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Laser scribing of thin dielectrics with polarised ultrashort pulses

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ABSTRACT

Laser processing of thin glass has proven problematic due to the inefficient coupling of optical energy into glass and difficulty achieving economical processing speed while maintaining cut quality. Laser glass processing is pertinent to touch screen display, microfluidic, microoptic and photovoltaic applications. The results of the laser scribing of 110 μm thick alkali free glass with ultrashort polarised laser radiation are presented. A novel ex-situ characterisation procedure is reported which enables effective characterisation of the scribe depth, width, shape and the morphology of the laser material interaction zone. A study of glass cross sections scribed with laser polarisation oriented parallel to the plane of incidence (P polarised) showed damage regions extending away from the trench walls and correlated damage on the rear surface; these regions are indicative of damage caused by light transmission. The damage was significantly reduced by altering the polarisation from parallel to be perpendicular to the plane of incidence (S polarised) due to the increased reflectance from the trench walls. The processing speed was also impacted by the laser polarisation; it was found that S polarised light required less passes to fully ablate through the glass substrate. A processing window capturing the peak of the polarisation effect was identified. An optical model was developed to predict the effect of polarisation on the intensity distribution reaching the rear surface of the glass. S polarised light increases the reflectance resulting in a waveguiding effect which confines a larger amount of the light in the trench. Consequently we see an increased fluence incident on the central region of the trench.

1. Introduction

Accurately structuring thin glass is of significant industrial interest due to the growing popularity of touch screen displays, microfluidic [1,2], microoptic [3,4] and photovoltaic [5] applications. Glass has a good chemical resistance, high optical transparency and moderate flexibility for thicknesses below 200 μm. For this reason glass is suitable for many applications. The flexibility of thin glass offers an opportunity to substitute sheet-fed processing with a fully reel-to-reel process [6]. Here it will be possible to process continuous rolls of substrates decreasing processing time significantly.

Ultrashort lasers potentially offer a sustainable, reconfigurable and versatile solution for structuring thin glass. The key features of ultrashort lasers are the ability to reach the high intensities required for non-linear absorption in glass at moderate pulse energies and highly localised energy deposition [7–9]. Lasers can manufacture a range of structures in dielectrics, such as trenches, bevels, local surface or bulk changes in refractive index [10] and high aspect ratio drilled holes [11]. Sub-micron ablation precision is possible with femtosecond pulses [12] due to the absence of thermal effects and deterministic damage threshold. This laser, combined with a CNC scanning system allows complex features to be quickly and precisely machined on a dielectric surface or bulk substrate. Techniques for improving feature quality and processing speed are of interest especially for industrial applications.

When the laser is incident on the trench the plane of incidence is defined by a vector normal to the trench walls and a vector parallel to the propagation direction of the laser (see Fig. 1). If the laser polarisation is parallel to this plane it is referred to as P polarised; if the laser polarisation is perpendicular to this plane it is referred to as S polarised. Extensive studies have been completed on hole geometries and morphologies created during polarised ultrashort pulse ablation. Nolte et al. [13] manufactured high aspect ratio holes in stainless steel using linearly polarised 170 fs laser pulses. Bulges were observed around the exit hole orientated perpendicular to the polarisation of the laser. Nolte concluded that the bulges are due to polarisation dependent reflections inside the hole and implemented a 'polarisation trepanning' technique to improve the uniformity of the exit hole. Kamalu [14] found the laser cutting speed of steel varied by a factor of two depending on the orientation of the linear polarisation. The cutting speed was highest when the polarisation was

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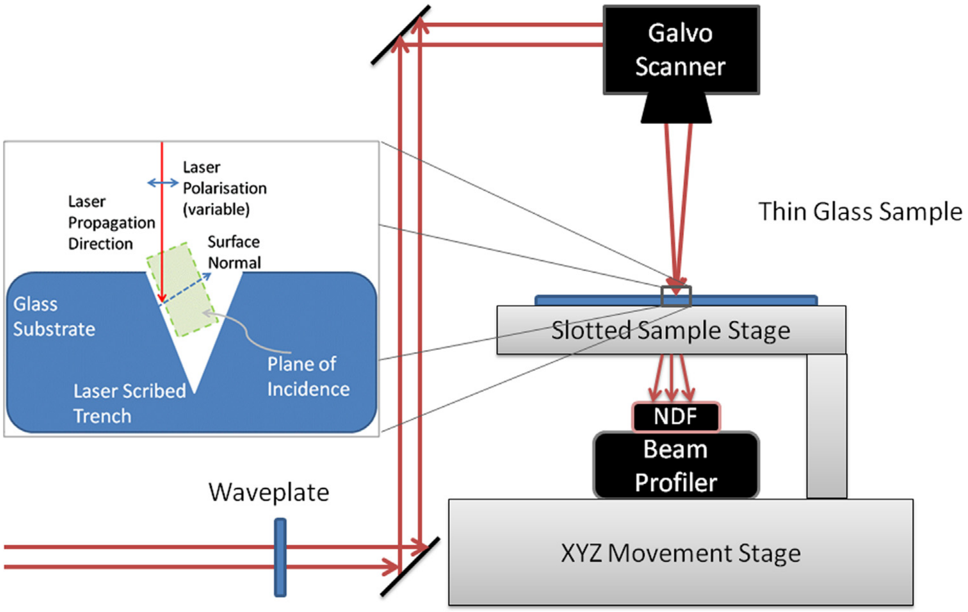

Fig. 1. Illustration of experimental setup. For microscope objective tests the galvo scanner is replaced with a fixed mirror and microscope objective. Laser scanning is achieved by moving the stage. The image insert demonstrates the definition of the plane of incidence.

orientated parallel to the plane of incidence (P polarised) at the cut wall. P polarised light has a lower reflectivity than S polarised light (Fig. 1) especially for glancing angles and for this reason it will be preferentially absorbed in the substrate leading to increased cutting speeds.

Other non-polarisation related ablation effects have been observed. Klimentov et al. [15] found severe deviation of the crater geometry when percussion drilling steel with 130 fs pulses. The effect was explained by dynamic non-linear propagation of the laser pulse in the ambient atmosphere before the geometrical focus, which distorted the beam profile from Gaussian to a wide angle cone. There is also some evidence of the ablated material lingering in the interaction zone causing further distortion to beam profiles of subsequent pulses [16]. Vanagas et al. [17] carried out glass scribing experiments using a circularly polarised femtosecond laser. Damage was observed at the rear surface of the glass after scribing. This damage was attributed to stress waves induced by the plasma ablation pressure pulse.

There is nominal linear absorption of IR and visible light in dielectrics due to the large bandgap. Non-linear absorption mechanisms can be used to couple laser energy into the material [18]. The initial interaction is mediated by multiphoton ionisation, two or more photons are absorbed simultaneously and the sum of their energies is sufficient to promote an electron from the valence band to the conduction band. Free electrons generated are highly absorbing of further photons through inverse bremsstrahlung. Excited free electrons can ionise additional electrons in a positive feedback process known as avalanche ionisation. The dynamic relationship between the ionisation processes has been modelled by several authors [9,19–21]. Rate equations with decay terms are used to describe the free electron density evolution. Various functions are used to represent the electron distribution (Fokker–Planck, Fermi). The criteria for material damage to occur is also considered; some authors take this to be a free electron density threshold while others take it as a certain lattice temperature. The models are generally accurate over a certain range but the difficulty remains to form a valid model over a large energy and free electron density range. The optical properties of an ionised dielectric surface will change dynamically over the course of the laser pulse with the effects peaking approximately 100–500 fs after the commencement of the laser material interaction [19,22]. The surface plasma will heavily attenuate the incident beam through linear absorption and a fluence dependent increase in surface reflectivity [22]. Breakdown of the material occurs when the density of free electrons reaches a critical value, typically taken as the density where the plasma becomes reflecting of IR wavelengths, approximately 10^{21} cm^{-3} [9]. Excited electrons will equilibrate with the lattice within a few picoseconds [18]. Rapid heating of the substrate leads to melting, vaporisation and material ejection.

Incubation effects have been observed in several types of glass [23,24]. Irradiation of a dielectric surface at close to the ablation threshold will initially have no effect but repeated irradiation will lead to formation of colour centres followed eventually by ablation. Colour centres will cause much higher absorption of the laser energy.

Lasers are versatile tools for material processing. This study examines the effect of laser polarisation on scribe quality and ablation rate for glass. The polarisation state of the laser will determine the reflectance. By increasing the reflectance we can hypothetically increase the confinement of the laser in the trench and improve coupling of the laser into the material, thereby increasing the ablation rate. Secondly the collateral damage to the laser scribed part is improved by considering the polarisation configuration of the incident beam relative to the side-walls of the laser scribed trench.

2. Experimental method

2.1. Experiment setup

Scribing was performed using an Amplitude Systemes s-Pulse laser with a wavelength of 1030 nm and a pulse duration of 500 fs. The laser had a Gaussian beam profile with a nominal propagation factor $M^2 < 1.2$. The laser emitted a linearly polarised beam. The laser power was varied using the built in laser attenuator which consisted of a motorised half waveplate and a linear polariser. The glass used was 110 μm thick AF32 alkali free glass (Schott). A galvo scanner with a 100 mm focal length telecentric lens (NA=0.71) and a 20 × microscope objective (NA=0.015) were used to focus