Multi-focal laser processing in transparent materials using an ultrafast tunable acoustic lens

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Received 8 November 2021; revised 11 February 2022; accepted 24 February 2022; posted 25 February 2022; published 18 March 2022

Fast and versatile alteration of focal positions is critical for applications including selective volumetric modification and parallel laser processing. In this Letter, we implement and characterize an ultrafast, variable focal system using a tunable acoustic gradient of index lens to achieve multi-focal laser processing. We apply our method to the femtosecond laser-induced intra-volumetric modification in glass to show the flexibility in controlling focal positions. Based on this understanding, we exploit the multi-focal nature of the system to demonstrate laser machining on both surfaces of a transparent glass slide in a single lateral scan. © 2022 Optica Publishing Group

https://doi.org/10.1364/OL.447854

Shaping the laser beam from a single focus to multiple foci is beneficial for many laser processing applications [1,2]. In these applications, multi-focal optical systems deliver energy efficiently to multiple designated locations on the beam path. Moreover, the development of multi-focal techniques increases the throughput of tightly focused laser processing systems with high spatial resolutions. For example, the multi-photon absorption of femtosecond laser in transparent materials occurs only in a highly confined focal spot of sub-micrometer size. By expanding the number of processing sites, the multi-focal beam shaping can boost the micromachining speed of transparent materials.

Traditional methods to achieve this goal mostly use diffractive or refractive optics, which can only generate a fixed multi-focal beam pattern once set up. The early invention of the dual-focal lens, for example, is a refractive optical element consisting of two concentric circular regions with different focal lengths [3]. Another refractive optics method adopts a modified Newton’s ring setup, which employs a lens splitter, a convex mirror, and a focusing lens to output two collinear beams [4]. Alternatively, one can use diffractive optical elements with the Fresnel zone plate (FZP) pattern to generate multiple foci [5]. The computed FZP pattern can be directly fabricated by lithography [6]. This method is adaptable in terms of the number of foci, the operating wavelength, and the energy distribution, but these parameters are all pre-set prior to manufacturing [7]. The recent advent of adaptive optics has paved the way for a more flexible beam shaping [8]. The phased-engineered patterns or the computer-generated holograms can be projected on digital micromirror devices (DMDs) or spatial light modulators (SLMs). However, many of the reported response rates are less than 100 Hz [9,10]. Overall, the above multi-focal methods may not adjust dynamically and promptly. They may also suffer from complexity in computation and overall fabrication. The lack of response rate and flexibility limits the efficiency of focal control and restricts multi-focal techniques to only certain applications. Fast and tunable alteration of focal positions to tailor focusing as needed remains a challenging task.

A strong candidate in pursuing ultrafast beam shaping with a response time of the order of one microsecond is the recently developed class of acousto-optofluidic (AOF) lenses. An AOF lens is a type of liquid adaptive lens driven by piezoelectric materials. The induced acoustic standing waves inside the liquid lens modulate its refractive index. With AOF lenses, a single laser beam can be engineered into multiple beamlets in the lateral (xy) plane [2,11] or a scanning focal spot along the axial (z) axis [12]. The family of AOF lenses has already proven effective in applications in both imaging [13,14] and micromachining [15–17]. In this Letter, we propose an ultrafast varifocal system that scans the axial dimension using an AOF lens, called the tunable acoustic gradient of index (TAG) lens. A TAG lens can oscillate between a converging and a diverging lens at rates ranging from kHz to MHz [12]. By synchronizing the laser pulses at selective single or multiple phases of the varifocal lens, we can shape the beam pulse-by-pulse into one or several focal spots at selected positions without physically moving any optics.

The schematic of the multi-focal micromachining setup, including a femtosecond (fs) laser (800 nm, 1000 Hz, Spectra-Physics), a TAG lens (Mitutoyo), an objective lens, and a three-axis stage, is displayed in Fig. 1(a). The axial focal position z oscillates continuously as a function of time t. We denote the positive z direction as the beam propagation direction and zero z at the exit of the objective lens. The TAG lens is powered by an RF signal (S1) with an amplitude of Vg from the TAG controller, as plotted in Fig. 1(b). A trigger signal (S2) can be sent from the TAG controller to the laser to enable focal control. Unlike a conventional single-focal setup, the focal position of the laser beam measured after the objective lens z(t) is described by

\[ z(t) \approx z_0 + z_{avg} \cos(2\pi f_{osc}t + \phi_0) , \]  

where \( z_0 \), \( z_{avg} \), and \( f_{osc} \) are the average, the amplitude, and the frequency of the oscillating focal position in z. Here \( \phi_0 \) is an
arbitrary initial phase. Taking \( \phi_0 = 0 \), we plot \( z(t) \) in Fig. 1(c).

Lumping all the phase terms in \( z(t) \), one can also describe the scanning focal position as

\[
z(\phi) \approx z_0 + z_{\text{tag}} \cos(\phi),
\]

where \( \phi \), the oscillation phase, is the key parameter for our focal control method as it is used to trigger the laser. Here \( z_0 \) is measured as the average of the minimum and maximum of \( z(t) \), also corresponding to \( z(90^\circ) \). The frequency \( f_{\text{tag}} \) is determined by the driving frequency of \( S1 \) and set at the resonance frequencies of the piezoelectric shell inside the TAG lens [12]. The focal oscillation amplitude \( z_{\text{tag}} \) is linearly proportional to the amplitude \( V_p \) of \( S1 \) [14], and this linear relation is later characterized. Fundamentally, \( z_{\text{tag}} \) is determined by the optical power of both the objective lens and the TAG lens. Considering an objective lens with a focal length of \( f_0 \) and placed immediately next to the TAG lens,

\[
\frac{1}{z(\phi)} = \frac{1}{f_0} + \alpha p(\phi),
\]

where \( \alpha p(\phi) \) represents the oscillating optical power of the TAG lens, and is a sine/cosine function of \( \phi \). Thus, the total scanning range is

\[
2z_{\text{tag}} = z(0^\circ) - z(180^\circ) \approx f_0 \cdot [\alpha p(180^\circ) - \alpha p(0^\circ)].
\]

Note that the approximation of \( z(t) \), \( \phi(t) \), and \( z_{\text{tag}} \) in Eqs. (1)–(4) is only valid when \( |\alpha p(\phi)| \ll \frac{1}{f_0} \). This condition holds for most micromachining systems because the optical power of the TAG lens is of the scale of \( m^{-1} \), which is significantly lower than that of the objective lens.

The laser system can run synchronized or asynchronized with the TAG lens. In the asynchronized (async) mode, the laser pulses at its repetition rate while the TAG lens scans continuously without externally triggering the laser \( (S2 = 0) \). The laser fires at its internal repetition rate and its focal position is described by \( z(t) \). For example, Fig. 1(d) plots the focal positions of a train of 40 asynchronized laser pulses with a frequency 10 times larger than \( f_{\text{tag}} \), marked by the hollow circles. In the synchronized (sync) mode, the laser is triggered at selected one or multiple phases \( (\phi) \) of the TAG lens by the transistor–transistor logic (TTL) pulse \( (S2) \) from the TAG controller. In Figs. 1(e) and 1(f), we plot the dual-focal scenario, where \( S2 \) rises at both \( \phi = 0^\circ \) and \( \phi = 180^\circ \), and the selected focal positions of synchronized laser pulses are at \( z = z_0 + z_{\text{tag}} \) and \( z = z_0 - z_{\text{tag}} \). The two focal positions are denoted by the up-pointing and down-pointing triangles.

To demonstrate the flexibility of our approach in manipulating focal positions, we perform fs laser-induced intra-volumetric modification in a 1 cm six-sided polished cube of borosilicate glass using the above multi-focal machining setup. Femtosecond pulses are directed through the TAG lens and a 40× objective lens [numerical aperture (NA) = 0.65], inducing damaged tracks inside the glass sample, as sketched in Fig. 2(a). The induced filamentation tracks are imaged laterally \((xz)\) with an optical microscope. The async mode and the sync mode with two or three selected phases are compared in Figs. 2(b)–2(d), with a pulse energy of 300 \( \mu \)J and the stage moves laterally at 10 mm/s in the \( x \) direction. Thus, the distance between adjacent tracks in the async mode is 10 \( \mu \)m. For the axial scanning parameters, we set \( f_{\text{tag}} \) to 140 000 Hz, \( V_p \) of the driving signal \( S1 \) to 12 V, and \( z_{\text{tag}} \) is measured to be roughly 25 \( \mu \)m from the tracks. Following the analysis of Eqs. (3)–(5) in [17], the frequency ratio between the laser \((1000\text{Hz})\) and the TAG lens \((140\text{kHz})\) creates an oscillating pattern with approximately 100 \( \mu \)m in length or equivalently 10 pulses per period in the async mode. In the sync mode shown in Figs. 2(c) and 2(d), only two and three out of the previous 10 laser pulses per period are triggered at the selected focal positions \( z = z_0 + z_{\text{tag}} \), \( z = z_0 \), and \( z = z_0 - z_{\text{tag}} \), corresponding to the selected phase \( \phi \) at 0°, 90°, and 180°. The measured average length of the periodic pattern \( L \) in Figs. 2(b)–2(d) is \( L = 109 \mu m \). Up to three focal planes are generated per axial scanning period, limited by the triggering signal’s width \( \Delta t \) at 1 \( \mu s \).

To avoid overlapping of the triggering signals, the maximum number of planes in a single axial scanning period is \( 1/(2f_{\text{tag}}\Delta t) \), which is 3.6 with \( f_{\text{tag}} = 140 \text{kHz} \) and \( \Delta t = 1 \mu s \). However, more axial positions can be created if the triggering phase is varied with time. For example, we include experiments showing four focal planes and further discussions on how \( \Delta t \) relates to the axial width of the written pulses in Supplement 1.
After successfully achieving focal control with the TAG lens, characterization of the optical system is necessary before applying it to multi-focal machining. We investigate dual-focal laser processing in particular for its potential application in transparent material scribing and dicing, which typically involves a single layer with two surfaces. Various ablation experiments are conducted on a Si wafer (500 \( \mu \)m thickness) to characterize the system with a 10x objective lens (NA = 0.25). To measure the beam radius, we perform a single-shot ablation experiment following Liu’s method [18] when the TAG lens is off. The areas of the ablated craters are measured and fitted in two energy regimes. In Fig. 3(a), the calculated beam radius \( w_p \) is 7 \( \mu \)m at the low-energy regime. Each data point is repeated five times. The focal oscillation amplitude \( z_{osc} \), at its resonance frequency \( f_{osc} = 140 \text{ 100 Hz} \) is characterized by a z-scan ablation experiment (see Supplement 1 for more details) and displayed in Fig. 3(b), where the TAG lens operates with varying amplitude \( \zeta \) and displayed in for a specific relation. Using this relation, we can look up for appropriate \( V_p \) for a specific \( z_{osc} \). To characterize the lens power of the TAG lens \( \zeta(\phi) \), we trigger laser pulses at several single phases between 0° and 180° and measure the beam curvature at each phase five times using a Shack–Hartmann wavefront sensor. Figure 3(c) plots the characterized optical power \( \zeta(\phi) \) for \( V_p = 15 \) V and a cosine fit to \( \phi \). Importantly, we can notice that the average optical power is not aligned with the zero optical power at TAG off \( (V_p = 0 \text{  V}) \), in solid line). This asymmetric optical power at the maximum diverging (0°) and converging (180°) phases stems from its lens mechanics, as documented in its manual [19]. Due to the oscillating optical power of the TAG lens, the variation in NA changes the beam spot size, which influences the ablation characteristics on materials. To assess this effect, we simulate the fluence of the beam at different phases. Figure 3(d) simulates the normalized intensity profile of the single-focal versus the dual-focal mode along the z axis. We also compare the fluence distributions for the single-focal and dual-focal mode, with laser energy of 10 \( \mu \)J in Figs. 3(e) and 3(f). Assuming a constant entrance beam size, \( NA(\phi) \propto z(\phi) \). For a 10x objective lens with NA = 0.25, \( NA(\phi) \) varies between 0.247 to 0.254, based on \( z(180°) \) and \( z(0°) \) calculated by Eq. (2). The variation in NA and beam spot size is responsible for the different ablation characteristics observed in our experiments.

Finally, we exploit the multi-focal nature of our method to prove the feasibility of laser machining on both sides of a transparent microscope glass slide in a single lateral scan. Figure 4(a) presents our machining target, where a transparent glass slide of 1 mm thickness is positioned on top of a Si wafer of 500 \( \mu \)m thickness and mounted on the stage. The three axes are labeled. As with our earlier discussion, \( z \) points in the beam propagation direction. At the exit of the objective lens \( z \) is zero. We refer to the top surface of the glass slide as surface A, and the Si surface (in contact with the bottom surface of the glass slide) as surface B. In the single-focal mode or when the TAG lens is turned off, one can only ablate the surface at A or B by focusing at the close vicinity of A or B. Since the distance between surfaces A and B is substantially larger than the Rayleigh length of the laser beam (<200 \( \mu \)m), simultaneous ablation of A and B is impossible.

A z-scan line ablation experiment with our multi-layer sample is included in Figs. 4(b) and 4(c). Here we can compare the single-focal (TAG off) and dual-focal (TAG on) modes. For both images, starting from the right, each line corresponds to an ablated line along the x axis, with a \( z \) incremental step of 100 \( \mu \)m (moving away from the objective lens). Laser pulses with energies of 10 \( \mu \)J and 15 \( \mu \)J are directed through the TAG lens and the 10x objective lens to the sample. The lateral speed of the stage in \( x \) is 0.65 mm/s. For clear notation, we denote the locations of both surfaces by \( z_A - f_0 \) and \( z_B - f_0 \), and label them in Fig. 4(c). For example, when the laser focuses on the surface A in the single-focal mode, \( z_A - f_0 = 0 \). We can approximate the optical distance between two surfaces using the physical thickness of the glass divided by its refractive index (at around 1.5), which gives a distance of 667 \( \mu \)m. From the experiment in the single-focal mode shown in Figs. 4(b) and 4(c), \( z \) distance between the ablated lines on A and B is measured between 700 and 800 \( \mu \)m. The difference between the calculated and measured value is acceptable considering the relatively low resolution of \( z \) stage with a coarse step size of 100 \( \mu \)m. The strategy to ablate both surfaces with one lateral scan is to direct sync pulses at \( \phi = 0° \) to surface B and sync pulses at \( \phi = 180° \) to surface A. Therefore, the focal scanning amplitude \( z_{osc} \) should be half of the distance between the two surfaces, which in our sample is around 334 \( \mu \)m from the theoretical calculation of the distance. Using the linear relation between \( V_p \) and \( z_{osc} \) in our characterization [Fig. 3(b)], we set \( V_p \) to 15 V, \( f_{osc} \) to 140100 Hz, so that \( z_{osc} \) is matched at 327 \( \mu \)m. In the dual-focal mode, combined ablation lines appear on both

![Fig. 3. Characterization of the multi-focal machining setup with a 10x objective lens.](image-url)
A and B at $z_A = f_0 - 0.2 \text{ mm}$ ($z_B = f_0 + 0.6 \text{ mm}$), indicating both surfaces are ablated at the same z location.

To better compare the single-focal and the dual-focal mode, the depth of the ablated lines on glass and Si are measured by a confocal microscope, as plotted in Fig. 4(c). The error bar is calculated from the standard deviation of the depth for a total of 1024 data points (or 256 µm in length) along the ablated line in the x axis. When the scanning center $z_0$ is positioned at the center of two surfaces, the maximum converging beam at $\phi = 180^\circ$ is focused on the surface A and the maximum diverging beam at $\phi = 0^\circ$ is focused on the surface B. This corresponds to the optimal ablation case where surface A is positioned off focus toward the objective lens by 0.2 mm. The overlapped shaded areas also indicate that both surfaces are ablated at the same location ($z_A - f_0 = -0.2 \text{ mm}$). The asymmetry of the ablation depth in the dual-focal mode, compared with the single-focal mode, originates from the optical power of the TAG lens as explained in Figs. 3(c) and 3(d). Since only half of the pulses are deposited on each surface, the ablated depths of both materials are about half of those in the single-focal mode. Figure 4(d) exhibits the direct comparison of single-focal and multi-focal strategies for marking a letter “P” (100 µm by 200 µm) on the glass slide with 15 µJ energy and using the same processing parameters as the above. Within one lateral scan, both surfaces of the glass are marked in dual-focal mode. This is not possible in the single-focal mode, where only the top or the bottom surface is marked.

In this Letter, we present and characterize an ultrafast and adaptable laser direct-write system based on a TAG lens. Practically, we apply our method to fs laser-induced intra-volumetric modification in glass with multiple focal spots and demonstrate dual-focal laser machining on both surfaces of a transparent glass slide in a single lateral scan. The key to our focal control method is triggering the laser at the selected phases of the TAG lens. This synchronization between the laser and the varifocal lens efficiently allocates laser energy to the desired locations without mechanically moving any optics. Therefore, our multi-focal system can be employed in many laser processing techniques for transparent materials, such as dicing, scribing, and marking. Another advantage of this method is its response rate at the hundreds of kHz scale, allowing for high throughput multi-focal processing to match the emerging ultrafast pulsed lasers at the MHz range.

Acknowledgment. We acknowledge the help from Dr. Kwangdong Roh for the fabrication of samples, and Dr. Wenxuan Zhang for helpful discussions. We acknowledge the support from Mitutoyo Corporation.

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this Letter are not publicly available at this time but may be obtained from the authors upon reasonable request.

Supplemental document. See Supplement 1 for supporting content.

REFERENCES