Abstract

Femtosecond laser pulses are of particular interest for internal modification of transparent materials as they enable nonlinear absorption due to the extremely high intensity in the focal volume. Since output from commercial laser sources currently exceeds single beam process requirements, parallel processing with multiple beams could provide a route to up-scaling processing speed and establish cost-effectiveness.

The use of spatial light modulators, driven by fast computer-generated holograms for splitting a parent laser beam into a number of beamlets and digitally manipulate their positions and the laser intensity is demonstrated. With successful blocking of the zero order beam and subsequent focusing of the diffracted beams inside transparent materials, high throughput dynamic 2D/3D refractive index modification of polymer and glass substrates with a gain factor \( G > 20 \) has been achieved. Fundamental IR (775nm) femtosecond laser pulses were employed to produce optical components. For example, thick volume gratings written with more than 20 beams have 1st order diffraction efficiency \( \eta > 60\% \), indicating a refractive index change \( \Delta n \approx 1.6 \times 10^{-4} \).

Characterization by microscopic examination and light coupling tests revealed the extent of resolution, process quality and assisted quantification of the process speed gain. The benefits and current limitations of this technique are discussed in detail.

Introduction

Multi-photon induced refractive index (RI) change \( \Delta n \) of optical materials has been suggested as a route to the creation of complex 3D integrated optical circuits [1, 2]. Use of pulse durations < 100 fs in the NIR shows clear advantages for generating highest \( \Delta n \) in, for example, fused silica and polymethyl methacrylate (PMMA) [3]. While for pulse durations > 160 fs, where optical breakdown is increasingly more likely, second harmonic UV refractive index modification of PMMA overcomes this limitation by reducing the order of non-linear absorption from three- to two-photon [4]. Laser repetition rates from kHz to MHz have been used for \( \Delta n \) structuring and this parameter is also important in determining the sign of refractive index change [5], while integrated fluence exposure still needs to be comparable. For example, at 1kHz, a NIR single pulse energy \( E_p < 1 \mu J \) is typically tightly focussed inside an optical substrate while \( E_p > 1 \) mJ is generally available, a light utilisation factor of < 0.1\%. At 1 kHz, \( \Delta n \) in PMMA (and fused silica) has been clearly shown to be positive, essential for single mode waveguides [4]. Phase gratings, optical waveguides, and couplers have previously been created with single point femtosecond processing in a wide range of materials [6 - 8]; however, the extension to complex 3D optical circuits may be significantly hampered, particularly as modification depths reach \( \sim 10 \mu m \) where a high numerical aperture (NA) objective would be required.

A Spatial Light Modulator (SLM) is a remarkable dynamic device of diffractive optical elements able to create a desired optical landscape through sophisticated control of the phase of an incident high intensity laser beam. Since parallel processing with arbitrary multiple-beam patterns using an SLM was first demonstrated by Hayasaki et al. [9], The approach has attracted increasing attention in many research areas, such as, dynamic high throughput laser parallel surface processing using SLMs with scanning galvanometers [10 - 12], 3D data storage in biological tissues [13], writing waveguides in glass with dynamic wavefront correction [14, 15].

In the work reported here, highly parallel refractive index structuring inside optical materials by combining a kHz femtosecond laser system with an SLM and thus producing a number of low fluence diffracted beams through applying CGHs is demonstrated. Consequently, the time for the fabrication of RI based optical engineering devices is reduced from hours to minutes, opening up new possibilities in optical circuit manufacturing processes.
Experimental

Fig. 1 shows a schematic of the experimental setup for internal structuring. The output from a Clark-MXR 2010 femtosecond laser system (775 nm, 160 fs, 1 kHz) was passed through a pick off (Autocorrelator) and 50/50 ultrafast beam splitter to turning mirror M1 then attenuated and expanded onto a Hamamatsu X10468-01 SLM. A 4f optical system consisting of two plano-convex lenses L1 and L2 (f1= f2 = 300 mm) reimaged the surface of the SLM (Plain A) to the back focal plain (plain D) of a microscope objective (Nikon, 0.15 NA). From the desired intensity distribution at focal plane of the objective, the corresponding CGH was calculated and applied to the SLM and the resulting phase pattern (8-bit greyscales) observed on a separate monitor elucidating phase distribution on the SLM. The zero order beam was blocked accordingly at plain P using a small target. Transparent substrates were scanned either transversely or longitudinally, as shown in Fig. 2.

Both Hamamatsu X10468-01 and Holoeye LC-R2500 used in the experiments were equipped with metallic coated mirrors, which cover a wide range of wavelength from visible to NIR, but offer relatively low light utilisation efficiency of about 75%. These two devices have different Liquid Crystal (LC) types. Applying a voltage to the X10468-01, which is a parallel-aligned nematic crystal device, results in the LC molecules aligning horizontally along the optical axis, hence leading to a phase change to the light polarised along the molecular axis, but leaving the light polarised perpendicular to the molecular axis completely unaffected. In comparison, the LC-R2500 has a 45° twisted nematic LC layer in which the LC molecules are arranged in a twisted array from the front to the back. This type of SLM can not only modulate the phase of light, but also rotate the plane of polarisation.

Previous work has demonstrated that the degree of symmetry of multiple-beam can greatly affect the intensity distribution across all beams [16]. Fig. 3(a) shows a common multiple-beam pattern with perfect symmetry for parallel processing. However, the symmetric multiple-beam suffers from low intensity uniformity even when using iterative algorithms like Gerchberg–Saxton (GS) (~ 60%) [17]. An approach to solve this problem is to introduce a small amount of random displacement to the multiple-beam pattern, since for most algorithms such as GS, Grating & Lens algorithm and Generalized Adaptive Additive algorithm, spatial randomization can significantly reduce the collective intensity variation [16]. Thus, in our experiments, the random displacement was applied to the Y-axis of the spots, while the separation Λ in the Z direction was fixed, as shown in Fig. 3(b), in order to optimize energy distribution across the multiple-beam. Holograms based on GS algorithm were calculated within a LabVIEW environment [18]. Other binary grating holograms were also employed.
Results and discussion

Static CGH multiple-beam 2D parallel direct writing

The result of parallel RI modification in PMMA with 12 nearly uniform beams having a period $\Lambda$ of 35 µm is shown in the optical micrograph of Fig. 4. The pulse energy in this case was 0.6 µJ/beam. Transverse scan speed was 1 mm/s and each modified region was scanned once only. Clear RI modification without optical breakdown was obtained.

Fig. 4: 12 beams direct writing in a PMMA sample.

Static CGH multiple-beam 3D parallel direct writing

By recalculating the CGHs to offset the focal planes of particular spots, simultaneous parallel 3D writing inside PMMA at different depths using 10 (2×5) diffracted beams in a double layer was demonstrated, as shown in Fig. 5. The writing parameters were the same as that used in Fig. 4.

Fig. 5: The result of ten (2×5) diffracted beams performing 3D direct writing in a PMMA sample, (a) front view of the top layer, (b) front view of the bottom layer and (c) cross section of two layers. The laser beams propagate along the +X direction.

3 beams (0 and ±1st order) with pulse energy of 5 µJ/beam produced by a binary grating hologram were used to fabricate cylindrical structures inside a fused silica sample (Fig. 6), which was translated in a helical motion at 10 µm/s towards the +X direction. The X-axis was parallel to the optical axis. The cylindrical structures produced, which were 1 mm in length and 200 µm in diameter, showed no sign of optical breakdown.

Fig. 6: Three beams direct fabrication of cylindrical structures in fused silica.

Dynamic CGHs multiple-beam 3D direct writing

The dynamic modification of fused silica with 5 beams (0, ±1st and ±2nd order), which were also generated by a binary grating, was demonstrated as shown in Fig. 7. The helical structures were produced by synchronising rotation of 5 beams through real-time display of 120 pre-calculated CGHs at a frequency of 20 Hz and a rotational interval of 3°, with linear translation of the stage along the +X direction at 0.5 mm/s. The laser beams with pulse energies of 1.5 µJ/beam propagated along the +X axis.
Fig. 7: A result of five beams, including 0, ±1st and ±2nd order, performing dynamic structuring of fused silica in a longitudinal writing geometry. (a) Schematic. The blue arrows indicate the rotation direction of the beams. (b) Micrograph of the modified region.

Fig. 8: A series of volume gratings written inside a PMMA sample and a magnified optical micrograph.

Fig. 9: Schematic showing the diffractive pattern with 21 diffracted beams. The volume grating was fabricated at a scanning speed of 1 mm/s.

Direct writing of volume gratings

As shown in Fig. 8, a series of 5 mm × 5 mm × 1 mm gratings with 19 µm period were written in PMMA. 21 diffracted beams with small randomisation (Fig. 9) were used for the parallel processing, hence greatly increasing the fabrication speed. Each of the gratings was completed within 10 minutes. The maximum diffraction efficiency of approximate 68% at the Bragg angle indicated that Δn was ~ 1.64 × 10⁻⁴, according to Kogelnik’s coupled wave theory [19]. The gain in writing speed meant that it was possible to increase the laser repetition rate by a gain factor G > 20, but without the drawbacks of higher laser frequencies, such as increased thermal accumulation effects and the necessity of increased translation speeds of the substrate, which would ultimately reach inertial limits of the motion control stages.

Conclusions

The work in this paper has demonstrated successful multiple-beam parallel ultrashort pulse laser internal structuring of PMMA and fused silica using SLMs. The desired diffracted beam patterns were modulated by CGHs, which were pre-calculated by appropriate algorithms. By focusing these diffracted beams using an objective into transparent materials, static and dynamic 2D/3D direct writing of different structures was achieved. The results revealed rapid precision microprocessing with high efficiency, signifying a potential route to fabricating a wide range of optical components inside optical materials at unprecedented speeds. The key limitations are the relatively low light utilisation efficiency and the low power handling capability of the SLMs here due to their metallic coated mirrors. However, other devices equipped with dielectric coated mirrors may solve these issues.

Acknowledgments

The authors gratefully acknowledge the support of the UK North West Development Agency under grant N0003200, the Technology Strategy Board (TSB) under the project PARALASE (Prog. No.: TP11/LLd/6/I/AF063B), and kind help from Prof. Miles Padgett and Dr. Jonathan Leach in the Department of Physics and Astronomy at the University of Glasgow, Scotland.

References


