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Damage characteristics of fused silica under low-temporal coherence light

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Abstract The damage characteristics of fused silica was investigated under low-temporal coherence light (LTCL). It was found that the laser-induced damage threshold (LIDT) of fused silica for the LTCL was lower than that of the single longitudinal mode (SLM) pulse laser, and for the LTCLs, the LIDTs decrease with the increasing of laser bandwidth, which is not consistent with the temporal spike intensity. This is due to the nonlinear self-focusing effect and multi-pulse accumulation effect. The specific reasons were analyzed based on the theoretical simulation and experimental study. The research work is helpful and of great significance for the construction of high-power LTCL devices.

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Key words: Low-temporal coherence light; Laser-induced damage threshold; Temporal spike; nonlinear-self focusing effect.

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I. Introduction

The successful "ignition" of laser inertial confinement fusion was marked by the achievement of a positive fusion energy output of 3.05 MJ at Livermore National Laboratory in the United States [1, 2]. The implementation conditions of inertial confinement fusion are very strict. In order to achieve the ignition condition, NIF has continuously increased the output capacity and the precision control level of the drive device, and the triplet-frequency fluence of the terminal components has almost reached their limitations [3]. To mitigate the negative effects of Laser Plasma Interaction (LPI) during ignition and further expand the ignition design space, the low-temporal coherence light (LTCL) has received extensive attention due to its instantaneous broadband characteristics [4]. The LTCL has a large bandwidth and its coherence time is much smaller than the pulse duration. Its spectral phases are randomly and uniformly distributed which are different from that of chirped pulses, conform to the statistical properties of the polarized thermal light. The LTCL could be considered as an accumulation of a series of pulses with the duration on the order of the coherence time [5]. Our team has built a high-power LTCL which delivering 1-kJ, adjustable ns-level pulses with a bandwidth of 15 nm [5-8]. The issue of laser-induced damage would also present a tremendous challenge to the application and development of the LTCL.

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There has been a lot of pioneering works on the mechanism of optical components under partially coherent light irradiation [9-15]. Smith and Do [13] studied the LIDT of fused silica bulk irradiation of multiple longitudinal mode (MLM) pulse at almost quarter of traditional single longitudinal mode (SLM) pulse, it is consistent with the relationship of the highest time spike intensity in MLM pulse with the intensity of SLM pulse. More recently, Diaz *et al*. [14] have investigated the laser-induced damage density on the fused silica surface produced by MLM pulse laser which is also higher than those produced by SLM pulse laser at 1064 nm, and the phenomenon is explained by the enhancement of the three-photon absorption due to the MLM temporal spikes. However, due to the characteristics of complex temporal structure for LTCL, the issue of laser-induced damage become more elusive and riskier, and the corresponding characteristics and mechanism have not been comprehensively researched yet.

In this letter, taking the fused silica bulks as test samples, we demonstrate the relationship between the LIDT and the temporal coherence of laser pulse. The key factors affecting the LIDT of the LTCL, including multi-pulse accumulation effect and self-focusing effect, are thoroughly analyzed through simulation and multiple experimental methods. The research work will be much helpful for improving the output power and energy of the LTCL drivers.

II. Experimental detail and test result

The light source could be switched from SLM pulse to the low-temporal coherence instantaneous broadband pulse, with a central wavelength at 1053 nm. The temporal coherence of the incident pulse could be adjusted by modifying the spectral width through the filter, and the spectral full widths at half-maximum (FWHM) are 3 nm, 10 nm and 15 nm, respectively, as shown as Fig. 1(a). In addition, each pulse has the same temporal waveform with a pulse duration of 3 ns

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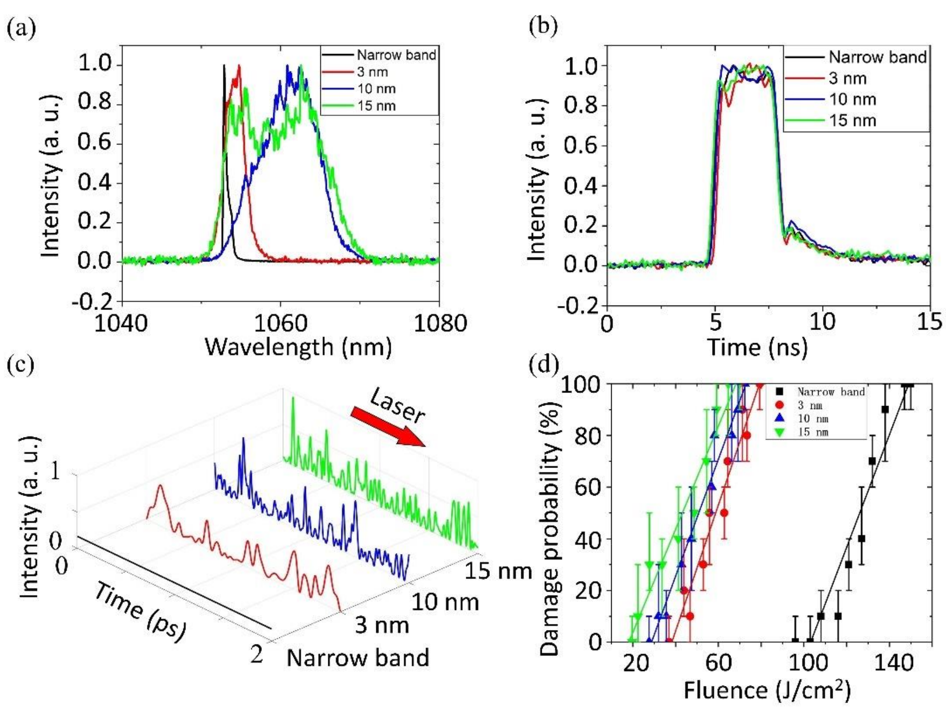
(full widths at half-maximum) (Fig. 1(b)). Since the LTCL has the property of random spectral phase distribution, its waveform has a random temporal spike structure. Figure 1(c) shows a simulation result of the randomly generated of the SLM pulse laser and the LTCLs with different bandwidths at 2 ps. For the temporal spiked structures, the widths of spikes are roughly 250 fs, 375 fs and 1.25 ps (obtained by theoretical calculations based on Fourier transforms of the spectra), corresponding to the bandwidth of 15 nm, 10 nm, and 3 nm, respectively. A fused silica bulk of 70 mm thickness is set as the test sample. Each incident laser has a Gaussian distributed circular beam spot with a diameter of 10 mm at $1/e^2$. The lens with a focal length of 500 mm was used for LIDT test, and the effective beam area is 0.0143 mm^2. The LIDT is obtained by the 1-on-1 test method with the same laser test number [16]. At last, the laser-induced damage of the fused silica bulks and corresponding time-resolved signal are recorded by the CCD camera, the InGaAs photodiodes labelled (Placed in the transmission direction of the sample, time resolution of 150 ps) and an oscilloscope with a bandwidth of 1 GHz and sampling rate of 5 GHz.



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Figures 1, The experimentally measured (a) spectrum, (b) temporal waveforms of each incident laser; (c) simulation of spike structures of different bandwidth; (d) the LIDT test results. The damage probabilities were obtained by 10 shots for one fluence step. The error bars were derived from the deviation in the damage probability at each incident fluence after five times LIDT tests.

The experimental results of the fused silica bulk LIDT under irradiation of different pulses are shown in Fig. 1(d). The LIDT of fused silica bulks of SLM pulse laser, 3-nm, 10-nm and 15-nm broadband pulse are 103.26 J/cm^2, 38.30 J/cm^2, 31.81 J/cm^2 and 18.38 J/cm^2, respectively. It can be clearly found that the LIDTs of fused silica bulks by the LTCL irradiation is lower than that of the SLM pulse laser, and it decreases with the increase of bandwidth for the LTCL. It should be noted that since the bandwidth of SLM pulse is much smaller than that of the LTCLs, the SLM pulse laser would have a greater Stimulated Brillouin Scattering (BSBS) [17], which also induces more energy loss and relatively higher LIDTs for the SLM pulse laser. Meanwhile, it could be observed that the damage probability fluctuation of the LTCLs of each bandwidth is larger than that of the SLM pulse laser. It caused by the fluctuation in the quantum starting noise for the different longitudinal modes (similar to the MLM pulse laser [13]), which would induce the temporal structure fluctuates of the LTCL from pulse to pulse, and ultimately induce a large fluctuation in the damage probability.

The LIDT test results mentioned above were obtained by placing the focal point at 35 mm from the input surface inside the fused silica. The position of the focal point inside the fused silica would influence the LIDT test results. The LIDT results of the focal points at 30 mm and 40 mm from the input surface are shown in Table. 1. It could be observed that for each incident laser, the LIDT decrease as the focal point moves further away from the input surface. It is due to the accumulative length of self-focusing during the laser transmission becomes longer, and the self-

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focusing effect may require less energy to collapse into the filamentation damage. It was worth noting that as the distance of the focal point from the input surface becomes longer, the LIDT of the LTCL decreases greater than that of the SLM pulse laser. It was mainly attributed to the stronger nonlinear self-focusing effect of the LTCL than that of the SLM pulse laser. This will be discussed in more detail below. Since the defect damage thresholds on the input and exit surfaces are much lower than that of the bulk damage, in order to avoid surface damage during the bulk damage test, the focal point was controlled near the center of the fused silica and does not continue to move towards the input and exit surface. However, it can also be demonstrated that the LIDT of the LTCL and the SLM pulse laser changes as the position of the focal point, but the overall relationship between each incident laser remains unchanged.

Table 1. The LIDT of each incident laser focus at different positions from the input surface

Focal position	LIDT (J/cm^2)			
	SLM pulse laser	LTCL-3 nm	LTCL-10 nm	LTCL-15 nm
30 mm	104.62	40.09	33.76	20.61
35 mm	103.26	38.30	31.81	18.38
40 mm	101.68	36.37	29.68	15.91

III. Discussions

There are two reasons for the relationship between the temporal coherence and the LIDT of fused silica. Firstly, the LTCLs have many temporal spiked structures, so the intensity is much higher than average intensity (as shown as Fig. 1(c)), and these spikes have a significant contribution to the LIDTs of the fused silica. Secondly, the enhanced self-focusing effect of the LTCL causes the decrease of the LIDTs of the fused silica.

The intensity probability distribution of the temporal spikes for these different bandwidths all satisfies the negative exponential distribution [8], and it means that the highest intensity of the

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temporal spikes is consistent for each different bandwidth pulses. As the relationship between the LIDTs of the MLM pulse and highest spike intensity reported by the pioneering group [13], the LIDTs should be the same for each bandwidth lasers and about 1/10 of the SLM pulse laser. However, in our experiments, the LIDTs of each LTCL did not drop dramatically like that, and the LIDTs of the fused silica varies with the bandwidth. It implies the intensity of temporal spikes is not directly correlated with LIDTs. The LIDTs of the LTCLs are not simply affected by spikes intensity exclusively, and there should be different physical mechanisms corresponding to different coherence light induced fused silica bulk damages.

The temporal spiked structures affect the LIDTs of fused silica through the accumulation effects by the irradiation of the LTCLs. These temporal spikes structures could be considered as a series of pulse trains, and the multi-pulse accumulation effect could reduce LIDTs [18] by laser-induced defects [19] and the band-gap [20]. According to the duration of the spikes and bandwidth are Fourier transform pairs, the wider bandwidth, the smaller duration of spikes, therefore, the number of the spikes would increase as the bandwidth increases at the same duration of the incident pulse. It means that the repetition frequency of spikes at the same pulse duration becomes higher. As a consequence, it caused the LIDTs of fused silica to drop more significantly [21]. This verifies the previous speculation on the reason for the multi-mode laser dropped the LIDT of SiO_2 [22].

Meanwhile, the difference in the self-focusing effect during the propagation in the fused silica of each beam also influences the LIDTs test results. In order to analyze the physical mechanism, the expression of the LTCL was established according to its instantaneous broadband and random phase distribution properties. Since the spectral intensity distribution and the temporal intensity signal are Fourier transform pairs, according to the relevant spectral parameter and the phase random distribution characteristics of the LTCL, the temporal signal of the LTCL can be

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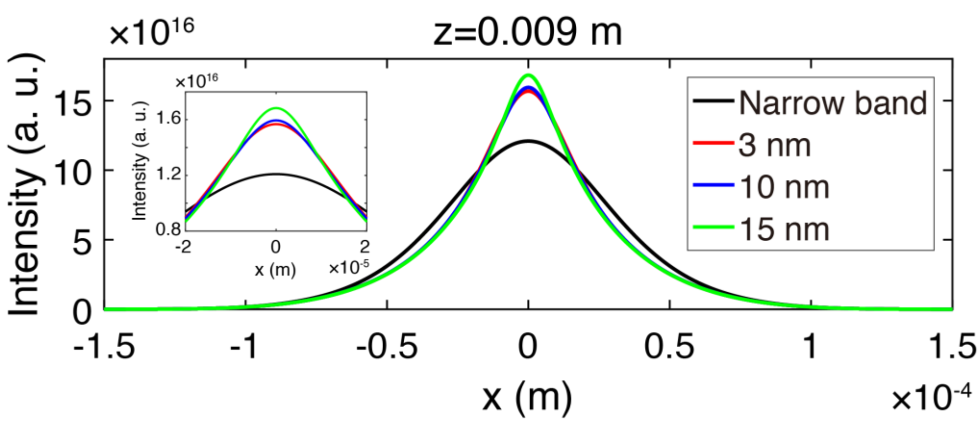
obtained by Fourier transform. Combining the nonlinear Schrödinger equation with the dispersion term (Eq. (1)) [23], the characteristics of self-focusing effect for each bandwidth could be distinguished clearly by Step-by-step Fourier algorithm.

$$2ik_0\frac{\partial A}{\partial z}+\nabla_\perp^2 A-k_0\beta_2\frac{\partial^2 A}{\partial t^2}+k_0^2\frac{n_2}{n_0}|A|^2A=0 \tag{1}$$

where, $k_0 = 2n_0\pi/\lambda$ is the propagation wave vector, n_0 is the linear index of refraction, and n_2 is the nonlinear index of refraction, λ is the central wavelength of incident pulse, β_2 is the group velocity dispersion coefficient and $\nabla_\perp^2 = \partial^2/\,\partial x^2 + \partial^2/\,\partial y^2$. t is in the frame moving at the group velocity. The second, third and fourth terms on the left side of Eq. (1) represent spatial diffraction, temporal dispersion and nonlinear effects, respectively. Fig. 2 shows the spatial energy distribution of each incident laser with the same parameters (incident energy: 2mJ; pules duration: 3 ns; focal point diameter: ϕ0.135 mm) transmitted at a distance of 0.009 m (the Rayleigh Length) obtained by simulation. The self-focusing effect of the LTCL is higher than that of traditional SLM laser under the same incidence parameters, and it becomes enhanced with the bandwidth increasing for the LTCL. The analysis agrees with the experiment result of LIDTs.



Figures 2, Simulation results of self-focusing effect for each bandwidth.

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In order to validate the analysis results, we conducted two experiments through different methods. Firstly, we applied closed aperture (CA) Z-scan to compare the self-focusing effect of each bandwidth lights, since the nonlinear phase variation under the nanosecond laser irradiation at fundamental frequency is too small for fused silica, a thick fused (5 mm) was chosen as the test sample, and two photodiodes were utilized to observe the variation of transmittance [24]. Figure 3 shows the experimental curves of CA Z-scan for the fused silica under the SLM laser and each different bandwidth of the LTCLs excitation. The experimental data are fitted according to Eq. (2) [27].

$$T(z) = 1 - \frac{4\Delta\phi_0(z/z_0)}{(1+z^2/z_0^2)+\left(9+z^2/z_0^2\right)} \quad (2)$$

where, $\Delta\phi_0 = k_0 n_2 I_0 L_{eff}$ is the phase change of the incident beam due to nonlinear refraction, I_0 , L_{eff} and z_0 are intensity at focus point, effective interaction length and Rayleigh diffraction length, respectively, z is the position of the test sample from the focus. According the relationship between the phase variation and the nonlinear self-focusing effect ($\Delta\phi_0 = k_0 n_2 I_0 L_{eff}$), it could be concluded that the larger nonlinear self-focusing effect (n_2), the more significant phase variation ($\Delta\phi_0$) under the same incident intensity (I_0). Meanwhile, based on the relationship between the peak-valley difference of the CA z-scan and the laser phase variation ($\Delta T_{P-V} \approx 0.406(1-S)^{0.25}|\Delta\phi|$, where S is the transmittance of the closed aperture), it could be found that the more significant phase variation ($\Delta\phi_0$) is, the bigger peak-valley difference (ΔT_{P-V}) under the same incident intensity (I_0), that is, the peak-valley difference (ΔT_{P-V}) would become larger as the self-focusing effect (n_2) was enhanced. Therefore, according to the CA z-scan test result (as shown in Fig. 3), the nonlinear self-focusing effect of the LTCL is stronger than that of the SLM pulse laser, and the nonlinear self-focusing effect increased with the wider bandwidth of the

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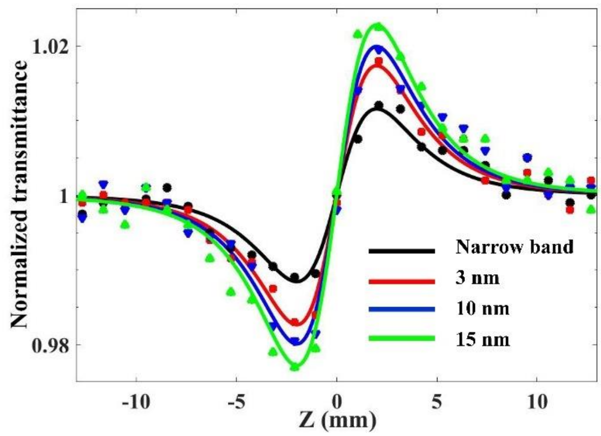
LTCLs. Under the same incident intensity conditions, the LTCL has a stronger self-focusing effect and more significant phase variation during the transmission, which produces a more serious self-focusing filamentation damage, ultimately makes its LIDT lower than that of the SLM pulse laser.



Figures 3, The result of Z-scan of the SLM laser and the LTCLs with each bandwidth. The curves are the simulation results, and the dots are corresponding experimental results.

Furthermore, to analyze the effect of bandwidth on the damage, we measured the laser-induced damage transient processes by time-resolved method. The temporal waveform variation of the fused silica damage process was recorded by an InGaAs photodiode (D2) in the transmittance direction. The experimental results are presented in Fig. 4. There are two temporal waveform variations of the laser-induced damage process. Previously, Shen *et al*. [25] have clearly obtained the process of the filamentary damage by pump-probe technique, and interpreted with the moving breakdown model. The filamentary damage of fused silica has two characteristic morphologies. The filamentary tail caused by the self-focusing effect occurs at the first time. Next, the head damage was formed by energy accumulation. These damage processes could also be obtained by the time-resolved method of transmitted light (as shown in Fig. 4 (a)). In the process of laser fluence absorption by the fused silica, when the laser phase change induces the self-focusing filamentation damage, then the laser energy will induce a rapid decrease in the

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transmission signal by a huge absorption and scattering due to the damage, which is recorded by the photodiode in the transmission direction (transmission signal) as the damage time (t_{d}) [29]. Then, as the filamentation damage absorbs the laser energy, it develops towards the input surface, and eventually micro-explosion occurs at the filamentation head. At this time, a lot of laser energy is scattered, causing a small rise in the transmission signal (recorded by the InGaAs photodiode (D2)). The micro-explosion produces a large head damage, resulting in absorption and scattering of the subsequent pulse. It leads to a second drop in the transmission signal after a small rise until the end of the pulse. Due to the damage in the nanosecond regime is intrinsically stochastic, the test results in Fig. 4(b) are the closest to the average of results obtained by each incident laser irradiation with the same fluence (156.73 J/cm^2) for 10 times. According to the damage time (t_{d}), the incubation fluence (F_{d}) filamentation damage for each incident laser could be calculated as:

$$F_d = \mathrm{I} * \int_{-\infty}^{t_d} f(t)dt. \tag{3}$$

Here, I is the incident peak intensity; t_{d} is the time of laser-induced damage, $f(t)$ represents a function of the temporal waveform (these incident lasers are all flat-topped square wave with a pulse width of 3 ns, so $f(t)$ is a rectangular function.). The total fluence could be expressed as $F_{\mathrm{tot}} = F_{\mathrm{d}} + F_{\mathrm{exp}}$ [28], where F_{exp} is the expansion fluence after the damage occurs (t_{d}) to the end of pulse. It could be observed that under the same incident fluence condition (156.73 J/cm^2), the damage times (t_{d}) are 1.20 ns (narrow band), 0.77 ns (3 nm), 0.54 ns (10 nm) and 0.33 ns (15 nm), respectively. The damage of the LTCL occurs before the SLM pulse laser under the same incident fluence. According to the Eq. (3), it can be concluded that the F_{d} of the LTCL is smaller than that of the SLM pulse laser, and for the LTCL, F_{d} decreases with increasing the bandwidth. The relationship between the F_{d} for each laser is consistent with the simulated beam evolution of

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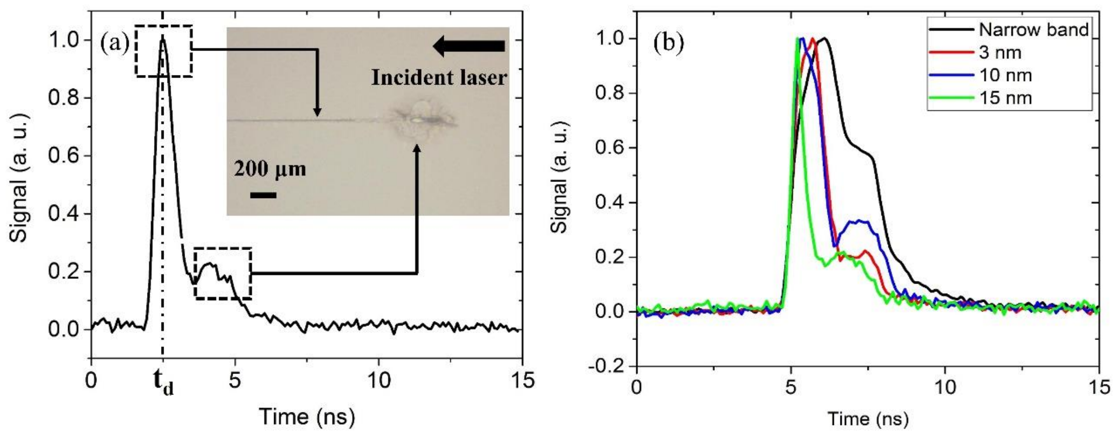
transmission process as mentioned above, that is the self-focusing effect of the LTCL is stronger than that of the SLM pulse laser, which made the LTCL induces a rapid phase evolution and forming the filamentation damage quickly with a low F_{d}, and for the LTCL, the broader bandwidth, the faster nonlinear self-focusing evolution process and the lower F_{d}. It was worth noticed that since each laser-induced damage is at the rising edge of the temporal waveform, after the normalization, the rising edge of the pulse with smaller t_d and earlier decrease would appear steeper.



Figures 4, The results of transmission signal variation by time-resolved test method: (a) Schematic diagram of the filamentary damage; (b) the test result of the SLM laser and the LTCLs with each bandwidth.

There are two reasons why self-focusing effect of the LTCL is stronger than that of the SLM laser. First of all, the LTCLs increased the self-focusing effects due to their own properties of temporal spikes and phase-random distribution, etc. Due to the Kerr effect, a nonlinear refractive index was induced during the interaction of the intense laser with the fused silica, therefore, the material's integral refractive index consists of both linear and nonlinear components:

$$n = n_0 + \Delta n = n_0 + I \times n_2 \tag{4}$$

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Where n is the integral refractive index of the fused silica, n_0 is the linear refractive index, Δn is the refractive index variation induced by the nonlinear effect, and n_2 is the nonlinear refractive index. Since the LTCLs are composed of a large number of ultrashort pulses of high intensity, it induces a larger overall nonlinear effect than the SLM pulse laser, which results in a larger phase variation during the transmission of the incident laser, eventually inducing a stronger self-focusing effect. Secondly, the accumulation effect of multiple pulses caused by the spikes structure would also change the nonlinear self-focusing effect of the fused silica [26].

The damage morphologies of fused silica also reveal the physical mechanisms of laser-induced damage for each incident laser (as shown in Fig. 5.). There is also randomness in the damage morphology for nanosecond laser, thus the experimental results show the closest to the average damage size with the same incident fluence for 10 times. The LTCLs have a shorter L length (where the distance from the input surface to the head of damage) in the direction of beam propagation (horizontal direction in the pictures) than that of the SLM laser at the same incident intensity (I=57.86 GW/cm^2). The self-focusing filamentation damage consist of the filamentation and micro-explosion damage at the head. The filamentation damage occurs firstly due to the self-focusing effect, and then the filamentation damage prevents most of the laser energy from continuing forward. The laser energy accumulates at the head of the filamentation, which eventually induces the micro-explosion of the head [25]. Micro-explosions are formed by the laser transmitted over a certain distance, where the accumulated phase variation causes the pulse to undergo self-focusing filamentation damage, which is ultimately induced by energy accumulation. Therefore, the position of micro-explosion is mainly determined by the self-focusing effect of incident laser. Under the same incident intensity, the stronger self-focusing effect, the greater phase variation of incident laser, the shorter distance required for self-focusing into the

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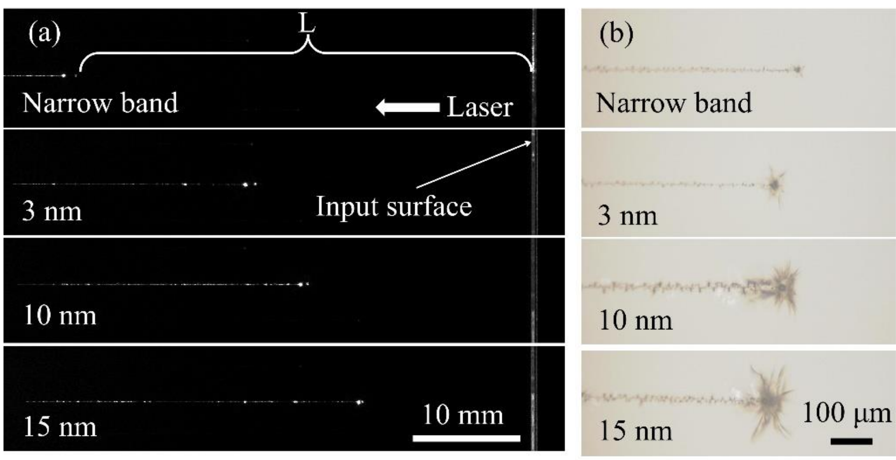
filamentation damage, ultimately induced the micro-explosion of head closer to the input surface. Therefore, as shown in Fig. 5, under the same incident intensity (I=57.86 GW/cm^2), the LTCL with stronger self-focusing effect induced the micro-explosion position of filamentation damage would be closer to the input surface than that of the SLM pulse laser. For the LTCL, the larger bandwidth, the closer micro-explosion position to the input surface. For the LTCLs, the explosion size of the damage head (vertical direction in Fig 5(b)) increased with bandwidth increasing, since the expansion fluence (F_{exp}) was increased with bandwidth according to the relationship between the F_{d} and the F_{exp} as mention above.



Figures 5, The damage morphologies of the fused silica for each incident laser: (a) Integral filamentation damage captured by CCD camera; (b) Head damage morphologies of filamentation damage captured by microscope.

Although, the LIDT of the LTCL is lower than that of the SLM pulse laser, the spatial mode of LTCL is single and will constant a well spatial coherence in the propagation. It is beneficial to the amplification and propagation, avoiding the divergence problem of spatial multimode laser. To eliminate the crossbeam scattering, the beam smoothing methods such as induced spatial incoherence (ISI) and continuous phase plate (CPP) are used. It induces the low-

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temporal coherence into space and achieves a good beam smoothing effect. Moreover, recently experiment results also confirm that low-coherence light has a significant effect on suppressing LPI processes [30]. Therefore, the research on the LTCL-induced optical components damage would be an important contribution to the development of the laser inertial confinement fusion.

IV. Conclusion

In conclusion, the LIDTs of the LTCLs with different bandwidth have been measured, and the correlation with traditional SLM laser are analyzed. The results reported in this work indicate that the LIDTs of the LTCLs are lower than that of the SLM laser, and decreasing with the broader bandwidth. The physical mechanism is analyzed and it is mainly caused by the nonlinear self-focusing effect and accumulative effect associated with the spikes structure of the LTCL simultaneously. An analytical model based on the physical properties of the LTCL has been established, and combined with the nonlinear Schrödinger equation the nonlinear self-focusing effect of the LTCL is analyzed. It shows that the broader bandwidth, the stronger nonlinear self-focusing effect for the LTCLs. The theoretical simulation was verified by CA z-scan and time-resolved test methods, and the experimental results are all verified that LTCL has a stronger self-focusing effect, and the wider bandwidth, the stronger self-focusing effect. These investigations will provide reliable boundary conditions for the application of the LTCL device, and provide a basis for the design of the high-power LTCL devices.

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