The study of nanojoule femtosecond laser ablation on organic glass

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The Ti:sapphire oscillator is used to realize structural change in an organic glass (polymethyl -methacrylate (PMMA)). Single pulse fluence threshold of PMMA and the relation of the breakdown threshold with different numerical aperture objectives are determined using a formula deduced from an existent equation. Three-dimensional dots in the organic glass is performed at the same time.

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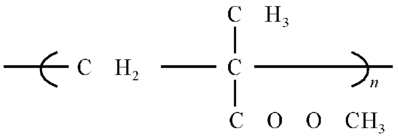
With the development of multimedia and information technology, the requirement of data storage is increasing rapidly. Three-dimensional (3-D) optical data storage offers the potential for large recording capacity. More and more researchers have been interested in pointlike or bitwise binary 3-D optical storage[1−3].

Glass can be easily processed into models with all kinds of size and form, thus becoming the main material for data storage study and 3-D optical elements fabrication[1−6]. Glezer *et al.* performed pioneering experiments by using femtosecond (fs) laser induced damage to record information inside fused silica in 1996[1]. Fused silica has a recording density limit of $\sim 10^{13}$ bits/cm^3 with an objective of numerical aperture (NA) of 0.65 in theory, using the amplified Ti:sapphire laser[1]. Now, the data storage capacity has reached $\sim 10^{11}$ bits/cm^3 and 3-D optical waveguides in glass have been fabricated[4−6].

In this paper, a method was used to determine single pulse fluence threshold for ablation on an organic glass (PMMA, Fig. 1) by using fs laser pulse. The fs laser pulses were obtained directly from an oscillator. It delivered 83 MHz fs laser pulses with a wavelength centered at 800 nm and the single pulse energy could be continuously tuned from 0 to 15 nJ with a series of neutral density step attenuators[7]. Objective lenses with different NA (0.25, 0.4, 0.65, and 1.25) were used to focus the fs laser into organic glass. A part of the backscattered light was imaged on a CCD camera, with which we could determine damage occurred or not by observing the intensity of the light in the focal region. A step motor-driven and computer-controlled $X-Y-Z$ table was used to move the sample in three directions with a resolution of 0.5μm. All the results were measured by a Hirox 3-D microscope system, which could amplify images within a continuous range of 350× to 7000×. Figure 2 is the experimental setup.

The main advantage of the fs laser ablation is that it has a definite threshold. If the laser pulse fluence was controlled very close to the ablation threshold, the ablation diameter can be smaller than the focal scale[8]. The fs laser oscillator had a high repetition, so in order to determine the organic glass damage fluence threshold, we changed the laser energy but kept the irradiation duration constant and inspected the focal region with CCD. In this experiment, we chose one second as the irradiation duration.

Figures 3 and 4 show the results when the average laser



$$\left(CH_2 - \underset{COOCH_3}{\overset{CH_3}{C}} \right)_n$$

Fig. 1. Monomers of PMMA.

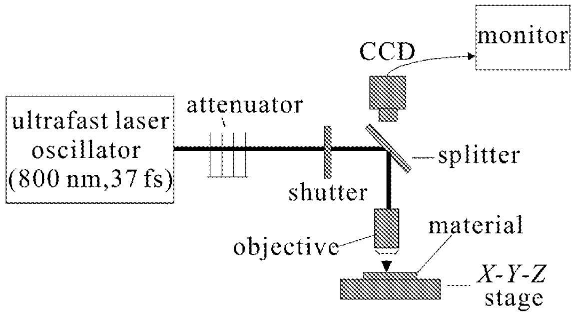


Fig. 2. The experimental set up.

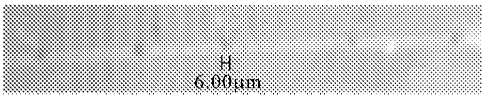


Fig. 3. The dots ablated by 37-fs laser pulses with single pulse energy of 1.2 nJ, 1.25-NA objective in the PMMA.

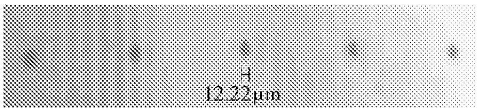


Fig. 4. The dots ablated by 37-fs laser pulses with single pulse energy of 2.87 nJ, 0.65-NA in the PMMA.

powers are 100 and 238 mW, respectively. The radius of the ablated dots is about 3 μm when NA=1.25 and 6.1 μm when NA=0.65.

When the incident pulse is a Gaussian wave, the far field focal equation is

$$\omega = \frac{4\lambda f}{\pi \omega_0}, \tag{1}$$

where f is the objective focal length; λ is the central wavelength of laser; ω is the radius of the beam waist at the focal plane; ω_0 is the beam waist radius of the incident light. In the experiment, the beam waist radius is 1.5 mm and the focal lengths are 4.51 and 1.9 mm for the objective of 0.65-NA and 1.25-NA, respectively. From Eq. (1), $\omega = 3.06$ and 1.29 μm for the 0.65-NA and 1.25-NA objectives can be calculated, respectively. This is the reason why the ablated dot diameter for an objective of 0.65-NA is almost double of that of a 1.25-NA objective, as shown in Figs. 3 and 4, if we assume the thermal transmission in the material is isotropic.

When the material, the pulse width and focal lens are fixed, the damage threshold is also fixed. The relation of the ablated dot diameter with the incident fluence is confirmed by S. Baudach[9]. The following equation can be deduced from that relation,

$$\phi_{\text{th}}(N) = \phi_0 / \exp\left(\frac{D^2}{2\omega^2}\right), \tag{2}$$

where $\phi_0 = \frac{2E_{\text{pulse}}}{\pi\omega^2}$ is the incident light fluence and $\phi_{\text{th}}(N)$ is the damage threshold for N pulses.

So it is possible to determine the damage threshold by measuring the diameters of the ablated areas D and the incident light fluence ϕ_0.

In the case of a high repetition rate oscillator, we must take into account the incubation effect[10]

$$\phi_{\text{th}}(N) = \phi_{\text{th}}(1) N^{\xi - 1}, \tag{3}$$

the value ξ indicates the degree of incubation. $\xi = 1$ means that no incubation effect is observable. For organic glass, ξ is 0.67[9]. Using Eqs. (2) and (3), the fluence threshold of single pulses can be determined. The relation of the single pulse fluence threshold with NA is shown in Fig. 5. The dots are the calculated results.

With a higher NA, the fluence threshold decreases quickly. But the fluence thresholds are only several or tens of mJ/cm^2, while it is 2.6 J/cm^2 by using 150-fs laser pulse[9]. The main reason is that laser duration in this experiment is much shorter. And the component of the PMMA is different, because they are not produced by the same manufacturer, the fluence threshold may be different. Reference [5] gives the relation of energy threshold of silica with NA. Although the fluence is related with the focal area, Fig. 5 also shows a similiar trend with the curve in Ref. [5].

Figures 6 – 8 show the 3-D dot arrays ablated with a 0.65-NA objective and 2.87-nJ pulses. The depths of the two layers of dots are 0.224 and 0.44 mm under the organic glass surface, respectively. We are designing an equipment to control the ablation duration precisely, so much smaller ablation diameters and much higher storage capacity will be got in the near future.

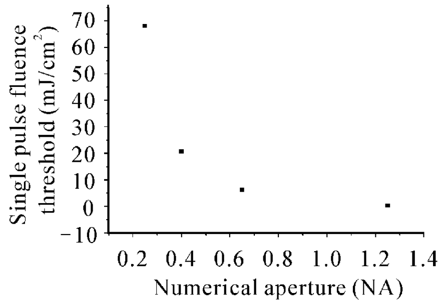


Fig. 5. Dependence of single pulse fluence threshold on the NA of the focal objectives for 37-fs laser pulses in organic glass.

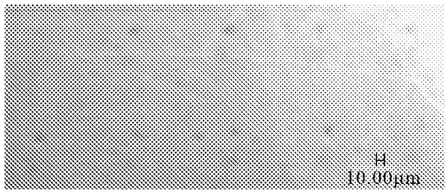


Fig. 6. The first dot array ablated by 37-fs laser with single pulse energy of 2.87 nJ, 0.65-NA objective in the PMMA.

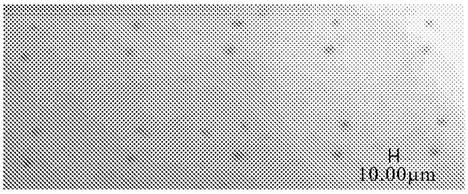


Fig. 7. The middle process is changed from the first to the second dot array ablated by 37-fs laser with single pulse energy of 2.87 nJ, 0.65-NA objective in the PMMA.

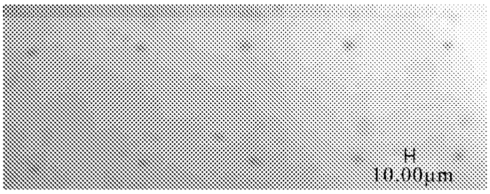


Fig. 8. The second dot array ablated by 37-fs laser with single pulse energy of 2.87 nJ, 0.65-NA objective in the PMMA.

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