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Focal zone engineering with hollow spatially variable waveplates applicable in laser micromachining

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Abstract

The ultrashort pulsed laser micromachining of transparent and opaque materials has become a mature technology providing microscale accuracy. While the ultrashort laser sources are being constantly developed with growing average power or more complex pulse temporal control, studies in the spatial domain can also lead to improving the performance i.e., higher process speed, better fabrication quality, etc. By purposely transforming the Gaussian beam of the laser output to a custom beam shape we are able to improve speed and quality in many laser micromachining tasks, where micro-welding of various materials is one of them. In this work, we apply custom hollow spatially variable waveplates based on nanograting technology (manufactured by Workshop of Photonics) that help to form curved or flat intensity distribution beams. Using numerical modeling and experimental research we will demonstrate beam transformations that could have an impact on enhancing the micro-welding process in terms of reduced stress or better heat dissipation.

Keywords: Glass welding; beam shaping; S-waveplate; nanogratings; flat-top beam

1.Introduction

The ultrashort laser irradiation has been proven to be an effective tool for various material micromachining tasks, one of that being the microwelding of similar and dissimilar materials [1]. The main advantages of this welding technique are localized modified material zone and avoidance of whole substrate heating,thus the whole process can be done under ordinary room conditions. It is an alternative to fusion bonding method in which high temperatures and vacuum conditions are needed. There are a lot of ongoing studies on improving the microwelding process in terms of enabling higher tolerances for possible gaps between weldable samples, as well as increasing bonding strength of joined glass [2,3]. Research works can be divided into two categories: temporal and spatial domain engineering. The welding process is mainly driven by heat accumulation and cooling off in the substrate, it requires complex improvements on laser sources to be able to shape pulses on time domain [4]. In this work, we investigate an improvement in microwelding with the alteration of a beam in the spatial domain using beam shaping techniques. We propose the use of hollow center spatially variable waveplates or so-called S-waveplates, that are manufactured by forming nanogratings inside fused silica glass [5,6]. The S-waveplate is a special optical element that alters the incoming beam polarization by creating azimuthally, radially or custom polarized light beams [7-9]. The created nanogratings are birefringent and the angle of their optical axis can be controlled during the fabrication process. By being able to create custom optical elements, we propose a concept of making spatially variable waveplates with hollow center zones. This element will induce polarization change in part of the beam, therefore it can be viewed as an element which splits the beam into two with different diffraction patterns and polarization states. This element enables us to form various beam intensity distributions of mixed polarization states that can be applied in transparent and opaque material laser micromachining.

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2. Focal zone engineering with hollow center S-waveplates

Method of beam shaping using the inscribed nanogratings in fused silica has been acknowledged for its efficient way to control polarization state, phase and amplitude of the input beams. The control of induced birefringence of the nanogratings and the angle of the slow/fast axis enables one to fabricate spatially variable waveplates [6]. Manufacture of custom designed retarders or waveplates helps to form new beam distribution applicable in various laser material micromachining: microcrack formation and dicing of various glasses [10,11].

In this work, we explore beam shaping perks to improve the welding process of thin glasses, in terms of better heat dissipation and reshaping the plasma region. By making custom hollow center S-waveplates, we make two beams, whose polarization states are different, and they can be superposed constructively [12]. The central part of the element lets the input beam propagate without a phase or polarization state change, while the outer part has inscribed spatially variable waveplate, that can be considered as a wave retarder transforming the phase and polarization state of the beam. The phase and polarization state alteration occurs due to so-called geometric (Pancharatnam-Berry) phase phenomenon [7]. For simplicity, we introduce a parameter η, that describes the ratio of input beam size w_{in} and the element's hollow zone diameter h. By adjusting this ratio, we are able to split the energy between the zones and alter the outcome after the element.

The simulation results of linear beam propagation in glass are shown in Fig. 1. The input beam is modelled as an ideal Gaussian beam with circular polarization state, described with Jones matrix calculus [13]. Then, it passes the hollow center S-waveplate, which is described as an optical element with retardance of half wavelength with continuously varying angle of the optical axis. Lastly, under the relatively low focusing conditions (NA = 0.2) we get expected beam patterns: from Gaussian-like distribution all the way to a donut intensity pattern just by changing the η parameter. The total intensity patterns are obtained as non-destructive interference results of two beams with opposite polarization states – right and left circular polarization what have different phase distributions.

The most interesting case is obtained when the size ratio is $\eta = 1.09$ [see Fig. 1 (b)]. With that, we are able to get a beam pattern of flat-top intensity distribution at the focus. The flat-top beams have been widely examined to increase the efficiency of laser ablation and create smoother craters with less tapered walls on various materials [14]. However, the true flat top beam does not have maximum intensity when the flat top beam forms, they usually have highest intensity at slightly different positions which becomes useless in the transparent material welding applications [15,16]. While this technique generates, the flat top beam which has maximum intensity at the formation of flat top position.

Another interesting case can be obtained when a polarizer is put into the optical scheme after our custom S-waveplate (see Fig. 1 I_x and I_y columns). By doing this, we emit half of the total energy and obtain a curved shape beam. The more expressed curve can be made with a bigger η ratio. All of those peculiar intensity distributions need to be examined whether they improve the welding process, as these beams can be generated in a convenient way using just a single custom optical element.

3. Experimental results

3.1 Optical setup

To verify the numerical simulation results, we carried out the experiment using the following optical setup shown in Fig. 2. The ultrashort pulse laser "Tangor" (Amplitude laser Ltd.) providing variable duration pulses from 500 fs to several ps at 1028 nm center wavelength and up to 2 MHz repetition rate was used. The pair of half waveplate and Brewster polarizer was used for power attenuation, then the manually variable beam expander was set to adjust input beam size relative to the size of manufactured hollow spatially variable waveplate.

Additional quarter wavelength plate was used to convert linear polarization to circular. The focusing lens of 8 mm focal length was used to induce modifications in the Schott D263T glass volume of two samples in optical contact.

3.2 Beam measurements

For the first iteration, S-waveplate of order $n = 1$ having a 3 mm diameter hollow center zone was manufactured. The retardance and slow axis measurements with a birefringence microscope are shown in Fig. 3.

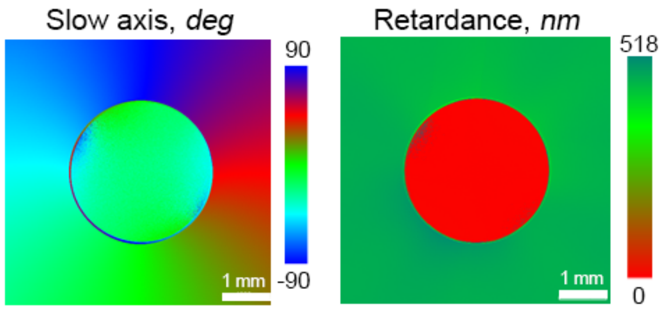

Fig. 3. Birefringence measurements of manufactured hollow S-waveplate center, where the central empty zone is 3 mm in diameter and the outer zone was made up to 8 mm in diameter.

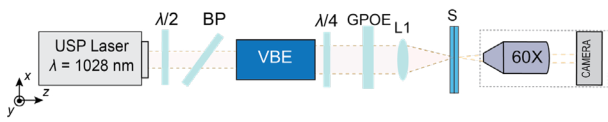

Fig. 2. Principal optical scheme for the hollow center S-waveplate testing experiments, where λ/2 is a half waveplate, BP is Brewster polarizer, VBE is manually variable beam expander λ/4 is a quarter waveplate, GPOE is hollow S-waveplate, L1 is focusing lens of 8 mm, S is glass substrate, consisting of two 200 µm thick samples in optical contact. The last part of the setup with 60X magnifying microscope objective and CMOS camera is used for beam intensity measurements and it is put away then glass fabrication is performed.

The most promising property of using our custom S-waveplates is the ability to form expected beam shapes at the focal zone where the intensity is the highest, that is very likely suitable for transparent material micromachining. As predicted in the modelling results, the final outcome shape at the focus depends on input beam size, from that, the most interesting case is the *semi* flat-top beam shape, obtained when the input size and hollow center ratio is $\eta = 1.09$. The experimental measurements at this condition over the focal area are shown in Fig. 4(a).

From the experiment measurements, we can see that the principle works well, creating rather a non-ideal flat-top beam distribution at the focus where the intensity is at the highest level. The flatness variation is less than 10% peak to valley. For better quality results, we would need an ideal input beam and remove any aberrations in the optical system that cause distortions, thereby better results can be expected with additional iterations. When a polarized beam was put in the scheme [see Fig. 4 (b) and (c)], curved shaped beams were also obtained. Depending on the polarizer's optical axis position, we registered two oppositely curved shapes, meaning that these two beams have opposite polarization states and their superposition does not have destructive interference. The isosurfaces graphs at the bottom row in Fig. 4 clearly show that the beams are formed in the highest intensity place of the Rayleigh range.

3.3 Glass welding

As the beam forming concept seemed to be effective, here in the last part, the obtained beams were tested to induce special modifications in transparent material. A comparison of microwelding performance between ordinary Gaussian beam,

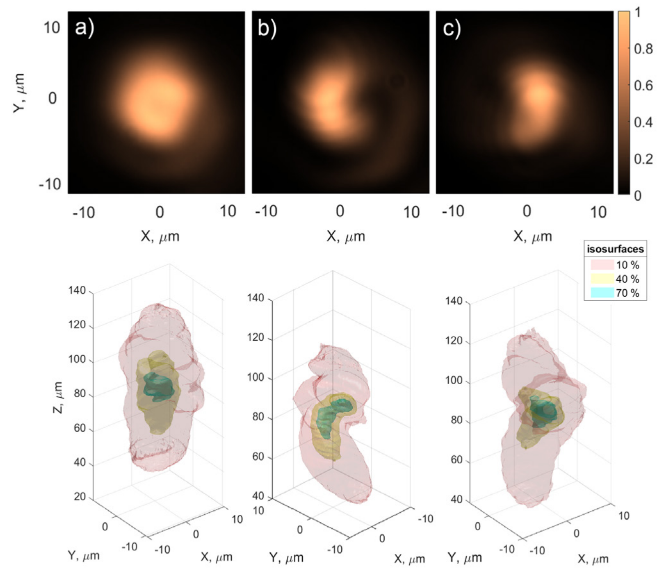

Fig. 4. Experimental beams measurements using hollow S-waveplate at the focal region, where (a) the best flat-top intensity distribution is achieved, (b) Ix component of the field and (c) Iy component obtained with additional polarizer. The bottom row represents isosurfaces of intensity fields at the focal zone.

flat-top and curved shape beams was done. The sideviews of induced modifications are shown in Fig. 5. Here, in part (a) the flat-top was used, while in part (b) the curved beam with a polarizer was used and ordinary Gaussian beam without any alterations are shown in part (c). Two regimes with different pulse duration were used: 500 fs and 5 ps. From the pictures, we can see the differences of plasma region shapes. The obtained plasma shape with ordinary Gaussian beam (c) has "growing" and an elongated form that resembles an outstretched droplet. At a fixed average power of 1.35 W and

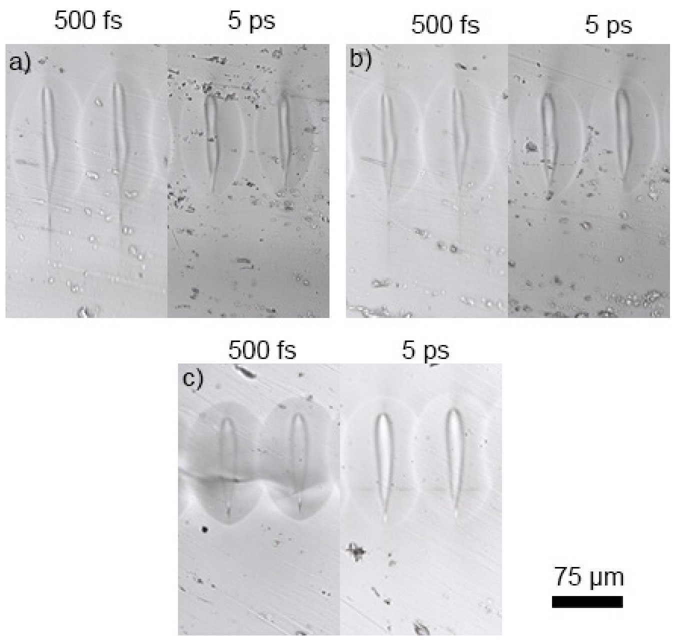

Fig. 5. Laser induced welding seams on a side view when two different pulse duration regimes were used: 500 fs and 5 ps. In (a) experimentally obtained flat-top beam was used, (b) curved shape beam and (c) normal Gaussian beam without alterations was used. Total 1.35 W average laser power was used at 2 MHz repetition rate, 10 mm/s scanning speed and focusing at 200 µm depth with 0.2 NA. The glass is Schott D263T. The pulse propagation direction is from top to bottom.

pulse repetition rate of 2 MHz, in the femtosecond regime, some cracking occurred at the interface of two bonded samples. Quite different results can be seen in parts (a) and (b) where plasma and molten material regions were created by altered beams using hollow center S-waveplate. The plasma shape resembles more like a constant width shape going from the focus point at the bottom to the top. While the molten material region is likely more elongated surrounding the plasma center. Any cracking was not observed of the induced modifications using pulse of 500 fs duration at the same average power of 1.35 W and 2 MHz repetition rate.

However, some sort of filament tracks below the plasma region induced by 500 fs duration pulses can be seen in Fig. 5(a) and (b). The cause of such defects remains unknown. We assume that the main advantage of using a flat-top beam could be bigger spot size at similar focusing conditions, providing better heat dissipation and slightly elongated molten material pool. Although the differences in weld seams between the results are distinguishable, more research work is needed to fully understand the benefits of using hollow S-waveplates for microwelding of various materials.

4.Conclusion

In this study, we have investigated hollow center S-waveplates that can be used to generate flat-top beams in the focal zone. The experimentally obtained flat-top intensity variation was less than 10% peak to valley. By adjusting input beam size, different beam shapes were also generated. The induced material modifications were compared and it was noted that there were no major advantages in the welding strength, while the differences in generated plasma region could be clearly seen. Using the same average power, weld seams made by focusing ordinary Gaussian beam induced cracks, while using our custom S-waveplate it was avoided. However, more studies are needed in order to fully understand whether the shaping technique is able to improve the welding task and as well as other possible uses in other forms of laser micromachining.

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