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D. LIU
Y. LI✉
M. LIU
H. YANG
Q. GONG✉

The polarization-dependence of femtosecond laser damage threshold inside fused silica

State Key Laboratory for Mesoscopic Physics and Department of Physics, Peking University,
Beijing 100871, P.R. China

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ABSTRACT The laser damage threshold inside fused silica is dependent not only on the numerical aperture (NA) of the focusing objective, but also on the polarization of the incident femtosecond laser pulses. The damage threshold for circularly polarized beams is higher than that for linearly polarized beams when NA > 0.4, but the former was lower than the latter when NA < 0.4. The reverse might be due to different damage processes: laser induced damage at high NA and the self-focusing induced breakdown at low NA.

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1 Introduction

Polarization sensitive interaction of femtosecond laser pulses with dielectrics is an attractive topic from the view of fundamental physics and applications. Experiments have proved that the surface damage threshold of fused silica induced by circularly polarized (CP) beams was higher than that of linearly polarized (LP) beams [1, 2]. Nevertheless, there have been no systematic studies about the dependence of the bulk damage threshold on polarization. This issue is essential to the fabrication of buried integrated devices such as waveguides [3–10], optical amplifiers [4, 10, 11], beam splitters [4, 5], and directional couplers [6, 7]. To ensure a higher refractive index modulation, these elements are usually written at an intensity slightly below the damage threshold. In this paper, we measured the bulk damage threshold inside fused silica and found that it was dependent on both the polarization of the incident beam and the NA of the focusing objective. When NA > 0.4, the threshold for the CP beam was higher than that for the LP beam; when NA < 0.4, the threshold for CP was lower. Different damage processes at low and high NAs might lead to the reverse. Moreover, it was observed that the similar reverse occurred by changing the pulse duration of the writing beam.

2 Experimental setup and results

An amplified Ti:sapphire laser that emitted 800 nm, 1 kHz, 120 fs pulses was employed. Through an objective, the laser beam was focused 170 μm beneath the surface of a polished silica glass plate to minimize the spherical aberration. With the help of a 3D translation stage, we moved the samples perpendicular to the incident beam to fabricate a series of 1 mm long lines at a speed of 50 μm/s. The energy of incident pulses was continuously changed by a combination of a half-wave plate and a Glan-prism. When the incident energy was varied from low to high, the written lines became brighter due to the enhancement of the refractive index change. At a certain damage threshold, visibly damaged spots appeared in the trace of the lines. At much higher energy, only damaged lines were observed.

In the tight focusing case (NA $= 0.5$), the damage threshold energy was 125 nJ for the CP beam, a bit higher than 113 nJ for the LP beam. To further investigate the threshold difference, we fabricated 1 cm long waveguides at 117 nJ with CP and LP beams, respectively. Figure 1a and b show the cross-sections of waveguides written by CP beams and LP beams, respectively. Some damaged regions were found in Fig. 1b as indicated by the arrow. This difference in the bulk threshold intensity for the CP beam and LP beam was also observed for the surface damage [1, 2].

In the case of loose focusing (NA $= 0.25$), the threshold for the CP beam was 385 nJ, lower than 455 nJ for the LP beam. The result was contrary to the case of NA $= 0.5$, where the threshold for the CP beam was higher. At a pulse energy of 400 nJ, serious damage was found in the waveguide fabricated by the CP beam as shown in Fig. 1c. No damage tracks were observed for the LP beam as shown in Fig. 1d.

The above experimental results indicated clearly that the bulk damage thresholds were dependent on both the polarization and the NA of the focusing objective. The influence of the NA was investigated by measuring the damage thresholds with different effective NAs: 0.218, 0.25, 0.3, 0.4, 0.5, 0.65, as shown in Fig. 2. The curves for the CP and LP beams intersected at NA $= 0.4$. With lower NA, the damage threshold for the LP beam was higher than that for the CP beam; with higher NA, the damage threshold for the LP beam was slightly

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✉ Fax: +86-10-62756567, E-mail: li@pku.edu.cn
✉ Fax: +86-10-62765884, E-mail: qhgong@pku.edu.cn

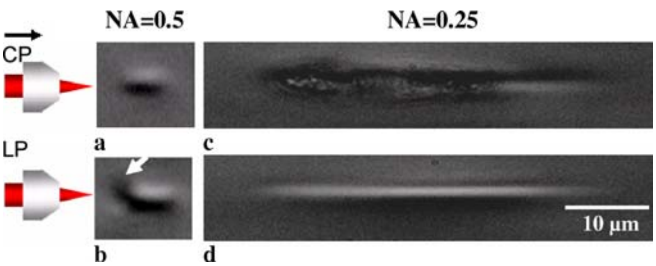

FIGURE 1 The cross-sections of waveguides written by focused laser pulses. The pulse duration is 120 fs. (**a**) CP beam, 117 nJ, NA = 0.5; (**b**) LP beam, 117 nJ, NA = 0.5; (**c**) CP beam, 400 nJ, NA = 0.25; (**d**) LP beam, 400 nJ, NA = 0.25

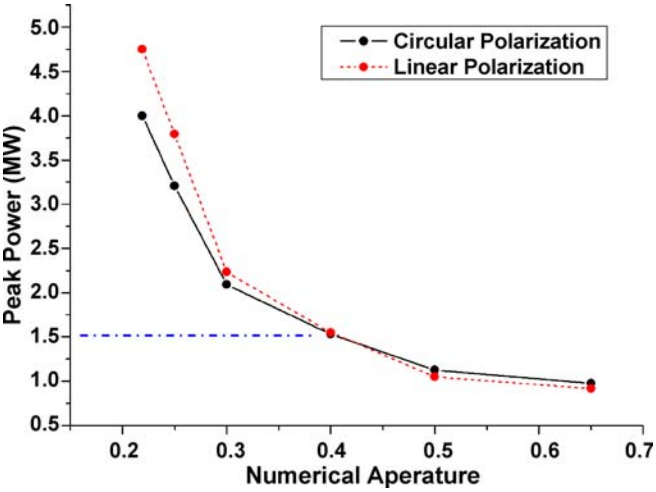

FIGURE 2 The dependence of the threshold peak power on NA for CP and LP beams. The pulse duration is 120 fs. The threshold at the intersection point (∼ 1.5 MW) was close to the self-focusing critical peak power P_{cr}

lower. The peak power of the intersection point (∼ 1.5 MW) was close to the self-focusing critical peak power P_{cr} [12, 13], which indicated that the strong self-focusing effect played an important role when NA < 0.4.

3 The mechanism of the damage threshold reverse

The damage processes for LP and CP beams are different due to the emergence of self-focusing effects. There are two kinds of damage mechanisms for the interaction of a femtosecond laser with transparent materials: laser induced breakdown (LIB) by external-focusing and the internal self-focusing induced breakdown (SFB) [14, 15]. When the damage threshold $P_{\text{th}} < P_{\text{cr}}$, the damage of fused silica was caused by LIB. When $P_{\text{th}} > P_{\text{cr}}$, the damage was mainly caused by SFB.

For tight focusing cases, the beam converges rapidly. The damage threshold can be reached when the incident power is lower than P_{cr}. The schematic is shown in Fig. 3a [16]. The plasma is mainly induced by multi-photon ionization (MPI), which is regarded as the dominant ionization mechanism for the fabrication in fused silica by using ultra-short laser pulses [17, 18]. It is easier for the LP beam to ionize more electrons than the CP beam at the same incident pulse energy because the cross-section of 6-photon ionization is higher for the LP beam [1]. Therefore, the damage threshold for the LP beam is lower than that for the CP beam when NA > 0.4.

In the case of loose focusing as shown in Fig. 3b [16], the strong self-focusing is induced before the damage takes place. The third-order nonlinearity χ^3_{linear} is higher than χ^3_{circular} [19], so the plasma density is higher for the LP beam at the beginning of ionization due to the tighter focusing. The subsequently stronger defocusing by the produced electrons prevents the LP beam from converging into a smaller region. As a result, more power is needed to reach the damage plasma density in an expanded focal volume and the threshold is higher for the LP beam [20].

According to the above analysis, the reverse can be observed when the damage process is selected by changing other experimental parameters. The pulse duration has influence on the damage [21] that is an accumulative process in time. The longer the interaction time, the lower the P_{th}. At the same time, P_{cr} is not sensitive to the pulse duration. Consequently, LIB or SFB can be selected by changing the pulse duration to control the P_{th}.

For the high NA focusing cases, the reverse will occur if we compress the pulse duration. In the low NA focusing cases ($P_{\text{th}} > P_{\text{cr}}$ at 120 fs), when the P_{th} is reduced lower than P_{cr} by stretching the pulse, the reverse of polarization dependent damage threshold will be observed. We measured the changing of damage thresholds for the CP beam and LP beam at the effective NA of 0.218 as shown in Fig. 4. The pulse duration was stretched to 290 fs by adjusting the chirp gratings and measured by an autocorrelator. As expected, the reversion appeared at the pulse duration around 250 fs. With shorter pulses, the threshold intensity for the LP beam is higher than that for the CP beam due to the domination of SFB. With longer pulses, the damage threshold for the LP beam is slightly lower owing to the LIB.

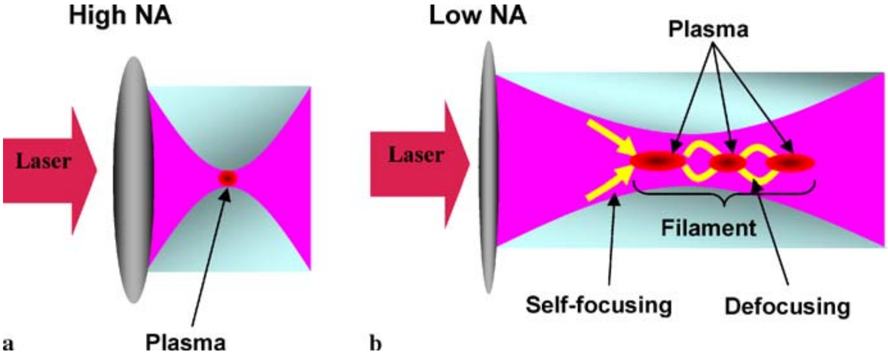

FIGURE 3 The schematics of the damage processes induced by (**a**) the external focusing and (**b**) the internal self-focusing

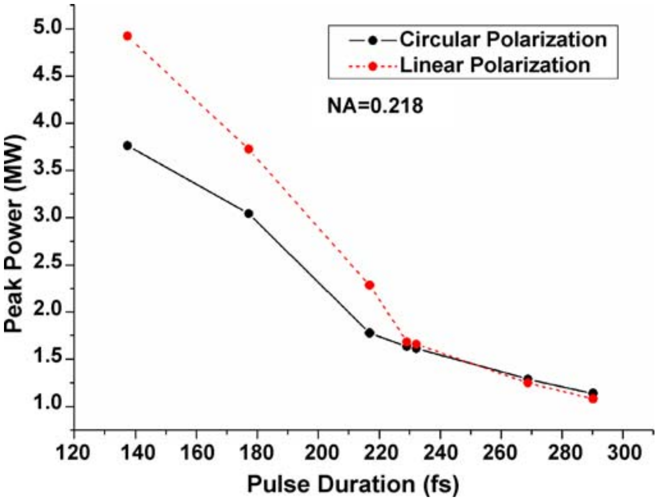

FIGURE 4 The relationship between damage threshold peak power and pulse duration with NA of 0.218

4 Conclusion

In summary, we studied the bulk damage threshold induced by linearly- and circularly-polarized femtosecond laser pulses inside fused silica, which was strongly dependent on the NA of the focusing objective. The damage threshold for the CP beam was higher than that for the LP beam when NA > 0.4, but the former was lower than the latter when NA < 0.4. The damage processes are reversed for LIB at high NA and SFB at low NA. We also observed a similar reverse process by changing the pulse duration to select the damage process.

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