Femtosecond laser fabrication of linear graphitized microstructures in a bulk of polycarbonate samples

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Abstract. We have fabricated high aspect ratio straight and curved graphitized lines inside of polycarbonate samples by using a femtosecond laser. Use of a spherical lens with high NA to focusing femtosecond pulse in the bulk of material leads to self-diffraction of laser beam and formation a filamentary structure. We fabricated two kinds of graphitized lines. The first type is a straight line extended in the direction of the laser beam. This type of lines was created by femtosecond laser scanning without pulse overlapping. The second type of graphitized lines is curved lines, which was created by scanning with a significant overlapping of focal spot. We determined conditions of the formation of straight graphitized lines by one femtosecond pulse with diameter about 2 μm and length greater than 1 mm in polycarbonate samples. Mechanism of formation and potential applications of these structures are also discussed.

1. Introduction

Laser fabrication with high-energy femtosecond (fs) lasers has great advantages such as highest precision of micromachining, absence of heat affected zone, ability of 3D intra volume direct writing without surface damage, so femtosecond laser has become a powerful tool for fabrication of embedded optical, fluid and electrical components inside transparent materials. When a femtosecond pulse is tightly focused in the bulk of material, it will lead to nonlinear absorption and produce micro scale modification within the focal volume [1]. The structural modification inside of material can be different. The articles [2, 3, 4, 5] reported about voids, cracks, refractive index changes, graphitization and birefringent structures [6].

The shape of femtosecond laser induced structures can be strongly extended in direction of pulse propagation due to spherical aberration, nonlinear effects or their combination. The length of modification depends on the focusing depth of laser pulse, pulse peak power and focusing system. In our time, in most cases, the microchannels in the bulk of material are formed by transverse or longitudinal femtosecond laser scanning with a significant overlap of focus spots. But we assume that using nonlinear effects (Kerr self-focusing) or a special focusing system such as axicon or a lens with strong spherical aberration you can create linear microchannels with great lengths.

In this paper, we demonstrate high-aspect ratio microstructure fabrication by focusing of high energy femtosecond laser pulse with highly aberrated spherical lens. In experiments, we achieved straight and curved graphitized lines inside polycarbonate samples with total length more than 1 mm.
Straight graphitized line with diameter about 2 μm and length 1 mm in the bulk of polycarbonate can be fabricated by one femtosecond pulse.

2. Scheme of experimental setup
Experimental setup is shown on figure 1. The polycarbonate (PC) sample was cut in a plate form of 50mmx20mmx3mm and four-surface polished. We used two femtosecond laser systems. First is Yb regenerative laser operating at the central wavelength of 1025 nm with pulse repetition rate of 2 kHz, pulse energy 150 μJ and pulse duration of 350 fs. Second laser system is Yb laser with central wavelength of 1030 nm, pulse duration about 300 fs and 26 μJ pulse energy at 80 kHz pulse repetition rate. To control the power and the pulse energy of the linear-polarized laser beam, we used a rotatable half-wave plate and thin film polarizer. Beam expander with 4x magnification was used to expand laser beam. We focused fs laser pulses by spherical lens (f=15 mm, clear aperture 22 mm). This lens has a strong spherical aberration. In experiments, we focused on bottom surface of sample. Sample was mounted on three-coordinate computer-controlled stage. Pictures of exposure of fs laser pulses were obtained using an optical microscope in transmitted light (Nikon LV100D).

![Figure 1. Scheme of experimental setup: (1) femtosecond laser beam; (2) beam expander; (3) focusing lens; (4) sample; (5) XYZ translation stage.](image)

3. Experiment

3.1 Beam intensity distribution conversion.
Tightly focused fs laser pulse can lead to various nonlinear phenomena due to very high intensity of radiation. The most typical phenomenon is the laser pulse filamentation. Filamentation of laser pulse can lead to long track formation inside transparent material, but not only by filamentation can be created these tracks. In our experiments, initial Gaussian laser beam intensity distribution was transformed into a set of Fresnel type diffraction rings after passing through the focusing lens. Figure 2 shows the intensity distribution of focused beam in four positions. Each intensity distribution is a set of Fresnel type diffraction rings. This picture was achieved at metalized film surface after ablation by 1000 fs pulses with pulse energy 60 μJ. It is seen that diffraction ring with highest diameter and set of merging diffraction rings in center of intensity distribution are most intense.

It is obvious that each diffraction ring has its own focus, so diffraction rings will focused at the different depths in the sample according figure 3.
3.2 Micromachining by fs laser pulses without focusing spots overlapping.
Experiments on micromachining polycarbonate samples confirmed our assumptions (figure 4). In this experiment have been used the first laser source. Femtosecond laser pulse generates a set of linear micromodifications in the sample volume. Modifications are located on the fs laser pulse propagation axis. In this case, we scanned a sample by fs laser pulses with no overlap of focus spots. The scanning speed was constant and equal to 800 μm/s. Figure 4 a) shows microstructures obtained at 15μJ pulse energy. It is seen that one fs laser pulse generates a set of four linear microstructures that are located on pulse propagation axis. Number of linear microstructures in set increases with increasing pulse energy up to 60 μJ (figure 4 b). It is also worth noting two trends. The first is increasing the length of each microstructure. The second is merging nearby linear modifications into one.
When the energy of the fs laser pulse reached 150 μJ linear modifications in the set are merged into one (figure 5). The total length of the modification in this case exceeds 2 mm.

**Figure 4.** Pictures of micromodifications inside PC sample. a) pulse energy - 15 μJ; b) pulse energy - 60 μJ. (1) direction of pulse propagation; (2) scanning direction. Scanning speed is 800 μm/s. Pulse repetition rate 100 Hz.

**Figure 5.** Picture of micromodifications inside PC sample. Pulse energy 150 μJ. (1) direction of pulse propagation; (2) scanning direction. Scanning speed is 800 μm/s. Pulse repetition rate 100 Hz.
3.3 *Micromachining by fs laser pulses with focusing spots overlapping.*

Scanning of material by powerful femtosecond laser in regime of generation one long cavity (figure 5) with focusing spot overlapping can be powerful tool for cutting. But in several cases it is impossible to obtain a uniform cut with good quality due to self-induced shift of the focusing spot towards the objective [7].

Figure 6 shows microstructures created in PC sample by fs laser pulse scanning with 50 percent overlap. In this case you can see curved lines produced inside the bulk of material in contrast to the expected continuous cutting. There are lines with different inclination relative to the direction of propagation of the pulses. We think that this phenomenon is caused by a gradual shift of focus towards the lens from pulse to pulse. In this experiment have been used the second laser source.

![Figure 6](image)

**Figure 6.** Picture of micromodifications inside PC sample. Pulse energy 26 μJ. (1) direction of pulse propagation; (2) scanning direction. Scanning speed is 40 μm/s. Pulse repetition rate 80 kHz. Pulse overlap 50%.

3.4 *Measurement of the electrical conductivity of the obtained microstructures.*

The blackening effect in the zone of the fs laser pulse impact in our view is evidence of material conversion to graphite-like form. A similar effect was observed in article [8]. The presence of graphite at the microstructure was confirmed by the results of electric conduction measurements in the layer of microscopic particles at the surface of the laser cut of the sample. The electric conduction of the layer is \( \sigma \approx 1.0 \text{ S/m}^{-1} \). It was estimated using the technique, analogous to [8].
4. Discussion of the results

Reasons for converting the Gaussian intensity distribution in the diffraction pattern at fs pulse passage through spherical lens may be different. In the first place it may be associated with the geometry of propagation of the beam through the lens. The second reason could be the non-linear interaction of powerful fs laser pulse with a lens material, analogous to [9]. This phenomenon requires additional research.

The formation of highly extended linear microstructures by focusing of fs laser pulses with a lens with strong spherical aberration may become a good tool in the production of high-aspect ratio microchannels and diffractive optics for various applications. Cutting of transparent materials by fs pulses in the long line generation mode is very promising method in terms of potential performance. However, as shown above, in some cases, it may not be applicable due to the effect of the self-induced displacement of the focus area.

The presence of the electrical conductivity of the obtained structures opens up opportunities for the creation of complex electro-optical devices in transparent materials.

5. Conclusions

Methods of producing of long length linear microstructures are presented. To create an extended microstructures were used a lens with strong spherical aberrations. In this case, the one femtosecond pulse generates a set of linear micromodifications in the bulk of material due to the conversion of a Gaussian beam into a set of diffraction rings. At energy of fs laser pulse about 150 μJ a set of linear micromodifications is combined into one line with a length of more than 2 mm.

Scanning of polycarbonate by fs laser pulses with 50% overlap of focusing spots leads to the formation of curved lines inside the material.

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