Optics and Laser Technology 108 (2018) 26–31

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Thin film enabling sub-250 nm nano-ripples on glass by low fluence IR picosecond laser irradiation

Nazar Farid [a,*], Daniel Nieto [a,b], Gerard M. O'Connor [a]

[a] National Centre for Laser Applications (NCLA), School of Physics, National University of Ireland, Galway, Ireland
[b] Microoptics and GRIN Optics Group, Applied Physics Department, Faculty of Physics, University of Santiago de Compostela, Santiago de Compostela E15782, Spain

ARTICLE INFO

Article history:
Received 23 January 2018
Received in revised form 27 May 2018
Accepted 25 June 2018

Keywords:
Nano-ripples
Glass
Periodic structures
LIPPS
Thin film
Indium-tin-oxide

ABSTRACT

Well-aligned parallel nanoripples, with spacing down to 250 nm, were engraved on a glass surface at a fluence 8 times less than the ablation threshold of glass using IR (λ = 1032 nm) picosecond laser system with a pulse duration of 10 ps. The glass surface was first coated with 175 nm ITO thin film prior to laser scanning. The nano-ripples were formed on the underlying glass surface during the selective removal of ITO thin film using substantially less fluence than that required without ITO on the glass surface. The laser scan speed and repetition rate determine the spatial overlapping of pulses (shots per area, SPA); this greatly influences the symmetry, spacing, and depth of the ripples achieved. The fluence ranging from 1.13 to 1.56 J cm^{-2} at scanning speed of 0.5 ms^{-1}, 25 SPA, 96% overlapping at laser repetition of 400 kHz was found to be the optimal laser parameters for generating nano-ripples with 0.25λ periodicity on large area glass surface. The process offers the opportunity for gratings to be integrated in structures consisting of transparent conductive materials.

1. Introduction

Photonic components such as Fresnel lenses, diffractive optical elements (DOE), or grating beam splitters, are of great importance because of their potential applications in creating integrated optics [1], polarization control, birefringence, optical memory storage devices [2], microfluidics [3], imaging/confocal microscopy, and in secure packaging [4]. In the recent years, extensive work has been carried out on transparent media like glass, to generate micro-to nanostructures such as nanogratings, to control the spacing and orientation of structures. Sophisticated and multistep techniques like photolithography and chemical etching are used to prepare high quality microstructures on glass materials [5–7]. There are still opportunities for new approaches to generate reconfigurable low cost and reliable structures in glass materials [3]. Direct write, short pulse, laser micromachining, because of its non-contact nature, offers several advantages for glass micro- and nano-structuring, including the capability to form complex shapes with minimal mechanical and thermal modification of the glass surface [8–11]. In particular, since the invention of the pulsed laser and first observation of self-generated microstructures, or so-called periodic ripples, a trend has been established to generate controlled well-aligned ripples inside [12–14] and on the surface [15–17] of transparent glass materials using laser beams. In general, the orientation of the laser generated ripples or nanogratings are dependent on polarization [18]; the grating's spacing depends on the incident laser pulse duration [19,20] and on number of applied pulses [17]. Several models based on experimental findings like standing waves [21], interference [22], nano-plasmonic [16], and self-organization [23] have been developed to explain the evolution of periodic structures because of growing interest and increasing applications of laser induced periodic surface structures (LIPSS). Laser produced ripples have been explained by different mechanisms like scattering and interference of the incident laser beam due to the excitation of surface plasma polaritons (SPP) [24], interference with harmonics of the incident laser radiation [25,26], self-organised structures due to hydrodynamic thermal instabilities [27,28], changes of the refractive index [29], plasmon polariton interactions [30–32], and effects caused by Coulomb explosion [33].

LIPSSs are categorized mainly into two types, the low spatial frequency LIPSS (LSFL) with a period close to the applied laser wavelength and high spatial frequency LIPSS (HSFL) having a spatial period significantly smaller than the laser wavelength.

In this paper, we report on the generation of well-aligned nano-ripples on borosilicate glass using 10 ps laser pulses with wavelength, λ = 1032 nm. A new method is proposed in which

* Corresponding author.
E-mail address: nazar.farid@nuigalway.ie (N. Farid).

https://doi.org/10.1016/j.optlastec.2018.06.059

the glass sample surface is first coated with a highly transparent thin indium-tin-oxide (ITO) film. We describe the formation of nano-ripples generated over large areas using a laser scanning system where multiple pulses are applied at a fluence of 8 times lower than the ablation threshold for uncoated glass. Highly transparent, clean and well-aligned parallel nano-ripples down to 250 nm spacing were generated on the glass surface, assisted by the ITO thin film coating. To our knowledge this is the first report on nano-ripples formation on a glass surface at a fluence lower than the damage threshold using ITO thin film on the upper glass surface. The technique presented offers an alternative approach to replace the existing conventional lithographic methods used to generate nano-ripples and structures on glass surfaces for future photonics applications. The results are also interesting for processes where short pulse lasers are used to selectively pattern conductive thin films at dielectric interfaces.

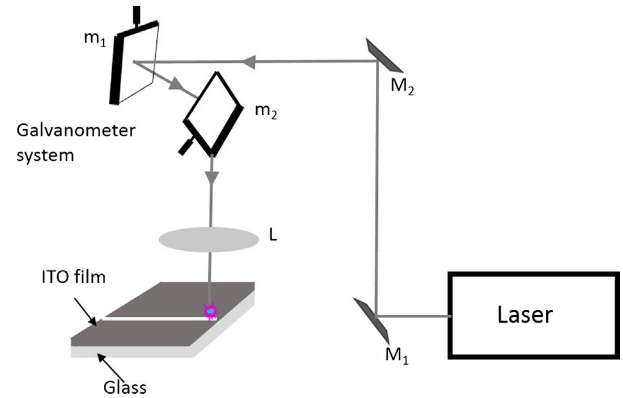

Fig. 1. Schematic of laser set-up for nanograting on glass.

2. Experimental details

The nano-ripples were engraved on a highly transparent borosilicate glass of thickness 0.8 mm. The composition of glass is provided in Table 1. Before engraving, the glass samples were coated with 175 nm ITO thin film by DC sputtering technique. Transmission of glass was not significantly affected after the deposition of an ITO thin film because of the highly transparent nature of ITO; the transmission was estimated to be 91% in the visible range while the sheet resistance was 15 Ω/sq.

A schematic of an experimental setup is shown in Fig. 1 where an IR picosecond pulsed laser system (Trumpf Trumicro5050) with wavelength 1032 nm, 10 ps pulse duration, operating at 400 kHz was used. The laser operated at 50 W and the output power was attenuated using a combination of half-wave plate and polarizer. The laser beam was focused on the sample with 100 mm focal length lens (NA = 0.014) of an XY scanning system which is coupled to machining stage through combination of different reflectors and mirrors. The system allows the control of the pulse overlap on the sample by adjusting the speed of the galvanometer based beam scanning system (Scanlabs). A precise 3D computer controlled stage (Aerotech) was used as a sample holder to change the target position with sub-micron accuracy. To check the dependence of the incident laser polarization on the orientation of the laser generated ripples, the polarization state could be changed by an additional half-wave plate placed before the beam entered the laser scanning system. An optical microscope, scanning electron microscope (SEM), and atomic force microscope (AFM) were utilized for measurement of the surface morphology and ripple spatial periodicity.

Considering the Gaussian nature of the laser, the laser spot diameter (D) at $1/e^2$ of its peak, and damage threshold is fluence φ_{th} were measured using well-known so called Liu's relation [34];

$$D^2 = 2\omega_0^2 ln\left(\frac{\varphi_0}{\varphi_{th}}\right)$$

where ω_o is beam waist radius of the Gaussian shaped beam at the focus and φ_0 is peak fluence at the centre of the beam, which can be calculated by $\varphi_0 = 2E_p/\pi\omega_0^2$, where E_p is laser pulse energy. The ablation threshold of glass sample without thin films was found to be 8.3 J cm^{-2}. The damage threshold of the 175 nm thick ITO thin film was found 0.45 J cm^{-2}; the damage threshold is defined as a fluence value at which a physical damage on the ITO surface can be seen by the optical microscope. The beam diameter, $2\omega_0$, was 32 μm.

Table 1
Chemical composition (wt%) of the glass materials used in this work.

Element	Weight %
O	58.1
Na	3.1
Al	0.95
Si	37.85

3. Results and discussion

Fig. 2a shows the structure attained when 3 laser pulses of 10 ps pulse duration, at 1032 nm wavelength, at a peak fluence of 0.92 Jcm^{-2} are incident on the ITO thin film at the same spot. At this fluence, no damage on the glass surface was observed using optical microscopy. Evidence of thermally activated processes on the ITO thin film were observed using the SEM technique; these included the observation of smooth nanostructures, localized stress cracking, and partial ablation. The fine nanometre –sized cracks observed in the thin film (Fig. 2b) propagate along grain boundaries with depths of a few nanometres and are most likely due to localized stress confinement [35]. Our understanding of the evolution of these structures are as follows. Nano-blister type structures were formed on the ITO surface after receiving the first pulse. It was proposed that that these conductive nano-blisters cause the enhancement in the local intensity of the applied electromagnetic field with higher electric field enhancement up to 5 times at the nano-blister edges; this electric field enhancement is aligned with the incident laser polarization [36]. The nano-blisters evolve into long range periodic structures following the application of subsequent pulses. The periodic structures in ITO are typically oriented in a direction perpendicular to the incident laser polarization at this particular fluence. This is in agreement with A. Rudenko et al.[37]; where local field enhancement in the vicinity of the inhomogeneous scattering centre was proposed as a mechanism for surface ripples and volume nanogratings. These scattering centres can be considered as surface laser-induced defects, nano-roughness, initial grooves, nanopores of voids.

The ITO thin film was removed following irradiation with successive laser pulses, thereby revealing structures formed on the underlying glass surface. The formation of nano-ripples on the glass surface is elaborated in Fig. 3, where an ITO thin film coated glass surface was scanned with different speeds. The figure shows the ITO film/glass substrate when scanned with overlapped pulses at a fluence of 1.1 J cm^{-2} at speeds of 0.5–3.7 ms^{-1}; the corresponding laser shots per area (SPA) from 25.6 to 3.4 which is equivalent to spatial pulse overlapping from 96 to 71%. For the highest speeds and lowest shots per area, the ITO film was not removed (Fig. 3a). An interesting effect is observed; the crests of the periodic