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Ultrashort pulse laser patterning of indium tin oxide thin films on glass by uniform diffractive beam patterns

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ABSTRACT

In the last decade, indium tin oxide (ITO) has been most commonly employed to create transparent conducting oxides (TCOs) thin films for many industrial applications. It is usually necessary to pattern ITO thin films to create functional structures for specific applications. Direct-write micro-patterning of ITO thin films by ultra-short pulse lasers has demonstrated high quality without requiring multiple processing stations, compared with conventional patterning technologies (e.g. wet-etch lithography). However, the processing efficiency and throughput with a single beam can be insufficient because of the high level of attenuation needed for the output to meet the required 'thermal-free' parameters. In this paper, high throughput surface direct micro-structuring of ITO on glass is demonstrated by parallel processing using diffractive multiple ultrashort pulse laser beams ($\lambda = 1064$ nm, $\tau p = 10$ ps). By avoiding periodic and symmetrical geometry design, the diffractive multiple beam pattern generated by a spatial light modulator has high uniformity (the energy variation between each diffractive beam is <9%). The ITO thin film is removed by laser ablation of 25 identical beams at the same time without any damage to the glass substrate. Additionally, by synchronizing a scanning galvanometer, the processing demonstrates high flexibility to generate various surface patterns.

1. Introduction

In the last decade, indium tin oxide (ITO) has been widely used as a transparent electrode for the fabrication of liquid crystal displays (LCDs), organic light emitting diode displays (OLEDs), thin film solar cells and so on, because it provides high electrical conductivity and transparency in the visible and near infrared (NIR) wavelengths. During the fabrication, ITO is applied as a continuous thin film coating and is then locally removed by patterning technologies without damaging the substrate material (e.g. glass) to create functional structures for specific applications. The conventional patterning technologies (e.g. wet-etch lithography and photolithography) are costly by requiring multiple processing stations. Thus, direct-write patterning of ITO film by lasers has been demonstrated as a replacement for the conventional technologies [1–4].

Compared with long pulse lasers, ultrashort pulse lasers have demonstrated higher quality when patterning ITO thin films [5]. This is because the pulse duration is shorter than the time required for energy transfer from the electrons to the material lattice and unwanted thermally induced defects can be minimized [6,7]. The processing efficiency and throughput with ultrashort pulse lasers are diminished, since the output power is attenuated to meet the required 'thermal free' parameters (e.g. pulse energy ~ μJ level). This can be significantly increased by creating diffractive multi-beams with a spatial light modulator (SLM) and performing parallel machining [8–14]. However, whether this multi-beam processing method can be used in direct-write patterning of ITO film significantly depends on the consistency of the diffracted beams.

In this paper, with considerations of multi-beam's uniformity, a parallel ultrashort pulse laser ($\lambda = 1064$ nm, $\tau p = 10$ ps) surface patterning of ITO on glass is demonstrated. By avoiding periodic and symmetrical geometry design, the diffractive multi-beam shows much higher uniformity. The ITO thin film is removed by laser ablation of 25 identical beams simultaneously without any damage to the glass substrate. Additionally, by synchronizing a scanning galvanometer, the processing demonstrates high flexibility to generate various surface patterns.

2. Experimental

The ultrashort pulse laser system used for the present research was a custom made Nd:VAN seeded regenerative amplifier laser system (High-Q IC-355-800ps, Photonic Solutions). Fig. 1 shows

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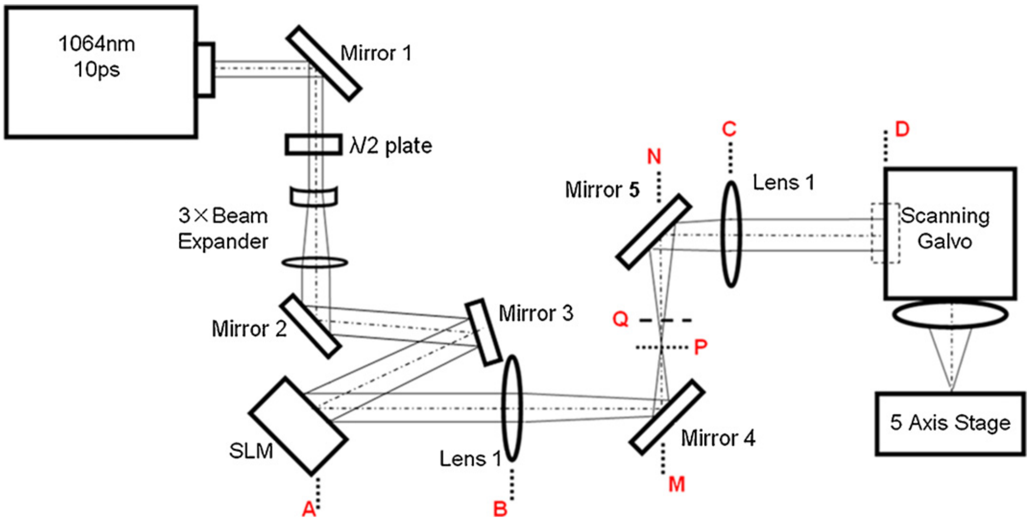

Fig. 1. Experimental setup.

schematic of the experimental setup. The output laser ($\tau p = 10$ ps, $\lambda = 1064$ nm, $F = 10$ kHz) passed through a half wave plate used for adjusting the linear polarization direction, a beam expander ($M \approx \times 3$), and after reflection on mirrors 1, 2 and 3, illuminated a reflective phase only SLM, A Hamamatsu X10468-03 liquid crystal on silicon (LCoS) device with 800×600 pixels and dielectric coated for 1064 nm wavelength (reflectivity $\eta \approx 95\%$), oriented at $<10^{\circ}$ angle of incidence. A 4f-optical system was formed from A to D to remove the unwanted 0-th order beam [11]. The beam then entered a scanning galvanometer with $f = 100$ mm flat field f-theta lens (Nutfield) producing an agile focusing system. Substrates were mounted on a precision 5-axis (x, y, z, p, q) motion control system (Aerotech) allowing accurate positioning of the substrate surface at the laser focus. The spectral bandwidth, $\Delta\lambda \approx 0.1$ nm, was relatively narrow and important in eliminating chromatic dispersion of the SLM [11,12]. The sample used for this research was generated from an ITO precursor solution prepared by SAFC Hitech. The precursor was evenly coated on a glass slide by a spin-coater and then annealed by a furnace to create the ITO coating (thickness ~ 50 nm) with high transparency and conductivity.

3. Results and discussions

3.1. Ablation test of ITO coating and glass substrate

When applying ultrashort pulse lasers for material removal, the threshold energy, at which the material ablation starts, is well defined [6]. The ablation threshold of the ITO film and the glass substrate was tested individually. Since the beam diameter measured before the aperture of the scanning galvanometer was approximately $\Phi \approx 6.3$ mm, the expected $1/e^2$ focused beam waist ($2\omega_0$) at the substrate surface was calculated to be $2\omega_0 \approx 23.8$ µm, using the following equation:

$$2\omega_0 = \frac{4\lambda f M^2}{\pi \Phi} \tag{1}$$

where $\lambda = 1064$ nm is the laser wavelength, $f = 100$ mm is the focal length of the flat field f-theta lens and $M^2 = 1.1$ is the beam quality factor. Since the beam is nearly Gaussian, the ablated hole diameter D, as a function of Fluence F, should theoretically follow the equation [15]:

$$D^2 = 2\omega_0^2 \ln\left(\frac{F}{F_{\rm th}}\right) = 2\omega_0^2(\ln F - \ln F_{th}) \tag{2}$$

where ω_0 is the radius of beam waist and F_{th} is the ablation threshold. Fig. 2 shows the measured diameter squared of single pulse drilled holes against logarithmic fluence. As shown, the experimental results well match the linear relationship between D^2 and $\ln F$. The slopes ($2\omega_0^2$) are similar and infer a focused spot size of $2\omega_0 = 22.3 \pm 0.1$ µm, close to the theoretical value of 23.8 µm indicating excellent beam quality. By extrapolation of D^2 to zero, the value for the ablation threshold fluence (F_{th}) can be inferred to be $F_{\text{th-ITO}} \sim 1.26$ J/cm^2 and $F_{\text{th-GLA}} \sim 2.74$ J/cm^2 for ITO film and glass substrate, respectively. The respective threshold pulse energies can then be easily calculated from $F = (2E_p)/(\pi\omega_0^2)$ to be $E_{\text{th-ITO}} \sim 2.4$ µJ and $E_{\text{th-GLA}} \sim 5.2$ µJ. Consequently, a required pulse energy (E_p) window, where the ITO film can be selectively removed without damaging the glass substrate, is bounded by: 2.4 µJ < E_p < 5.2 µJ.

As shown, the measured ablation threshold of the glass substrate is higher than the ITO film. This is because ITO has absorption coefficient at 1064 nm, $\alpha_{\rm ITO} \sim 2 \times 10^3$ cm^{-1} (ITO is transparent only because the thickness of film is so thin, ~50 nm), whereas $\alpha_{\rm glass}$ is likely to be much less, $\alpha_{\rm glass} \sim$ few cm^{-1} [16].

Diffractive multi-beam patterns were created by computer generated holograms (CGHs) displayed on the SLM (Hamamatsu

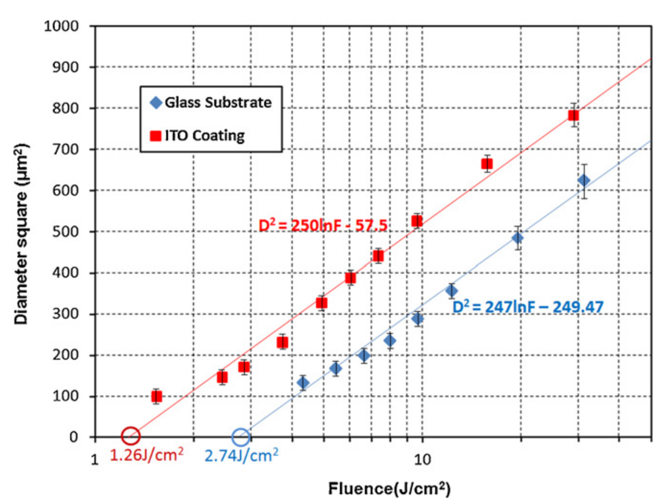

Fig. 2. The diameter square (D^2) of single-pulse drilled holes against logarithmic fluence (F). As shown, for both ITO and glass, D^2 linearly increased by gaining logarithmic F, which reasonably matches the equation, $D^2 = 2\omega_0 \ln(F/F_{\rm th}) = 2\omega_0 (\ln F - \ln F_{\rm th})$.