Nanofabrication with UV Femtosecond Fiber Laser

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ABSTRACT

In this paper, a UV femtosecond fiber laser direct writing is used for nanofabrication on different materials. The smallest line widths are found to be around 100 nm for both glass and polymer materials. It is found that the size of direct written features depends strongly upon pulse energy, as well as the relative position of the laser focal spot with respect to the material surface. Furthermore, periodic nano-structures are also fabricated on the surfaces and the periodic patterns extend coherently over many overlapping laser pulses and scanning tracks. Nano-periodic structures with 100 nm period and grooves with about 50 nm width and 50 nm depth were found. This UV fs fiber laser based technique is inherently simple, direct, highly-reproducible and material independent.

Keywords: Femtosecond laser, fiber laser, direct writing, nanofabrication, UV.

1 INTRODUCTION

In laser fabrication technologies, the minimum achievable structure size is determined by the diffraction limit and is on the order of the laser wavelength. However, this is different for femtosecond (fs) laser pulses since it has a unique feature of deterministic damage threshold due to the short pulse duration. When the pulse duration decreases below a picosecond, the damage threshold shifts from stochastic to deterministic. This highly non-linear dependence of optical breakdown on intensity allows the process to be limited to regions smaller than the spot size of the focused laser. So the laser pulse energy can be selected to let the peak fluence slightly above the threshold so that only the central part of the beam can modify the material and it becomes possible to produce sub-wavelength and nano structures [1-4].

Recently, methods of micro and nano-processing of materials by direct fs laser irradiation have aroused great interests in the field of laser processing and have become a powerful micro and nanofabrication technique for different applications [5-12]. Fs lasers can produce extremely fine features in almost any material without less or even no thermal damages to the surrounding material since the pulse duration is much shorter than the heat-diffusion time. Though numerous applications have been demonstrated using large and cumbersome solid state fs lasers systems [9, 11], these systems are complex and expensive compared with fiber lasers. Advances in laser technology have produced much more compact and reliable fs fiber lasers and this makes the industrial application of fs fiber laser possible.

In this paper, we present micro and nano-fabrication results of different materials using a UV fs fiber laser direct writing technique. Single line writing is used to generate ablation line features on the sample material surface. The ablation line widths can be around 100 nm for both glass and polymer materials. Furthermore, periodic structures are also fabricated on the surfaces scanning tracks. This simple fs fiber laser based direct writing technology shows great potential for two or three dimensional nanostructures fabrications.

2 METHODS & MATERIALS

2.1 Experimental Setup

The laser direct writing experimental setup is shown in Fig.1. The fs laser employed for direct writing is a commercialized mode-locked seed fiber laser (PolarOnyx, Inc. - Uranus Series, www.polaronyx.com), generating 750 fs pulses (FWHM) at 1030 nm wavelength with pulse repetition rate tunable between 1 Hz and 1 MHz with an acousto-optic modulator (AOM). The output collimated beam is a nearly symmetric Gaussian with $M^2<1.3$ and the maximum output pulse energy is 10 μJ. An attenuator is used to control the laser pulse energy for fabrication and a mechanical shutter is synchronized with the laser system. The total beam delivery loss is less than 20 percent. The fourth harmonic generation (FHG, 258 nm) is generated by nonlinear crystals placed at the focus of plano-convex lens. The FHG conversion efficiency of this set up was about 10%. The sample is mounted on a motorized 3D translation stage and the linear motion stage is controlled by computer to achieve different sample moving speeds. A CCD camera is used to obtain a live view for the laser direct writing. In the experiments, the laser beam was guided by mirrors and focused by an objective lens towards the sample.

The sample is written in transversal direction which is perpendicular to the laser incident direction. For each line scanning, it is scanned only once in the transverse direction (Y axis). After each line translation, a step of increase is

added for X axis so that fresh sample surface is ablated. More importantly, the focus position is also finely adjusted from out of focus to deep focus for the sample surface so that the part of the beam to modify the material is variable.

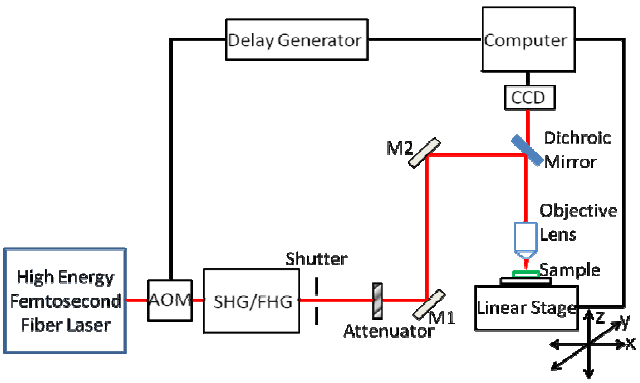

Figure 1: Experimental set up for fs fiber laser direct writing.

2.2 Materials

In this study, different types of materials with different band gaps (ablation thresholds) were choosen include polymers (PDMS & PMMA) and glasses (soda lime glass, Eagle XG glass & fused silica). Among these materials, fused silica has the highest band gap (~8 eV).

Both polymer and glass samples are pre-polished for the main surfaces with original dimensions of 20 mm x 20 mm x 2 mm and 25 mm x 25 mm x 9 mm, respectively. Before processing, each sample was carefully cleaned by isopropanol.

2.3 Microscopy & Measurements

After laser direct writing, the micro topography of the the laser written structures were checked by optical transmission microscopy (ME520T-9M). Then a scanning electron microscopy (SEM, FEI QUANTA FEG 600) was used to further characterize and measure the ablation line width and depth.

3 RESULTS

The size of direct written features depends strongly upon pulse energy, as well as the relative position of the laser focal spot with respect to the material surface. So different pulse energies, writing speeds and relative focal positions to the material surfaces were used for surface line direct writing. To systematically study the fs laser modification, the sample was scanned at speeds from 0.5 to 100 mm/s, pulse energies ranging from 100 nJ to 1 µJ, N.A. of 0.40 or 0.55 and 1 MHz repetition rate.

3.1 Microfabrication by Laser Direct Writing

At the beginning, the laser beam was focused deep onto the surface with features close to the focal spot size. Figure 2 shows the SEM image of surface linear direct writing of soda lime glass (scalar bar is 4 µm). The laser direct writing condicitions include 1030 nm wavelength, 0.65 µJ pulse energy and 1 mm/s writing speed. As shown in Fig.2, the ablation line width is about 1 µm and and the depth is about 0.5 µm.

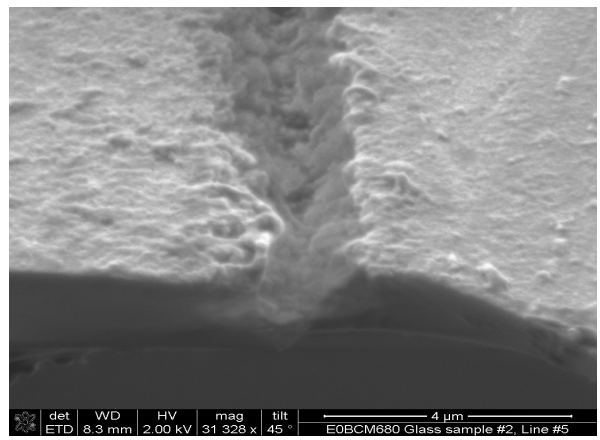

Figure 2: Microscopic view of PDMS surface writing

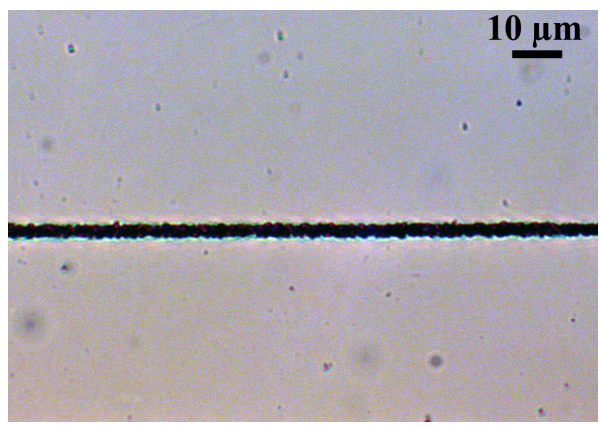

Figure 3: SEM view of soda lime glass surface writing

Figure 3 shows the microscopic view of PDMS surface single line writing with UV fs laser. The laser direct writing condicitions include 258 nm wavelength, 54 nJ pulse energy and 50 mm/s writing speed. The ablated line width from microscopic view is about 2.66 µm. No crack or thermal damage was found after processing.

As shown in Fig. 2 and Fig.3, the ablation line widths for both sample writings are close to the beam focal spot size. Furthermore, different writing speeds were also compared and results show that higher the writing speed, the smaller line width.

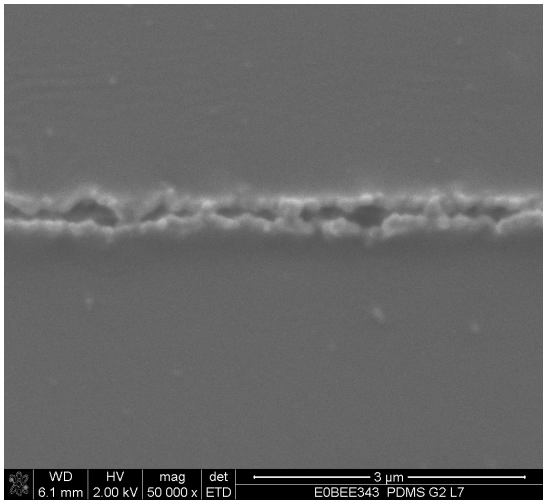

Figure 4: SEM view of PDMS surface writing

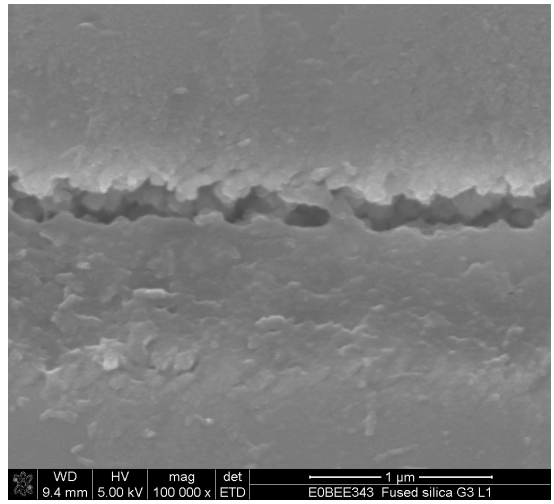

Figure 5: SEM view of fused silica surface writing

3.2 Nanofabrication by Laser Direct Writing

With further fine adjustment of the pulse energy and the focus position, much smaller line ablation can be achieved.

Figure 4 and 5 shows the SEM view of the single line direct writing with fine adjustment of the focus position by using UV fs laser. Figure 4 shows the PDMS surface writing result with average ablation line width of 110 nm and the laser writing conditions include 50 mm/s writing speed and 54 nJ pulse energy. Fig. 5 shows the fused silica surface writing result with line width of 160 nm and the laser writing conditions include 10 mm/s writing speed and 30 nJ pulse energy.

It should be pointed out that the optic microscopic view and measurement of these nanofabrication features is inflated by the debris and redeposited materials on the edges and my not reflect the actual line width. Further SEM check and measurement is needed.

From the comparison of microfabrication and nanofabrication, we can see with fine adjusment of the focuse position, the ablation line width tends to be smaller since the peak fluence is slightly above the threshold for only the center region of the focused Gaussian beam. For the transition from the smallest feature to larger ones, the focus position adjustment is within 10 µm, or even smaller for objective lens with larger numerical aperture.

To further obtain large are continuous line ablation line with sub 100 nm line width, more accurate adjustment for the focus position is needed and the sample flatness is another critical factor.

3.3 Periodic Structures

Besides the nanofabrication of single lines, periodic nano-structures were also found in the surface line direct writing region. Figure 6 shows the overview of one single line surface writing on fused silica material surface with UV fs laser (50 mm/s & 30 nJ). And we can see well-organized parallel periodic nano-structures at the bottom of the ablated line and the feature is uniformly spaced along the writing path. The periodic nano-structures have 100 nm periods with 50 nm width and 50 nm depth.

Figure 6 shows enlarged SEM view of another periodic nano-structures written on fused silica glass surface with UV fs laser (50 mm/s & 30 nJ). It is found that the periodic nano-structure is generated right on the surface of the fused silica. The periods and width of the nano-structures are same as Fig.5.

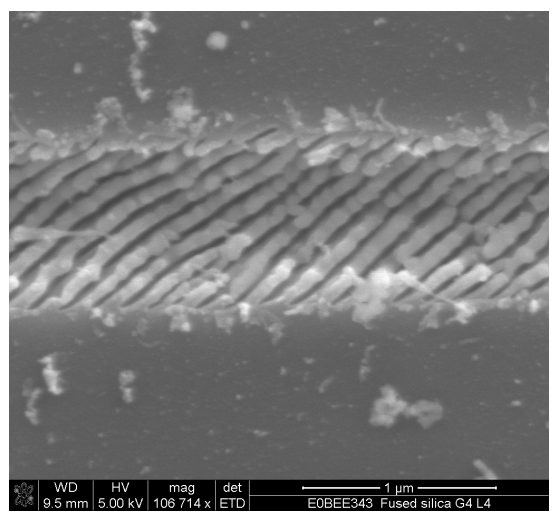

Figure 6: SEM view of fused silica surface periodic nano-structures writing

A lot of experimental parameters has been revealed to have influence upon the periodicity of the laser induced surface structures, such as material properties, laser fluence, number of laser pulses, pulse duration, laser wavelength, radiation polarisation, incidence angle [13-16]. The angle of the inclined feature shown in Fig. 6 is about 42 degrees and is related to the polarization direction of the laser beam. As

a general observed behavior, the periodic nano-structures are oriented perpendicular to the polarisation of the radiation. Similar periodic nano-structures are also observed for Eagle XG glass direct writing, but the quality is not as good as fused silica. This results show great potential for nanofabrication especially for large area nano line feature fabrications.

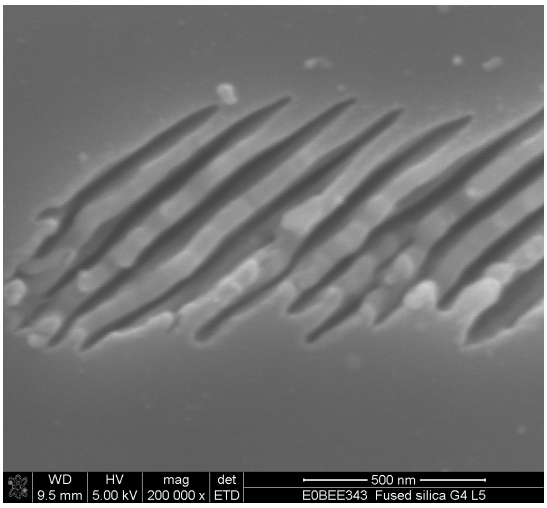

Figure 7: Enlarged SEM view of periodic nano-structures on fused silica surface

4 SUMMARY

In this paper, a UV fs fiber laser was used for direct writing nanofabrication on different materials. It is found that the size of direct written features depends strongly upon pulse energy, as well as the relative position of the laser focal spot with respect to the material surface. The smallest line widths were found to be around 100 nm for both glass and polymer materials. By reducing the pulse energy to a value slightly above the threshold at which features vanish, we can consistently write line features with sub wavelength width. Furthermore, periodic nano-structures with 100 nm period and grooves with about 50 nm width and 50 nm depth were also found.

This fs UV fiber laser based technique is inherently simple, inexpensive, direct, highly-reproducible, material independent and is capable of 3-D nanofabrication. Only an optical lens is needed to focus a laser beam in this direct writing technique. For many applications it is more reliable and reasonably inexpensive compared with other methods such as electron-beam lithography and nanoimprinting. This enabling technology has potentially broad applications for MEMS construction, ultra-high-density microelectronics, nanofluidics, materials science, optical memory, and biological science.

REFERENCES

[1] C. B. Schaffer, A. Brodeur, E. Mazur, Meas. Sci. and Technol. 12, 1784, 2001.
[2] B. Stuart *et al.*, Phys. Rev. B 53, 1749, 1996.
[3] A. Joglekar *et al.*, Appl. Phys. B 77, 25, 2003.
[4] F. Korte *et al.*, Appl. Phys. A 77, 229, 2003.
[5] Y. Lu, S. Chen, Adv. Drug Deliver Rev. 56, 1621, 2004.
[6] C. P. Grigoropoulos, D. J. Hwang, A. Chimmalgi, MRS Bull. 32, 16, 2007.
[7] R. R. Gattass, E. Mazur, Nat. Photonics 2, 219, 2008.
[8] J. Koch, F. Korte, C. Fallnich, A. Ostendorf, B. N. Chichkov, Opt. Eng. 44, 051103, 2005.
[9] B. Chichkov, C. Momma, S. Nolte, F. Von Alvensleben, A. Tünnermann, Appl. Phys. A 63, 109, 1996.
[10] Y. Shimotsuma, K. Hirao, P. G. Kazansky, J. Qiu, Jpn. J. Appl. Phys. 44, 4735, 2005.
[11] M. Huang, F. Zhao, Y. Cheng, N. Xu, Z. Xu, Opt. Express 16, 19354, 2008.
[12] H. Huang, Z. Guo, J. Micromech. Microeng. 19, 055007, 2009.
[13] A. Ozkan *et al.*, Appl. Phys. Lett. 75, 3716, 1999.
[14] R. Wagner, J. Gottmann, A. Horn, E. W. Kreutz, Appl. Surf. Sci. 252, 8576, 2006.
[15] M. Hörstmann-Jungemann, J. Gottmann, D. Wortmann, J. Laser Micro/Nanoeng. 4, 135, 2009.
[16] T. H. Her, R. J. Finlay, C. Wu, S. Deliwala, E. Mazur, Appl. Phys. Lett. 73, 1673, 1998.