SPIE Paper Number: 8519-21
SPIE Optics and Photonics
12-16 August 2012
San Diego, California, USA

Femtosecond fiber laser based micro- and nano-processing

(Invited talk)

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ABSTRACT

Micro- and nano-processing are performed by using a high energy mode-locked femtosecond (fs) fiber laser. The laser beam has 1030 nm center wavelength, 750 fs pulse duration and up to 10 μJ pulse energy. Firstly, direct writing of optical waveguide inside glass materials is presented and a 3-D curved waveguide is demonstrated. Secondly, by taking advantages of fs laser deterministic damage threshold, micrometer and sub-micrometer features are obtained for surface ablation. Thirdly, fs UV (FHG, 258 nm) laser processing is investigated and nanometer features are obtained. Periodic structures in good order are also found and the patterns extend coherently over many overlapping laser pulses and scanning tracks. It has 100 nm period, 50 nm width and 50 nm depth. Such micro and nano processing method suggests a possible technique to produce nanogratings, microelectronics, or nanopatterned surfaces of micro-sensors for space optoelectronics.

Keywords: Femtosecond laser, fiber laser, micro-processing, nano-processing, direct writing.

1. INTRODUCTION

In recent years, methods of micro and nano-processing of materials by direct femtosecond (fs) laser irradiation have aroused great interests in the field of material processing and have become an attractive option for high quality material processing on the surface or in the bulk of solid transparent materials. An unprecedented advantage of using fs pulses instead of longer pulses is that the fs pulse width is shorter than the thermal diffusion time; so the energy of the pulses can be efficiently and precisely deposited into a material without heat diffusion. This nonlinear absorption of laser light in the transparent material also gives the 3D capability for the in-volume material processing. So their ability for minimal damage, precise and 3D processing has been thoroughly researched for many applications in microelectronics [1], telecommunications [2] and medicines [3-4].

When fs laser pulses are tightly focused inside glass by a focusing lens, the strength of the electric field at the focal point of the laser beam is sufficient for inducing various nonlinear physicochemical reactions in materials, such as refractive index change. Many research efforts have been devoted to the field of 3D microscopic modifications to transparent materials by using fs lasers and it has been proven as one of the promising approaches to the manufacturing of optical waveguides [5-6], micro/nano gratings [7], micro channels [8] and 3D integrated systems [9-11].

In addition, the nature of the interaction between fs laser pulses and matter makes it possible to overcome the diffraction limit of light. Generally 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 fs laser pulses since it has a unique feature of deterministic damage threshold due to the ultra short pulse duration. When the pulse duration decreases below a picosecond, the damage threshold shifts from stochastic to deterministic [1, 12]. This highly non-linear dependence of optical breakdown on intensity allows the process to be limited to regions smaller than the focal spot size of the 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, 13-15].

In this paper, we investigated the fs laser-induced micro- and nanostructures via direct writing on the surface and in the bulk of material. Direct writing of optical waveguides is demonstrated inside glasses and a wide range of laser direct writing parameters is examined. Then micrometer and sub-micrometer features are directly written on the surface of different materials. Furthermore, by using fourth harmonic generation (FHG, 258 nm), fs UV laser processing is investigated and nanometer resolution features are obtained. The minimum ablation line width is less than 100 nm. Periodic structures are also found on the surfaces scanning tracks. This simple fs fiber laser based direct writing technology shows great potential for three dimensional micro- and nano-processing of versatile materials.

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2. METHODS & MATERIALS

2.1 Experimental setup

The experimental setup for laser direct writing is shown in Fig.1. The fs laser system is a commercialized mode-locked fiber laser (PolarOnyx, Inc. - Uranus Series), 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. The total beam delivery loss is less than 20 percent. The optional second and fourth harmonic generations (SHG-515nm and FHG-258 nm) are generated by nonlinear crystals placed at the focus of plano-convex lens. The total FHG conversion efficiency of this set up was about 10%. 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 focal spot size for the laser beam can be calculated by $1.22*\lambda/N.A.$, where λ is the laser wavelength and N.A. is the numerical aperture of the objective lens. The sample is mounted on a motorized 3D translation stage.

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). More importantly, the focus position is also finely adjusted for both interior writing and surface writing.

2.2 Materials

In this study, different types of materials were used for laser direct writing, including polymers (PMMA), glasses (soda lime glass, fused silica, borosilicate glass and Eagle XG glass) and indium tin oxide (ITO) film coated glass. Among these materials, fused silica has the highest band gap (~8 eV). Samples are pre-polished for the main surfaces. Before experiments, the sample was carefully cleaned. For waveguide writing, the glass samples were cut to different widths after processing and polished for the edge surfaces for waveguide characterization.

2.3 Microscopy & measurements

After laser processing and polishing, the top view and cross section view of the laser written structures were captured and characterized by optical transmission microscopy (ME520T-9M) at first. Then a scanning electron microscopy (SEM, FEI QUANTA FEG 600) was used to further characterize and measure the ablation line width and depth. The waveguides were further characterized by launching 638 nm red laser using butt-coupled single-mode optical fiber. Near-field mode profiles were also captured using CCD camera.

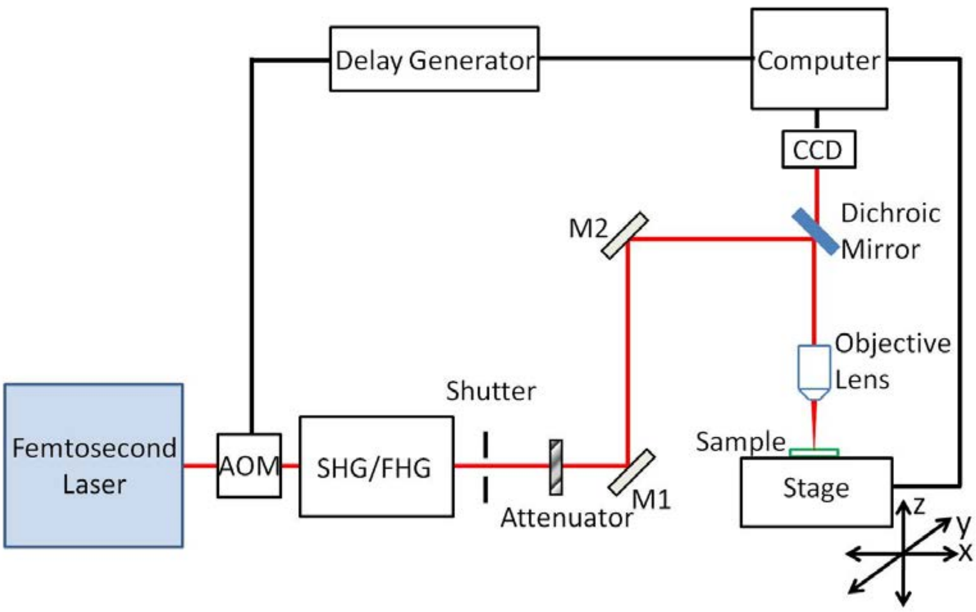


Figure 1. Experimental set up of fs laser micro- and nano-processing.

3. RESULTS & DISCUSSION

3.1 Micro-processing by fs laser direct writing

Generally it is difficult to develop the interaction between light and glass by linear absorption when the wavelength of the excitation light differs from the resonant absorption wavelength of the glass. However, various localized structural changes can be induced on the surface or inside a glass sample by focusing fs laser pulses with a non-resonant wavelength.

At first, fs laser waveguide direct writing was systematically studied. The fundamental laser beam light (1030 nm) was applied at writing speeds from 0.1 to 50 mm/s, incident pulse energies from 100 nJ to 5 µJ, and focal lens N.A. of 0.40 or 0.55 at repetition rates of 1 MHz. For all the fs laser writing lines with different laser parameters, each line was scanned only once.

Figure 2 shows the typical direct writing results inside borosilicate glass sample by using fs laser pulses with different writing speeds and the same pulse energy. Top half shows the top view and the writing direction is from top to bottom; and the bottom half shows the cross-sections view and the laser was irradiated from top. The writing depth is about 200 µm.

From the top view of the results, when the writing speed is above 5.0 mm/s, smooth structure can be seen corresponding to traditional waveguides; when the writing speed is small such as 0.1 mm/s, pearl-chain structure is observed. Similar structures and waveguides were also found by other researchers [16]. Although possible mechanisms for this pearl-chain structure were discussed, the dynamics of this structure creation is not completely clear yet.

The cross sections are asymmetric because of the transverse writing method. The laser modified areas clearly show a double structure, a center core with a droplet-like surrounding volume. This kind of structure is typical for this irradiation conditions and can be interpreted by considering the inner core as the directly irradiated focal region and the outer structure as the region modified by thermal diffusion of the energy stored in the inner core.

From the comparison result as shown in Fig.2, it is worth noting that by increasing the writing speed at constant pulse energy the overall modified volume width shrink from 10 µm to 5 µm, while the total modified volume depth changes from 20 µm to 8 µm.

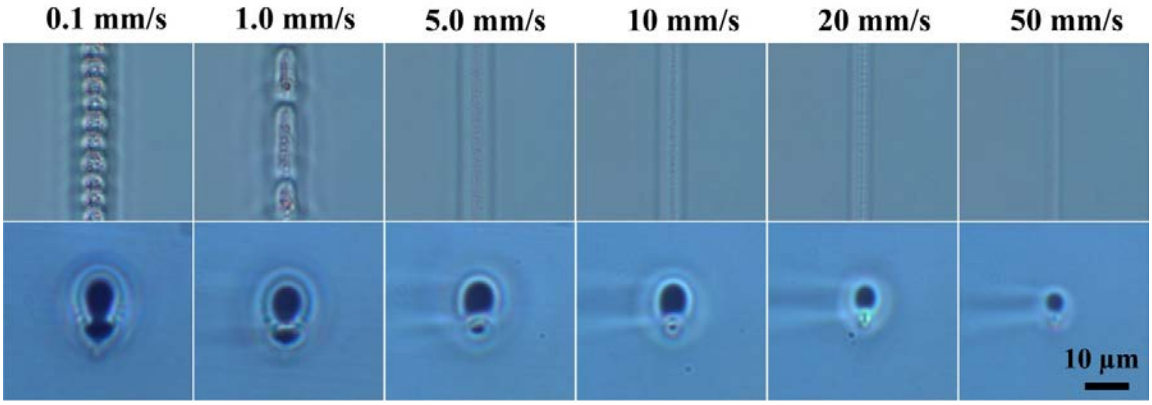
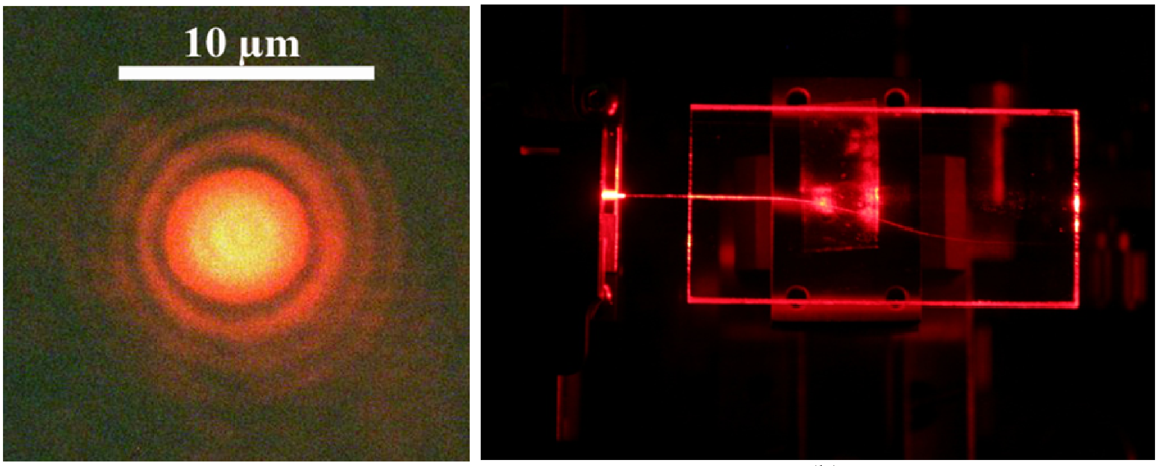


Figure 2. Optical microscope images of top views (top) and cross-sections (bottom) of the borosilicate glass waveguides written with different writing speeds (0.1, 1.0, 5.0, 10, 20, 50 mm/s from left to right) and constant pulse energy (260 nJ).

Figure 3(a) shows the near-field mode profile of output facet when using green laser coupling. An almost circularly symmetric transverse mode was obtained. When changing the alignment of the coupling fiber or objective, it is observed that the near field of the waveguide mode maintained its shape while varying its amplitude. This indicates that the waveguide is single mode at this wavelength. The mode field diameter is about 5.0 µm.

Furthermore, to demonstrate the 3D micro-processing capability inside glasses samples, multiple curved waveguides were written at different depth. Figure 3(b) show one of the curved waveguide coupling result with single mode fiber butt-coupling from left side. The total dimension of the sample is 50 mm long, 25 mm wide and 2 mm thick. The written waveguide consists of two linear line sections on both ends and one curved section in the middle. The radius of the curve is 46.25 mm.

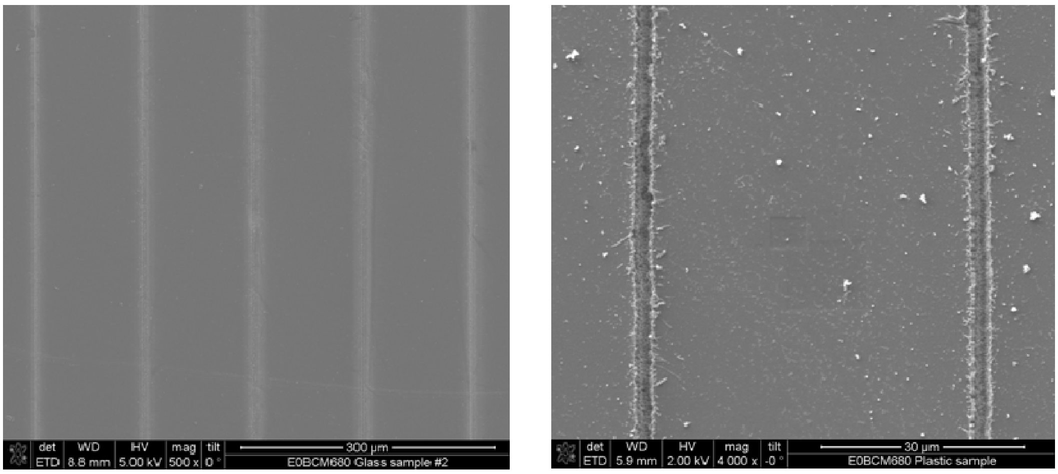


(a) (b)

Figure 3. (a) Near-field mode profile of waveguide output with 638 nm red laser coupling input; (b) Camera top view of one of the curved waveguides with fiber butt-coupling from left side.

Besides the interior writing, surface writing was also investigated for different materials. The size of direct written features depends strongly upon the focal spot size, the 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.

At the beginning, the laser beam was focused onto the surface without adjustment of pulse energy and focus position, so the generated features has dimension close to the focal spot size. Figure 4 shows the SEM image of surface line direct writing of soda lime glass and PMMA. The laser direct writing conditions include 1030 nm wavelength, 0.65 µJ pulse energy and 1 mm/s writing speed. As shown in Fig.4, the ablation line width is about 1.5 µm and the depth is about 0.5 µm.



(a) (b)

Figure 4. (a) NIR (1030 nm) fs laser direct writing of soda lime glass; (b) NIR fs laser direct writing of PMMA material.

As shown in Fig. 4, 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 the line width.

To further reduce the minimum achievable structure size, the laser wavelength was reduced via harmonic generation (SHG & FHG) and the obtained UV fs laser wavelength is 258 nm. This can give a diffraction limit spot size of less than 500 nm.

Figure 5 shows the ITO film scribing result using UV fs laser via FHG. The laser direct writing conditions include 258 nm wavelength, 54 nJ pulse energy and 0.5 mm/s writing speed. The ablated line is about 1.3 µm. From the figure shown, the ITO film was totally removed while the glass substrate was not damaged.

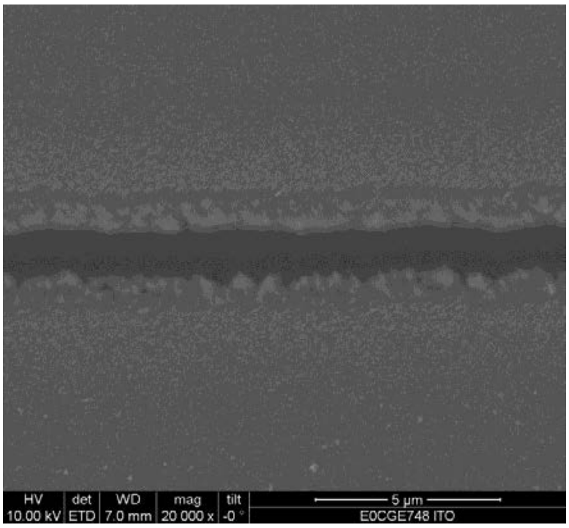


Figure 5. UV fs laser direct writing of ITO thin film on glass substrate.

3.2 Nano-processing by fs laser direct writing

Figure 6 shows the SEM view of Eagle XG glass single line surface writing with UV fs laser and control of focus position. The laser direct writing conditions include 258 nm wavelength, 54 nJ pulse energy and 50 mm/s writing speed. The ablated line width from both samples are about 289 nm respectively. So the single line ablation width was largely reduced due to the smaller focal spot size and controlled focus position.

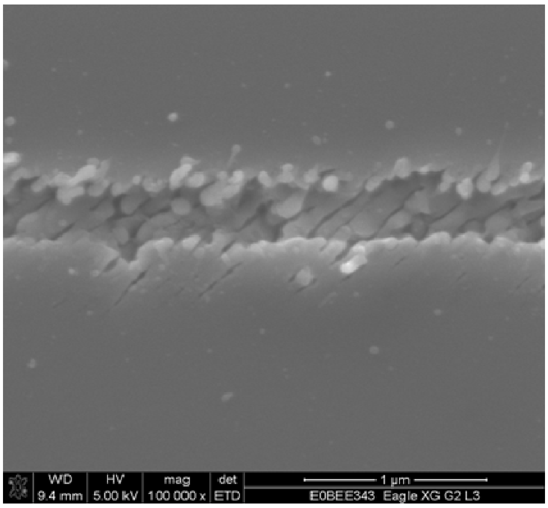


Figure 6. UV fs laser direct writing of Eagle XG glass.

With further precise adjustment of the pulse energy and the focus position, much smaller line ablation can be achieved. Figure 7 shows the SEM view of the single line direct writing with fine adjustment of the focus position by using UV fs laser. The fused silica surface writing result as shown in Fig. 7 has ablation line width of 85 nm and the laser writing conditions include 10 mm/s writing speed and 30 nJ pulse energy. Meanwhile, modified region on both sides of the ablation lines can be observed.

From the comparison of microfabrication and nanofabrication, we can see with fine adjustment of the focus position and the pulse energy, 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.

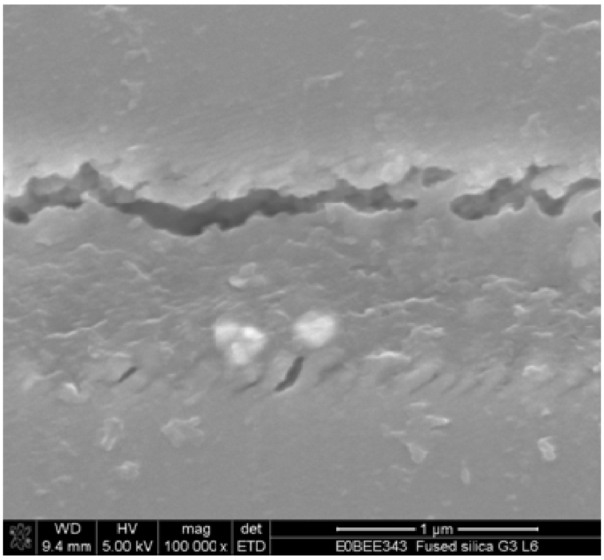


Figure 7. SEM view of UV fs laser direct writing of fused silica.

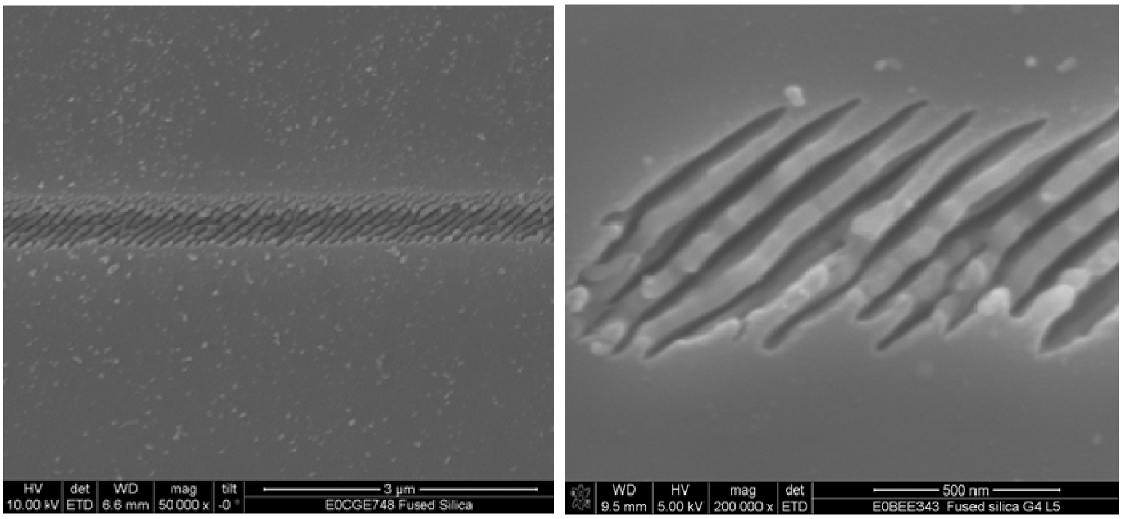
3.3 Periodic Structures

Besides the nanofabrication of single lines, periodic nano-structures were also found in the surface line direct writing region. Figure 8(a) 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 8(b) shows enlarged SEM view of another periodic nano-structure written right 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.

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 polarization, incidence angle [17-20]. The angle of the inclined feature shown in Fig. 8 is about 42 degrees and is independent of the writing direction. As a general observed behavior, the periodic nano-structures are oriented perpendicular to the polarization of the radiation. Similar periodic nano-structures are also observed for direct writing of other materials, but the quality is not as good as fused silica.

Figure 9 shows another single line writing result on fused silica sample surface by using UV fs laser. The ablation line has width of around 1 µm with periodic structure on the bottom. This shows the capability of massive processing of continued periodic structure for nanograting fabrication by scanning overlapping lines since the periodic structure continue coherently regardless of the scanning direction.



(a) (b)

Figure 8. (a) SEM view of ripple structure by UV fs direct writing of fused silica; (b) Enlarged view of ripple structure.

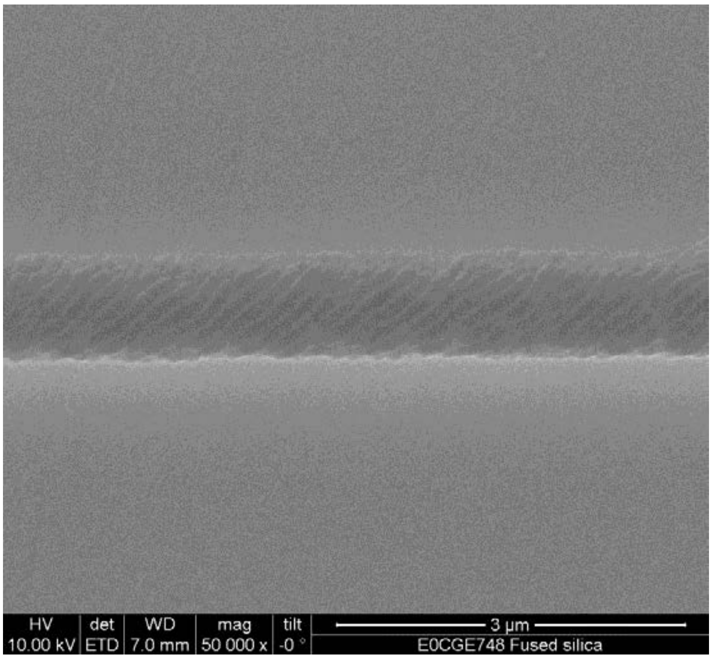


Figure 9. SEM view of single line writing result on fused silica by UV fs laser.

4. SUMMARY

Femtosecond fiber laser micro- and nano-processing of different materials were investigated in this paper. At the beginning, direct writing of optical waveguide inside glasses was investigated and 3D waveguide writing was demonstrated. Then micro/nano meter surface direct writing was presented with both fundamental laser wavelength and FHG. By controlling the pulse energy, focus position and scanning speed, we can consistently write line features with sub wavelength and nanometer size. The smallest line widths were found to be less than 100 nm. In addition, the feature sizes of the direct writing can be tuned in a wide range by varying the irradiation wavelength, pulse energy and focus position. Furthermore, periodic structure in good order with 100 nm period, 50 nm width and 50 nm depth were also obtained.

This fs fiber laser based micro- and nano-processing technique is inherently simple, 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, environmentally friendly, and reasonably inexpensive compared with other traditional fabrication methods such as electron-beam lithography and nanoimprinting. This enabling technology has potentially broad applications for MEMS, ultra-high-density microelectronics, and space applications.

ACKNOWLEDGE

This work was funded by NSF and AFOSR.

REFERENCES

[1] Stuart, B., Feit, M., Herman, S., Rubenchik, A., Shore, B., and Perry, M., "Nanosecond-to-femtosecond laser-induced breakdown in dielectrics," Physical Review B 53(4), 1749 (1996).

[2] Gattass, R. R. and Mazur, E., "Femtosecond laser micromachining in transparent materials," Nature Photonics 2(4), 219-225 (2008).

[3] Lu, Y. and Chen, S., "Micro and nano-fabrication of biodegradable polymers for drug delivery," Advanced drug delivery reviews 56(11), 1621-1633 (2004).

[4] Wortmann, D., Gottmann, J., Brandt, N., and Horn-Solle, H., "Micro-and nanostructures inside sapphire by fs-laser irradiation and selective etching," Optics Express 16(3), 1517-1522 (2008).

[5] Nolte, S., Will, M., Burghoff, J., and Tuennermann, A., "Femtosecond waveguide writing: a new avenue to three-dimensional integrated optics," Applied Physics A: Materials Science & Processing 77(1), 109-111 (2003).

[6] Chan, J. W., Huser, T. R., Risbud, S. H., Hayden, J. S., and Krol, D. M., "Waveguide fabrication in phosphate glasses using femtosecond laser pulses," Applied Physics Letters 82, 2371 (2003).

[7] Okamuro, K., Hashida, M., Miyasaka, Y., Ikuta, Y., Tokita, S., and Sakabe, S., "Laser fluence dependence of periodic grating structures formed on metal surfaces under femtosecond laser pulse irradiation," Physical Review B 82(16), 165417 (2010).

[8] McDonald, J. P., Mistry, V. R., Ray, K. E., and Yalisove, S. M., "Femtosecond pulsed laser direct write production of nano-and microfluidic channels," Applied Physics Letters 88, 183113 (2006).

[9] Della Valle, G., Osellame, R., and Laporta, P., "Micromachining of photonic devices by femtosecond laser pulses," Journal of Optics A: Pure and Applied Optics 11, 013001 (2009).

[10] Glezer, E., Milosavljevic, M., Huang, L., Finlay, R., Her, T. H., Callan, J. P., and Mazur, E., "Three-dimensional optical storage inside transparent materials," Optics Letters 21(24), 2023-2025 (1996).

[11] Sugioka, K., Cheng, Y., and Midorikawa, K., "Three-dimensional micromachining of glass using femtosecond laser for lab-on-a-chip device manufacture," Applied Physics A: Materials Science & Processing 81(1), 1-10 (2005).

[12] Du, D., Liu, X., Korn, G., Squier, J., and Mourou, G., "Laser‐induced breakdown by impact ionization in SiO2 with pulse widths from 7 ns to 150 fs," Applied Physics Letters 64(23), 3071-3073 (1994).

[13] Schaffer, C. B., Brodeur, A., and Mazur, E., "Laser-induced breakdown and damage in bulk transparent materials induced by tightly focused femtosecond laser pulses," Measurement Science and Technology 12, 1784 (2001).

[14] Joglekar, A., Liu, H., Spooner, G., Meyhöfer, E., Mourou, G., and Hunt, A., "A study of the deterministic character of optical damage by femtosecond laser pulses and applications to nanomachining," Applied Physics B: Lasers and Optics 77(1), 25-30 (2003).

[15] Korte, F., Serbin, J., Koch, J., Egbert, A., Fallnich, C., Ostendorf, A., and Chichkov, B., "Towards nanostructuring with femtosecond laser pulses," Applied Physics A: Materials Science & Processing 77(2), 229-235 (2003).

[16] Graf, R., Fernandez, A., Dubov, M., Brueckner, H., Chichkov, B., and Apolonski, A., "Pearl-chain waveguides written at megahertz repetition rate," Applied Physics B: Lasers and Optics 87(1), 21-27 (2007).

[17] Ozkan, A., Malshe, A., Railkar, T., Brown, W., Shirk, M., and Molian, P., "Femtosecond laser-induced periodic structure writing on diamond crystals and microclusters," Applied Physics Letters 75, 3716 (1999).

[18] Wagner, R., Gottmann, J., Horn, A., and Kreutz, E. W., "Subwavelength ripple formation induced by tightly focused femtosecond laser radiation," Applied surface science 252(24), 8576-8579 (2006).
[19] Zamfirescu, M., Dinescu, A., Danila, M., Socol, G., and Radu, C., "The role of the substrate material type in formation of laser induced periodical surface structures on ZnO thin films," Applied surface science (2012).
[20] Yasumaru, N., Miyazaki, K., and Kiuchi, J., "Femtosecond-laser-induced nanostructure formed on hard thin films of TiN and DLC," Applied Physics A: Materials Science & Processing 76(6), 983-985 (2003).