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Xiaohan Du\textsuperscript{a,b}, Camilo Florian\textsuperscript{b}, and Craig B.Arnold\textsuperscript{a,b}

\textsuperscript{a}Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ 08544.
\textsuperscript{b}Princeton Institute for the Science and Technology of Materials, Princeton University, Princeton, NJ 08544.

ABSTRACT

Multi-focal beam shaping can enhance laser processing throughput by increasing the number of processing sites and lowering processing time. This paper implements multi-focal beam shaping by adopting a tunable acoustic gradient of index (TAG) lens, which scans the focal position in the axial direction at 140 kHz. When the laser is synced with the corresponding phases of the TAG lens, multiple focal spots can be selected, allowing for ultrafast and flexible multi-focal modulation without physically moving any optics. We further characterize the tuning parameters of the TAG lens, such as its frequency, amplitude, and phase, and demonstrate the dual-focal marking on both sides of a glass slide in a single lateral scan.

Keywords: multi-focal, dual-focal, ultrafast, z-scanning, acousto-optofluidic, femtosecond laser, TAG lens

1. INTRODUCTION

The ability to deliver energy efficiently to designated locations is critical in laser processing, especially for the micromachining of transparent materials. The majority of laser micro-machining systems employ a single-focal approach, in which the laser energy is concentrated to a single, tiny voxel to treat the surface or bulk of a substrate. When the single voxel is expanded to multiple focal spots, the number of processing sites and hence the machining throughput increases for laser processing of transparent materials.\textsuperscript{1,2} Commonly, multi-focal processing adopts an additional varifocal optical element in the beam path. However, some of the varifocal lenses are incapable of rapidly adjusting focal spots. For example, the mechanical Alvarez/Moiré lens,\textsuperscript{3,4} the membrane-based microfluidic lens,\textsuperscript{5} the electro-optical liquid crystal lens,\textsuperscript{6} and the computer-generated holograph (CGH) on spatial light modulators (SLM)\textsuperscript{7} are limited to a response time in the scale of ms for varifocal applications.\textsuperscript{8}

In addition to the response rate, another key feature required for high-efficiency multi-processing is the flexibility of the adopted varifocal lens, which enables flexible alteration of both the number and position of the generated foci.

To accomplish both ultrafast and tunable multi-focal beam shaping, we use a tunable acoustic gradient of index (TAG) lens.\textsuperscript{9} The TAG lens acts as an acousto-optofluidic z-scanner to continuously oscillate its focal position at rates ranging from kHz to MHz without physically moving any optics or repositioning the sample.\textsuperscript{10–12} The laser is triggered at one or multiple selected focal positions when synchronized with the matching phases of the TAG lens for versatile multi-focal control. To characterize our method, the additional tuning parameters introduced to the system by the TAG lens, such as its frequency, amplitude, and phase, are studied. Based on this parametric analysis, we optimize the TAG lens characteristics for a chosen multi-focal machining target and perform multi-focal laser marking on both sides of a glass slide in a single lateral scan.

Further author information: (Send correspondence to C.B.A.)
X.D.: E-mail: xiaohand@princeton.edu
C.F.: E-mail: camiloflorian@princeton.edu
C.B.A.: E-mail: cbarnold@princeton.edu
2. METHODS

Fig. 1 (a) shows a schematic of the multi-focal laser machining system. The laser is a femtosecond laser with a wavelength of 800 nm and a pulse duration of 100 fs. The laser repetition rate, $f_{\text{laser}}$, is fixed at 1 kHz. A TAG lens (TLHP, Mitutoyo) is placed before the objective lens with a focal length of $f_0$. It generates an oscillating focal position $z$, which can be expressed as $z(t) = z_0 + z_{tag} \times \cos(2\pi f_{tag}t)$, where $f_{tag}$ and $z_{tag}$ are the frequency and amplitude of focal oscillation, determined by the operating condition of the TAG controller. The positive $z$ points in the beam propagation direction. The TAG lens can operate at a tunable frequency $f_{tag}$ around 140 kHz and a tunable voltage amplitude $V_p$ up to 15 V. The voltage amplitude adjusts the optical power of the TAG lens and the resulting axial scanning amplitude $z_{tag}$. By synchronizing the laser at certain operating phases $\phi$ of the TAG lens, laser pulses are focused at specifically desired locations. For example, Fig. 1 (b) plots the measured focal position after subtracting the original focal length of the objective lens ($z - f_0$) of laser pulses triggered by a single phase $\phi$ of the TAG lens ranging from 0° to 180°. The measurement is performed by a z-scan ablation experiment on Si wafers with a 10× objective, $f_{tag}$ at 140100 Hz, and $V_p$ at 15 V. Note that the $z_0$ is not equivalent to $f_0$ due to the asymmetry of the TAG lens. The total scanning range $2z_{tag}$ is approximately 1 mm, as measured by $z(0°) - z(180°)$. If the laser is triggered at multiple phases of the TAG lens, multiple focal positions are created quasi-simultaneously as $f_{\text{laser}} \ll f_{tag}$.

![Figure 1](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)

3. RESULTS

3.1 Parametric study of the TAG lens

3.1.1 Frequency

Although the TAG lens operates at a frequency set by its resonating liquid cavity (around 140 kHz), a small change in its resonance frequency can produce a distinct periodic focal scanning pattern for a pulsed laser. For example, Fig. 2 displays the femtosecond laser-induced damage in BK7 glass for $f_{tag} = 140100$ Hz and $f_{tag} = 140050$ Hz. Experiments are performed with a 40× objective lens and 300 µJ energy per pulse. The lateral distance between the induced filaments is 10 µm, and the laser is not synchronized with the TAG lens. Due to the frequency mismatch between $f_{tag}$ and $f_{\text{laser}}$, periodic focal scanning patterns of 10 and 20 pulses are generated, as shown in Fig. 2 (a) and (b). Here, we plot approximately 60 pulses (6 and 3 periods of the
scanning pattern, respectively) for each scenario. Fig. 2 (c) and (d) exhibit the corresponding focal pattern for synchronized pulses at \( \phi = 0^\circ \), \( \phi = 90^\circ \), and \( \phi = 180^\circ \). One can observe that with synchronization, the laser only fires at the predefined focal positions corresponding to the three selected phase angles. It is worth mentioning that the same number of pulses (18 pulses) is displayed in Fig. 2 (c) and (d). We can explain this phenomenon by examining the overall repetition rate of the laser when synced with the TAG lens.

The overall repetition rate of the synchronized laser is determined by the pulse width (\( \Delta t \)) of the trigger signal. The product of \( \Delta t \) and \( f_{\text{laser}} \) defines the ratio of repetition rate between the synchronized and asynchronized scenarios. Given that the laser’s internal repetition rate is \( f_{\text{laser}} \), the overall repetition rate of the laser \( f \) when triggered at any single TAG lens phase is given by, \( f = f_{\text{laser}} \cdot f_{\text{tag}} \cdot \Delta t \). All experiments in the study are conducted with a pulse width of 1 \( \mu s \) in the trigger signal. Thus, for \( f_{\text{tag}} \) around 140 \( kHz \), the corresponding \( f \) for a laser synchronized at a single phase is around 140 \( Hz \). The laser is triggered at three phases in Fig. 2 (c) and (d), resulting in an overall repetition rate of 420 \( Hz \). The pulse width \( \Delta t \) also determines the accuracy of focal position control. The lower \( \Delta t \), the more accurate the focal position. A small \( \Delta t \), on the other hand, leads to a lower overall repetition rate. When selecting \( \Delta t \) and other machining parameters, one should consider the trade-off between accuracy and repetition rate.

![Figure 2](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)

**Figure 2.** Femtosecond laser induced damage in BK7 glass. Asynchronized laser with (a) \( f_{\text{tag}} = 140100 \ Hz \), and (b) \( f_{\text{tag}} = 140050 \ Hz \). Synchronized laser at three selected focal positions with (c) \( f_{\text{tag}} = 140100 \ Hz \) and (d) \( f_{\text{tag}} = 140050 \ Hz \).

### 3.1.2 Amplitude

The amplitude of the focal scanning \( z_{\text{tag}} \) is proportional to the driving voltage \( V_p \) of the TAG lens.\(^\text{10}\) We characterize the depth of \( z \)-scan line ablation experiments under varied driving amplitudes \( V_p \) to explore their effects on multi-focal machining. Experiments are performed on two samples, borosilicate glass and silicon wafers, with a 10× objective lens and 50 \( \mu J \) pulse energy. Samples are mounted on a 3D stage with a translational velocity of 0.65 \( mm/s \). Fig. 3 compares the ablated depth of glass and Si under the single-focal mode (TAG lens off, \( V_p = 0 \ V \)) and the dual-focal mode (TAG lens on, laser triggered at both \( \phi = 0^\circ \) and \( \phi = 180^\circ \)) with \( f_{\text{tag}} \) fixed at 140100 \( Hz \), and \( V_p \) ranging from 6–15 \( V \). The single peak at \( z = f_0 \) splits into two peaks of depth in the dual-focal mode. Since the numerical aperture of the maximum converging phase at \( \phi = 0^\circ \) is higher than that of the maximum diverging phase at \( \phi = 180^\circ \), the two peaks of ablated depth in the dual-focal mode are asymmetric.

### 3.2 Dual-focal laser marking

Based on the parametric study of frequency, amplitude, and phase of the TAG lens, we demonstrate how to select the TAG lens parameters for a given machining target, such as a microscope glass slide with a 1 \( mm \) thickness. Since the thickness of the glass slide is larger than the depth of field (DOF) of the 10× objective lens, laser pulses can only modify either the top or the bottom surface of the glass slide within one lateral scan. In
Figure 3. Depth of z-scan line ablation experiments under varied driving amplitudes $V_p$ with laser triggered at both $\phi = 0^\circ$ and $\phi = 180^\circ$, for (a) Glass, and (b) Si.

Figure 4. Optical images of the laser marking lines on the top and bottom surfaces of a 1 mm glass slide, processed with (a) the dual-focal mode (TAG on with $f_{tag} = 140100$ Hz and $V_p = 15$ V, laser triggered at both $\phi = 0^\circ$ and $\phi = 180^\circ$); (b) the single-focal mode (TAG off, laser focused at the top surface). The scale bar in (a) and (b) is the same, representing 200 $\mu$m. The corresponding ablated depths in (a) and (b) are plotted in (c).

In this scenario, a dual-focal laser system is capable of delivering concentrated pulse energy to both surfaces in a single lateral scan. Fig. 4 compares the laser marking of the glass slide in the dual-focal (TAG lens on, laser triggered at both $\phi = 0^\circ$ and $\phi = 180^\circ$) and single-focal (TAG off, laser focused at the top surface) mode. Based on the characterization in Fig. 3, the axial scanning frequency and amplitude are set around 140100 Hz and 0.4 mm ($V_p = 15$ V), respectively, in order to modify both surfaces of the glass slide effectively. As the pulses are...
designed to be focused on both the top and bottom of the glass slide in the dual-focal mode, two marking lines are produced in a single lateral scan along $x$. As a comparison, in the single-focal mode, laser modification of the glass is constrained only locally to the top surface of the glass. Fig. 4(c) plots the ablated depth of the marking lines on both surfaces for the experiments in (a) and (b).

4. CONCLUSION

In this paper, we implement multi-focal laser processing by adopting a tunable acoustic gradient of index (TAG) lens, which oscillates the focal position at 140 $kHz$. By triggering the laser at designated focal positions with the matching phases of the TAG lens, we quasi-simultaneously create a tunable multi-focal pattern without mechanically moving any optics. The varifocal TAG lens’s frequency, amplitude, and phase are characterized, and their implications for laser processing are investigated. Finally, an example of dual-focal marking on both sides of a glass slide in a single lateral scan is shown.

ACKNOWLEDGMENTS

We acknowledge funding by the Princeton University Eric and Wendy Schmidt Fund (DG5709). C.F acknowledg- edges funding by the European Commission (Marie Curie Fellowship IF, FOCUSIS, Grant Agreement 844977). We acknowledge the support from Mitutoyo Corporation.

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