Thermal character in organic polymers with nanojoule femtosecond laser ablation

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Ablation experiments with femtosecond (fs) laser pulse (pulse duration 37 fs, wavelength 800 nm) on organic polymers have been performed in air. The ablation threshold is found to be only several nanojoules. The diameters of the dots ablated in the organic polymers are influenced by the laser fluence and the number of laser pulses. It is observed that heat is diffused in a threadlike manner in all directions around the central focus region.Explanations of the observed phenomena are presented. A one-dimensional waveguide is also ablated in the organic polymers.

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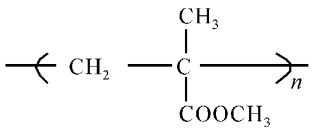
Polymeric micro-structures or nano-structures have important applications potentially in making useful integrated optic systems. Many nonlinear optical polymers offer the potential of high-speed response, great sensitivity, and low-cost processing for use in advanced optoelectronic systems[1]. Organic polymers have many advantages over their inorganic counterparts because they are easy to process and can be applied to any substrate, promising direct integration with electronic ICs in single hybrid optoelectronic packages.

High power femtosecond (fs) laser can be applied to micromachining in most transparent materials[2−4]. But the fs laser amplification system has some disadvantages, such as complex equipment and difficult management[5].

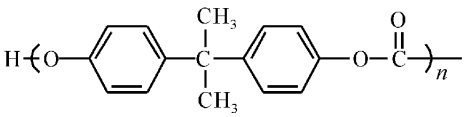
In this experiment, we used the fs laser from an oscillator directly to ablate the organic polymers. The oscillator delivered fs laser pulses with a high repetition rate of 83 MHz and the single pulse energy could be continuously tuned from 0 to 15 nJ with a neutral density step attenuator[6]. An objective with numerical aperture (NA) of 0.65 was used to focus the fs laser into organic polymers. A part of the backscattered light was imaged on a CCD camera. We could determine whether damage occurred or not by observing the intensity of the backscattered light, which would change a great deal when the focal region was damaged. The step motor driven and computer controlled X-Y-Z stage with a resolution of 0.5 μm was used to move the sample in three directions. All the results were measured by a Hirox 3D microscope system, which could magnify the image within a continuous rang from 350× to 7000×. The organic polymers used in the experiment are polycarbonate (PC) and polymethyl-methacrylate (PMMA) with the same thickness (3 mm). Figure 1 shows the monomers of PC and PMMA, and Fig. 2 shows the experiment setup.

The fs laser oscillator had a high repetition rate, whose effect was like that of a CW laser in average. In order to determine the damage fluence threshold of the organic polymers, we changed the laser fluence and inspected the focal region using the CCD camera at the same time. In this experiment, we also chose one second as the experiment duration[5]. With this method, we obtained the fluence thresholds: 1.12 and 6.23 mJ/cm^2 for PC and PMMA respectively. We set the fs laser fluence around the threshold value and changed the experiment duration to observe the thermal character. The incubation effect of the organic polymers could be seen clearly at the same time.

Figures 3 and 4 show the ablated dots in the PC and PMMA when the single pulse energy is 3.01 and 2.87 nJ respectively. Because the damage fluence threshold of



PMMA



PC

Fig. 1. Monomers of organic polymers.

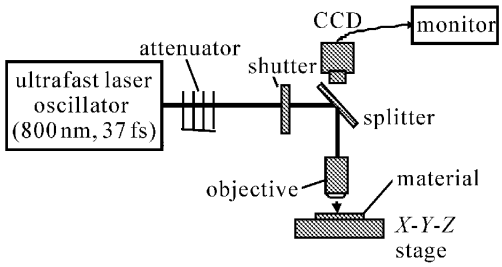


Fig. 2. The experiment setup.

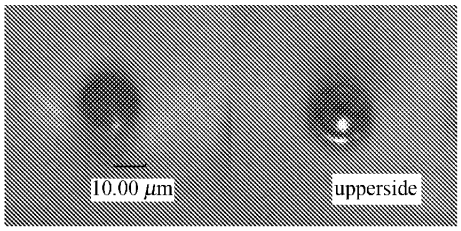


Fig. 3. The ablated dots are 0.6mm under the PC surface (single pulse energy: 3.01 nJ, ablation time: 1 s).

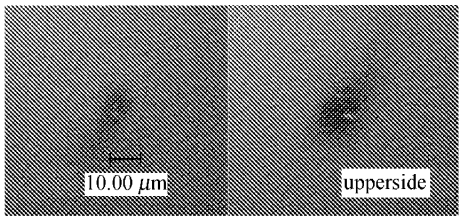


Fig. 4. The ablated dots are 0.6 mm under the PMMA surface (single pulse energy: 2.87 nJ, ablation time: 1 s).

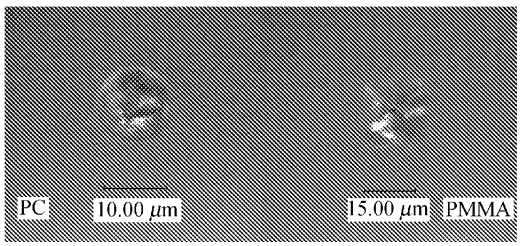


Fig. 5. The ablated dots were imaged from the surface of the organic polymers (single pulse energy: PC 4.61 nJ, PMMA 3.51 nJ, ablation time: 1 s).

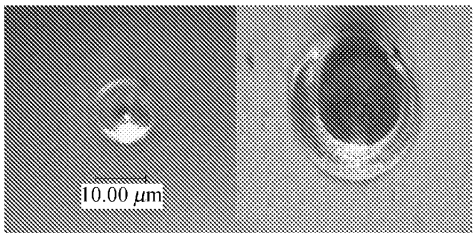


Fig. 6. The dots were ablated inner the PC, and the right is the image amplified two times of the left (single pulse energy 4.62 nJ, ablation time: 1 s).

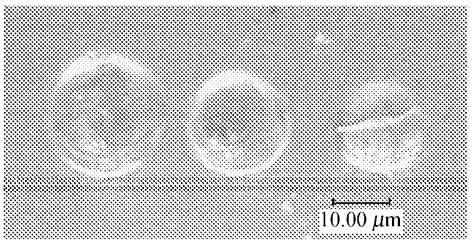


Fig. 7. The dots were ablated at 0.4 mm depth of PMMA with bondbreaking obviously (single pulse energy: 2.43 nJ, ablation time is: 3, 5, 10 s from right to left, respectively).

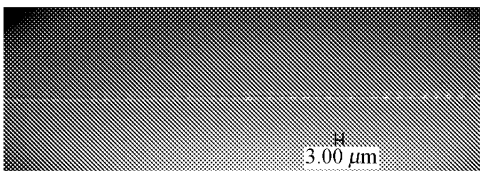


Fig. 8. Part of one dimension waveguide in PC material (pulse energy: 5 nJ, processing speed: 0.5 mm/s).

PC is smaller than that of PMMA, the ablation diameter in PC is larger than that in PMMA. When we imaged the upside of the dots, we found that there was a little hole in the center of the images (the right images in Figs. 3 and 4). If we increased the energy of the laser pulses, the hole above the focal center would become lager and debris would occur around it, which looked like something ejecting from the inside. Figure 5 shows the images from the surface of the organic materials.

This can be interpreted in terms of polymer fractionation by CO−O bondbreaking, and the formation of the gaseous products (e.g., CO_2) takes place[2]. In the direction of laser incidence, the material is heated and become softer than in the other directions, so the gas ejects upwards. With the laser fluence rising, the gaseous products are also increasing, which leads to a localized bursting of the surface and ejection of the melt (Fig. 5).

If we focused the laser on the surface, only the crystal lattice fraction occurred (just like the results of Ref. [2]). The gaseous production might escape directly into the air. To see the thermal diffusion, we magnified the photograph of the dots in the materials. Figure 6 shows the results of PC. Figure 7 is the images on the surface of PMMA with different duration times.

From Fig. 6, we can see that there are some threads from the center to the boundary. When the fs laser is focused into the organic materials, the energy is injected with high speed. We assume that the injected energy is lower than the product of the heat capacity and the volume of focal region, so the heat is diffused by the material from the focal region in all directions, and the threads may be the reflection to that progress. In the opposite case, which also means that the speed of the energy injection is faster than the speed of the heat conduction, the dark damaged region will occur. But the threads also can be found at the boundary in the later experiments. Figure 7 shows the incubation effect and the escaping process of the gaseous production. From Figs. 1 − 7, we also can find that the damaged region of PC is darker than that of PMMA. This can be explained by the fact that the content of carbon in the monomers (Fig. 1) of PC is larger than that of PMMA.

So if we want to micromachine some optical elements (e.g. splitter) in the organic polymers, we must control the fs laser pulse energy accurately to avoid the dark region occurring.

We have already realized 3D data storage in PMMA[5]. Figure 8 is a 1D waveguide which is about 0.4 mm under the PC surface and 2 mm long. Two- and three-dimension waveguides in the organic polymers are under study. Based on the gaseous production in the ablated organic polymers, the hollow waveguide could be produced by controlling the laser pulse energy accurately, and this work is being conducted in our lab.

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