiment under both atmosphere and high vacuum circumstance to distinguish the effect of thermal convection.

2. Model and method

The fundamental component of light is photon according to quantum physics, which carries energy and momentum. For a single photon, the energy and momentum it carries are given in equations (1) and (2)

\[
E_0 = \hbar \nu, \tag{1}
\]

\[
p_0 = \frac{\hbar \nu}{c}, \tag{2}
\]

where \( E_0 \) is the energy, \( \hbar \) is the Planck constant, \( \nu \) is the frequency of the incident light, \( p_0 \) is the momentum, \( c \) is the light speed. When a bunch of light irradiates on the surface and reflects, a part of energy and momentum of
the light is transferred to the surface, and the surface therefore acquired a pulling off force that is called radiation pressure. Specifically, when the surface is smooth enough and reflects most of the light instead of absorbing the incident light, the radiation pressure can be amplified and induces observable deformation to the surface. The light source used in this study is high power pulsed laser, and the sketch map for radiation pressure model is shown in figure 1. The coated aluminum plate is attached to the PLA base that is assumed to be a indeformable surface. The incident angle of high-power laser beam is \( \theta \), and the irradiated aluminum plate has a slight inclination angle \( \varphi \) because of radiation pressure. The plate rotates with angular velocity \( d\varphi \), so the reflection angle is not the same as the incident angle, which has a micro increase of \( d\theta \). The momentum of incident light per pulse is:

\[
P_{\text{incident}} = \frac{Nh\nu}{c},
\]

where \( N \) is the number of photons acquired by the reflective plate per pulse. The power output for pulsed laser is discontinuous, and for each pulse we have:

\[
E_p \cdot T = \frac{P}{f_p} = Nh\nu,
\]

where \( E_p \) is the power output per pulse, \( P \) is the energy of the incident beam per second, \( f_p \) is the repetition frequency of the pulsed laser, and \( T \) is the pulse width of the laser. Thus, the momentum of the incident light carried per pulse is:

\[
P_{\text{incident}} = \frac{E_p \cdot T}{c} = \frac{P}{f_p c}.
\]

In order to get the theoretical value of radiation pressure, this model has been idealized under the following assumptions. Firstly, the reflective index \( r \) of coated aluminum plate is high enough (above 99.998%) so that thermal effect can be neglected to some extent, and the surface is smooth enough (\( S_a < 5 \text{ nm} \)) so that there is no diffuse reflection in process. Secondly, the incident laser beam has beam shaped and expanded so that the aluminum plate is equally irradiated. Lastly, the deformation of the plate is continuous and smooth, so that the circular plate can be treated as a flat plane with a virtual cantilever by the middle as figure 2 shows. The cantilever beam deformed under radiation pressure and the model can be now simplified as a bunch of light irradiates directly on the cantilever, so that the equivalent incident light momentum distribution along the cantilever beam is thus:

\[
P_{\text{incident}}(y) = \frac{2P \cos \theta}{\pi R_f^2 c} \sqrt{R^2 - (R - y)^2},
\]

where \( y \) is the distance from the bottom of the reflector to the point where light is reflected as shown in figure 1. The wavelength of the incident light is \( \lambda \). The reflective light has a micro frequency shift according to Doppler effect. Theory of relativity is neglected in our analysis because the whole experiment is carried on under low speed environment. The \( XY \) plane coordinate is set as figure 1 shows, here we get:
where \( V_{\text{mirror}} \) is the rotation speed of the reflective plate. The relative velocity between the incident light and the reflective plate is thus:

\[
V_x = V_{\text{mirror}}(x) \cos(\theta + d\theta) = y \cos(\theta + d\theta) \frac{d\varphi}{dt},
\]

\[
V_y = V_{\text{mirror}}(x) \sin(\theta + d\theta) = y \sin(\theta + d\theta) \frac{d\varphi}{dt},
\]

where \( V_x \) is the normal relative velocity and \( V_y \) is the tangential relative velocity. The wavelength of reflective light is thus:

\[
\lambda' = \lambda + \frac{1}{v} \cdot V_x,
\]

where \( \lambda' \) is the wavelength of the reflected light. Put equation (5) into (7) and we get:

\[
\lambda'(y) = \frac{c + y \cos(\theta + d\theta) \frac{d\varphi}{dt}}{v}.
\]

The frequency of the reflected light is thus:

\[
v'(y) = \frac{cv}{c + y \cos(\theta + d\theta) \frac{d\varphi}{dt}}.
\]

Therefore, the momentum of the reflected light per pulse is:

\[
P_{\text{reflected}}(y) = -\frac{cr}{c + y \cos(\theta + d\theta) \frac{d\varphi}{dt}} \cdot \frac{2P \cos(\theta + d\theta) \sqrt{R^2 - (R - y)^2}}{\pi R^2 f_p c},
\]

where \( r \) is the reflective index of the reflector. The momentum transferred in process is thus:

\[
P(y) = P_{\text{incident}}(y) - P_{\text{reflected}}(y) = \frac{2P \cos(\theta + d\theta) \sqrt{R^2 - (R - y)^2}}{\pi R^2 f_p c} \left( \cos \theta + \frac{cr \cos(\theta + d\theta)}{c + y \cos(\theta + d\theta) \frac{d\varphi}{dt}} \right).
\]

The \( d\theta \) and \( d\varphi \) components can be left out when the reflective plate comes to the equilibrium point when the radiation pressure equals restoring force of the aluminum plate. Equation (15) can then be transformed as:

\[
P(y) = \frac{2P \cos \theta \sqrt{R^2 - (R - y)^2}}{\pi R^2 f_p c} (1 + r).
\]

It has been mentioned previously that this force is uniformly distributed on the plate, as shown in figure 2.

Figure 2. Radiation pressure distribution on the reflective plate.

\[
V_{\text{mirror}}(x) = y \frac{d\varphi}{dt},
\]

\[
V_{\text{mirror}}(y) = 0,
\]
ABCD is the coated circular plate irradiated by laser beam, and the bottom of the plate is attached to a tiny holder DO’ of the PLA base fabricated by 3D-printing. Considering the circular plate as a flexible beam with center line on DOB, and the force distribution along this flexible beam is thus:

\[ F(y) = \frac{P(y)}{T} = \frac{2P}{T} \frac{\cos \theta}{\sqrt{R^2 - (R - y)^2}} \left(1 + r\right). \]  \hspace{1cm} (17)

The torque and deflection formula along DOB can then be given by integral of equation (17) as:

\[ M(y) = \int F(y)y dy = \int \frac{2Py}{T} \frac{\cos \theta}{\sqrt{R^2 - (R - y)^2}} \left(1 + r\right) dy, \]  \hspace{1cm} (18)

\[ \Delta x(y) = \int \frac{M(y)}{EI} dy = \frac{1}{EI} \int \int \frac{2Py}{T} \frac{\cos \theta}{\sqrt{R^2 - (R - y)^2}} \left(1 + r\right) dy dy, \]  \hspace{1cm} (19)

where \( E \) is the elastic modulus of the material, which is 70 GPa for our simulation. And \( I \) is the inertia moment. The flexible beam is assumed to be the same width as the holder DO’, and the thickness is the same as the plate itself. Thus the inertia moment is given by:

\[ I = \frac{ab^3}{12}, \]  \hspace{1cm} (20)

where \( a \) is the width of the attachment, which is approximately 1 mm in our experiment. And \( b \) is the thickness, which ranges in 100, 200 and 300 \( \mu m \). We can get the estimated radiation pressure force by integral of equation (17), which is 0.00024 N. And the theoretical deflection curve for the plate is given in figure 3 with input laser repetition rate of 80 MHz, pulse width of 10 ps and pulse power of 36.25 kW. The horizontal axis is variable \( y \) that is the distance from the attachment to the point on the plate, and vertical axis is the theoretical displacement. It is shown that the deformation increases greatly as the plate thickness decreases. The greatest displacement predicted is about 1.8 \( \mu m \) for the 100 \( \mu m \) thick plate, yet as for the 300 \( \mu m \) thick plate, the maximum displacement is below 0.07 \( \mu m \).

Further simulation on the whole plate dealt by finite element methods also shows accordance about deflection along BOD. In our theoretical analysis, thermal effect is neglected, but experimental realization of observation of radiation pressure would be faced with the disruption of thermal expansion or thermal convection. Therefore, thermal effect is taken into consideration in our experiment and managed to distinguished from radiation pressure effect.

Usually, the laser beam output is formed as Gaussian beam or quasi-gauss beam with a dominant central peak, and the beam spot is rather small. The laser device used in experiment is high-power pulsed laser with an output laser at the wavelength of 1064 nm, repetition rate of 80 MHz and pulse width of 10 ps. The output continuous power of the pulsed laser beam in our experiment is set to 29 W, and the single pulse power is about 36.25 kW, focusing to intensities of up to 1153.9 kW cm\(^{-2}\). This typical light intensity distribution can easily bring about ablation to the irradiated object and has to be prevented. Figure 4 shows the schematic view of the experimental setup. The output laser beam goes through a quarter-wave plate which can be used to adjust beam’s polarization, and enters into the Brewster window which can reflect the S-polarized component of the incident beam. The beam then goes through a couple of 45° total reflection mirror that can adjust the height as well as the pitch angle of the output beam. Beam shaping lens designed by means of free-form optics is used to relieve the Gaussian distribution and expand the original light beam, resulting in the 10 mm radius flatten light with intensities of 11.5 kW cm\(^{-2}\). The thickness of reflective plate is designed so that the radiation pressure

![Figure 3](image-url) Theoretical displacement curve of the reflector with thickness of 100, 200 and 300 \( \mu m \).
induced deformation fits the measuring accuracy of the single-beam interferometer (SIOS SP-S 120), which can distinguish object’s displacement of over 20 pm from ambient noise under ideal circumstances. The plate structure is placed on a six-axis displacement table so that the adjustment of incidence angle can be precisely controlled. The incidence angle in following experiment is set to $4^\circ$ so that the ray will not be vertically reflected and damage the laser device. Furthermore, high polymer organic material behaves rather soft at glass transition temperature, which is around $40^\circ$C for PLA. The temperature is recorded by thermal imager and the irradiation time is set to 2 s, which is the proper time that the temperature of the plate structure rises to only $32^\circ$C, well below the glass transition temperature.

3. Results and discussion

Measuring the whole surface’s deformation proves to be difficult and unnecessary. Therefore, we measured several points along the middle line of the reflective plate, and finally picked three typical points’ displacement in analysis, which are the top, middle and the bottom point of the plate. Signal acquisition frequency for single-beam interferometer is set to 1000 Hz. The time–displacement curve of the plate under atmospheric pressure is shown as below.

Spectral analysis in figure 5 shows that the frequency of ambient noise peaks at 51, 67 and 108 Hz, which belong to low-frequency noise. The experiment data has then been filtered and low frequency signals are neglected. Red curve is the displacement variation of the top point along with time. The curve can be divided into three part: preparation part, irradiation part and cooling part. The preparation starts from 0 to 3 s when the laser beam in blocked by an opaque mask, and the curve behaves to be a flat line with minor oscillation caused by ambient noise and apparatus errors. The irradiation part starts from 3 to 5 s, which means the coated plate is fully irradiated by the laser beam. Radiation pressure induced deformation can only be observed in a short time within the irradiation part as figure 6 shows, that the curves turned negative direction by the time the opaque mask is removed and the plate is irradiated. Radiation pressure is now exerted on the reflective plate and pushes the plate towards the interferometer, and the displacement curve has thus a vertical decrease. This negative displacement is soon overwhelmed shortly afterwards due to thermal expansion as shown in figure 7. The back side of the reflector is attached to the holder and will be moved with the thermal expansion of the holder. The interferometer is applied in measuring displacement of back side of the reflector, so that the interferometer beam has the same direction with thermal expansion induced displacement of the reflector and positive displacement is thus observed. The cooling part starts from 5 to 30 s, when the laser beam is blocked again by the opaque mask and the plate structure is cooled under room temperature. It turns out that the curve has a smooth rise phase until reaches the summit, and then undergoes smooth decrease till the end. The rise phase of the
Figure 5. Spectral analysis of ambient noise.

Figure 6. Top, middle and bottom point’s displacement under atmosphere pressure for high-reflection coated plate of (a) 100 um thickness (b) 200 um thickness (c) 300 um thickness.
displacement curve is due to the heat transmission delay between the reflective plate and the PLA base, which means that the temperature of the plate is higher than the PLA base when laser beam is blocked by the mask. The PLA base will continue absorbing heat and the PLA holder will keep expanding in a short time, and drives the plate attached to it moving further away from the interferometer. But when the temperature of PLA base and the reflective plate equals, the holder will not expand so that the displacement reaches the summit, and smoothly shrinks back to its original position because of cooling as the curves show.

The comparison of displacement curves among figure 6 also indicates that the thickness of coated plate will greatly affect the experimental results. The red curve stands for the top point’s displacement, and radiation pressure induced deformation of the 100 μm thick plate can be as large as 1 μm scale, but it decay almost an order to 0.2 μm as the thickness of the plate increases to 200 μm, and eventually becomes immeasurable for interferometer when the plate thickness becomes 300 μm. On the other hand, thermal expansion also behaves inconspicuous as the thickness of the irradiated plate increases. Green curve is taken from the center of the plate and it is clear that radiation pressure induced displacement can only be dimly seen for 100 and 200 μm thick plate, and even vanishes for the 300 μm thick plate. We also observed a unique crossing of red curve and green curve in figure 6(b), that the green curve behaved abnormal during the cooling period. The possible cause of this phenomena is friction that prevents the PLA base from shrinking back to its original position, which means edge instead of the center of the PLA base moves, so the cooling curve measured stays plain.

It is now confirmed that the plate does move forward when the laser beam is applied and the second part displacement curve is very likely to be a combination of forces induced motion and thermal expansion. But whether the force is derived from radiation pressure or thermal convection as the laser is applied remains a question. Therefore, the experiment is later carried out under vacuum circumstance in order to eliminate the influence of thermal convection of the air, which can also bring a tiny force to the irradiated plate. The plate structure is placed in a cubic vacuum chamber with two high-transparency glass window placed at left and right side, one for laser beam transmission, another for single-beam interferometer measurement. The pressure in the vacuum chamber is pumped down to 10 kPa, which is about 10% of the atmosphere pressure. The single-beam interferometer is re-calibrated to meet the requirement of measurement in vacuum circumstance. The irradiation period also starts from 3 s and ends at 5 s, and three typical points’ displacement are measured again as shown in figure 8.

Comparing the results of displacement curve taken under atmosphere pressure and under vacuum pressure, it is clear that the negative tendency does not shrink or vanish as the air are pumped out, but becomes even clear to observe, which means that such negative displacement is irrelevant with thermal convection. Another interesting fact is that thermal expansion seems to be suppressed under vacuum circumstance, yet it takes relatively long time for cooling the plate structure as the cooling curve from 5 to 30 s decreases rather slowly than before. The maximum amplitude for negative displacement are recorded and has been shown in figure 9 with colored dots, theoretical curves are also shown for comparison. Under atmosphere pressure, it turns out that the experimental value of 100 μm thick plate and 300 μm thick plate fits the theoretical value fairly well, but the 200 μm plate’s deformation is greater than expected. As for vacuum circumstance, the experimental value is greater than theoretical value, this is possibly caused by two mean factors. One is about the refractive index variation from atmosphere pressure to vacuum circumstance. Single-beam interferometer can measure displacement by phase change of the emergent light and the reflected light. The linear displacement formula for the single-beam interferometer is given by equation (21).
\[ \Delta L = \frac{\lambda \cdot \arctan \left( \frac{I_x}{I_y} \right)}{4\pi n}, \]  

where \( \lambda \) is wavelength of the measurement beam, which is 632 nm in our experiment. \( I_x \) and \( I_y \) are signal intensity difference, and \( n \) is the refractive index. The interferometer is sensitive to refractive index variation and that the displacement measured will have a shift to negative when under vacuum circumstances, which has also been proved when we try to measure the displacement variation of a static reflector inside vacuum chamber while vacuumizing. Another reason is about random error, that when we block the laser after 2 s irradiation, there will be an abrupt change of displacement induced. This process cannot be precisely distinguished when under ambient noise so that the displacement measured at this moment, which is also when the radiation pressure induced displacement peaks, will be influenced. The amplitude of ambient noise under atmosphere pressure reaches approximately 2 \( \mu \)m, but under vacuum circumstances, it is only 0.4 \( \mu \)m, which means the influence on maximum displacement expands if the chamber is not vacuumized. This influence could either make the displacement shifting positively or negatively, and it turns out to be negatively in our cases so that the laser induced deformation appears to be larger than that in ambient air. Another interesting phenomena that draws our attention is that the thermal expansion seems to be suppressed when under vacuum circumstance. This is possibly caused by the temperature difference, that the temperature inside the vacuum chamber decreases.

Figure 8. Top, middle and bottom point’s displacement under vacuum circumstance for high-reflection coated plate of (a) 100 \( \mu \)m thickness (b) 200 \( \mu \)m thickness (c) 300 \( \mu \)m thickness.
due to vacuumization, and according to Newton’s law of cooling, the temperature of the whole structure will 
decrease faster under vacuum circumstance so that the thermal expansion will be suppressed.

In addition, the maximum negative displacement point recorded on the curve is not exactly the point when 
radiation pressure equals the restoring force of the bent plate, but actually the point when restoring force combined with thermal expansion exceeds radiation pressure. Furthermore, the rise of temperature can greatly 
affects the plasticity of the PLA base as well as the reflector, making them easier to deflect. This can also be the 
reason for why the value of experimental radiation pressure induced displacement is more or less drifted from 
the theoretical value.

We also noticed that there may be a question of whether the negative displacement could be caused by the 
uniformly heating of PLA holder and the base. Furthermore, high polymer organic material behaves rather soft 
at glass transition temperature, which is around 40 °C for PLA. Thus, the pure thermal expansion curve is 
measured by directly irradiating the holder on PLA. The PLA is vertically irradiated by unshaped laser beam 
from above, and the laser power is set to about 5 W as the thermal absorption of PLA is greater than the coated 
plate. Thermal imager shows that the maximum temperature on PLA base is about 34 °C after 2 s illumination, 
which is appropriate for thermal expansion measurement as figure 10 shows. The irradiation time is still set from 
3 to 5 s, and three thermal expansion curves of the top point for different plate are recorded and shown as 
figure 11.

The expansion curve by directly irradiating the PLA base shows abrupt rise as the laser is induced, and no 
negative displacement is detected compared to previous experiment. The displacement curve of 200 and 300 μm 

thick plate are identical thermal expansion and cooling curve, yet for the 100 um thick plate, a unique increase of 
displacement is observed after 5 s when the laser beam has been completely blocked, and repetition experiment 
shows accordance with figure 10. This abnormal curve of 100 μm thick reflector may be caused by shape error of 
the aluminum plate that thin, such as in-homogeneous curvature changes and ripples, which can generate 
disordered displacement when heated and bring error to the single-beam interferometer. We conducted 
confirmatory test by measuring a 100 μm reflector with more distinct shape error under laser radiation, and the 
displacement of all three typical points behaves to be randomized. It is believed that the shape error can affect the 
experiment result as well as the measuring apparatus, but the quantitative relation among them has not been 
identified so far.
4. Conclusions

We have presented experiments that radiation pressure induced deformation is precisely measured by single-beam interferometer and the experimental results matches well with our theoretical model. Quantum theory proves correct in our simulations, indicating that light can be regarded as particles in radiation pressure related analysis. This can be applied in similar radiation pressure related experiment like laser induced propulsion or optical levitation.

We managed to reduce the thermal effect by coating the reflector with HR film, and eliminate the affect of thermal convection by conducting the experiment under vacuum circumstance. The laser beam used in the experiment must be shaped and expanded to avoid overheating or even ablation of the irradiated object. Meanwhile, thermal expansion curve of the reflector is also measured and proved to be distinguished from radiation pressure induced motion. It is important to emphasize that the thermal convection does not affect the experiment as much because the reflector is thin enough, which means the temperature gradient by the front and back side of the plate is negligible. On the other hand, vacuum circumstance still proves to be advantageous in our experiment because air vibration is greatly suppressed and that the radiation pressure induced motion has been magnified, making it even distinct for measuring apparatus.

Radiation pressure induced motion is largely depended on the reflectivity of the reflector. Therefore, such observable deformation of reflectors under high-power pulsed laser can be possibly applied in HR index measurement. Our present apparatus is capable of measuring displacement of 20 pm from ambient noise if under ideal conditions, which means that we can at most distinct 0.001 % change of the reflective index for the 100 µm thickness reflector. This mechanism could be further enhanced by applying laser beam with greater

![Figure 10. Thermal imager graph of temperature distribution on the PLA base after 2s illumination (a) laser irradiated on the plate (b) laser irradiated on the PLA base.](image)

![Figure 11. Thermal expansion curve by directly irradiating the PLA base.](image)
power output and/or reduce the thickness of the reflector, yet the aluminum plate we used is by far the best option for fabricating such thin reflector. And thermal expansion curve could be possibly prevented by directly mount the reflector on the PLA base somehow without the reinforcement bolder to keep geometrical symmetry of the whole structure or choose other base with low thermal expansion rate.

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