3D BEAM SHAPING FOR VOLUMETRIC LASER PROCESSING

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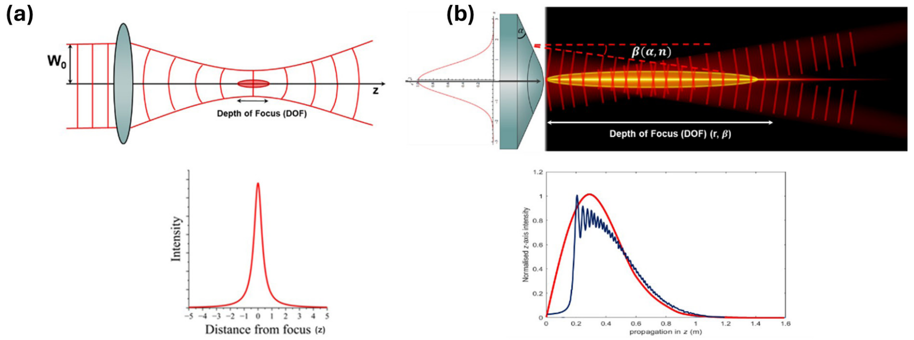

Figure 1: Diagram of beam propagation through a standard convex lens (a), compared to the formation of a Bessel beam through an axicon (b). Illustrating the difference in the on-axis intensity profile and extended depth of focus. Blue line in (b) also shows effects of tip rounding on the resultant intensity profile.

As microelectronics continues to scale toward smaller dimensions with higher performance, conventional silicon-based manufacturing and packaging technologies are approaching their physical limits. In response, alternative interconnect technologies, such as through-glass vias (TGVs) are beginning to emerge as a promising solution for next generation chipset integration [1]. Glass interposers offer several advantages including lower electrical losses, higher electrical resistivity, and the potential for a higher density of interconnections at reduced manufacturing costs. However, fabricating high aspect ratio uniform vias in glass quickly remains challenging, with conventional laser-based methods producing tapered and non-uniform features limiting throughput and overall productivity.

ULTRASHORT LASER SELECTIVE ETCHING

While there has been recent work investigating direct drilling of TGVs [2], these are typically fabricated using a two-step process that combines ultrashort laser inscription, and selective chemical etching. During laser inscription, the glass substrate is translated through the laser focus, inscribing localised modification tracks. These modification regions are then preferentially etched at a faster rate than the pristine glass, enabling the formation of well-defined microstructures.

Current methods generally rely on Gaussian beam focussing, where the focal spot size and focal depth are inherently coupled, restricting achievable aspect ratios. To generate high-aspect ratio vias the focal volume must be translated throughout the full sample, since small focal volumes are required to achieve non-linear absorption. This necessitates multiple pulses to be delivered at different locations to mark larger volumes, hence increasing processing time. Due to the modification shape following the axial intensity profile of the beam, TGVs often taper along their length producing a distinct hourglass feature limiting via density (Figure 1a).

As a result, the use of non-Gaussian beam profiles such as quasi-Bessel beams (QBBs) in laser material processing is increasing, due to their ability to generate extended focal volumes with an invariant spot size along the axis of propagation, where the spot size and focal depth are also decoupled [3]. They can exist in the order of centimetres with micron-sized focal spots, unlike the much shorter focal depths of gaussian beams in the order of ~1×10^{-5} m for comparable spot sizes [4]. However, standard Bessel beams display an asymmetric intensity profile along the axial direction (see Figure 1(b)), which results in variations in the produced feature shape. Imperfections in the manufacturing of the optic can also cause interference due to tip rounding errors [5]. Therefore, a method to shape and modify the intensity profile along the full focal depth is required.

3D BEAM SHAPING

Conventional beam shaping methods such as diffractive optical elements (DOEs) or spatial light modulators (SLMs) are effective at generating an arbitrary beam shape in the transverse direction but offer limited control over the axial intensity, where away from the focal plane the beam quality rapidly degrades, making these methods unsuitable for volumetric laser processing.

Here we propose a three-dimensional beam shaping solution based on QBBs (Figure 2). Since the resultant on-axis intensity of the QBB is determined by the incident intensity profile and radius dependant refraction angle; shaping the incident wavefront gives a method to manipulate the axial intensity profile. This is achieved using a pair of custom refractive optics: the first shapes the input Gaussian intensity to a desired target transverse profile, whilst the second compensates for any phase aberrations, producing a collimated output. By redistributing the energy of the beam into a ring-shaped profile, contributions from rays interacting with the axicon tip are suppressed, mitigating unwanted interference effects due to tip rounding.

EXPERIMENTAL DEMONSTRATION

To demonstrate the feasibility of this method for laser processing, we generated single-pulse laser modifications in bulk fused silica for a range of pulse energies in the region of 100s μJ in the picosecond regime.

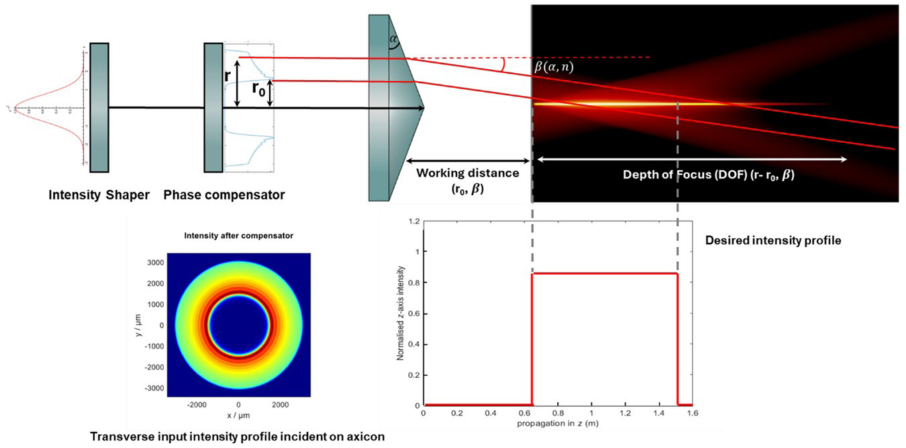

Figure 2: Schematic diagram of the proposed 3D beam shaping solution to produce a uniform on-axis intensity profile from a QBB by exploiting the fact that the radial intensity incident on the axicon is proportional to the axial intensity within the QBB. Refractive optics reshape the input Gaussian beam into a desired transverse profile.

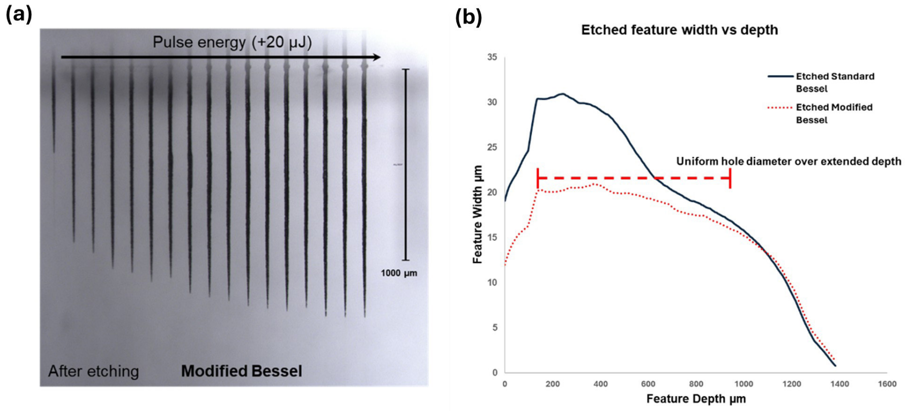

Figure 3: (a) Cross section of microchannels laser inscribed and etched in fused silica with modified Bessel beam with increasing pulse energy. (b) Comparison between the etched feature width vs depth for both standard and modified Bessel beam.

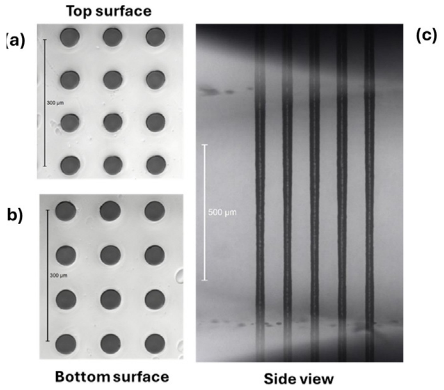

Figure 4: Etched through holes in 1 mm thick fused silica substrate, generated by single picosecond pulses with modified Bessel beam. (a) Top surface, (b) bottom surface (c) cross section of hole profile.

Modifications were made using both a standard quasi-Bessel beam, and a modified Bessel beam, with a unform axial intensity distribution spanning ~800 μm, which were subsequently analysed after selective chemical etching in NaOH for 24 hrs (Figure 3).

Features made with the standard Bessel show significant variation in the hole width along the propagation direction, consistently following the asymmetric intensity. In contrast, the modified Bessel produced features with a significantly more uniform modification observed over a several hundred-micron range, hole dimeter of ~20 μm for ~700 μm.

We extend this work to the fabrication of through-holes in 1 mm thick fused silica samples. We observed similar levels of uniformity throughout the bulk of the material, and with minimal variation in the inlet and outlet hole diameters (Figure 4).

With only a single pulse required per modification this technique allows for substantially faster processing times, whilst also offering the ability to process thicker glass substrates with high aspect ratios; currently we have achieved aspect ratios of 1:40.

CONCLUSION

Modified Bessel beams provide a simple and intuitive method to generate arbitrary circularly symmetric axial intensity profiles. Here we show one example of a uniform intensity over an extended focal depth, allowing for minimal taper high-aspect ratio modifications in glass to be fabricated. Taking advantage of the extended focal depth afforded by quasi-Bessel beams, with their spot size invariance, it is possible to laser inscribe thicker glass substrates with a single pulse, drastically reducing laser processing times and increasing productivity. We envisage this beam-shaping approach being extended to other applications such as laser welding, waveguide inscription, and various applications which require the use of volumetric processing in transparent materials.

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