RAPID BEAM SHAPING AND FOCUSSING USING TUNABLE ACOUSTIC GRADIENT INDEX LENSES

Thomas Lipp, Alexandre Mermillod-Blondin, Euan McLeod and Craig B. Arnold

Department of Mechanical and Aerospace Engineering
Princeton University
Princeton, NJ 08544

Rapidly shaping or refocusing an incident Gaussian laser beam enables a variety of novel local materials processes in pulsed and CW applications. Spatial light modulators and other adaptive technologies have been successfully used for beam sculpting, however in high energy and power materials processing applications their physical size, associated pixelation, slow switching speeds, and incident power limitations can be undesirable. Here we present a new device, the tunable acoustic gradient index (TAG) lens, which provides a scalable, rapid, high throughput alternative for spatially modifying incident beams. Under single-frequency operation, we show that a cylindrical geometry allows this lens to generate a single multiscale Bessel beam [1, 2], or under multiple-frequency operation it can generate a superposition of Bessel beams, approximating any radially-symmetric pattern [3]. Using pulsed input, these tunable devices enable one to select an instantaneous pattern or focal length for a desired imaging or processing configuration. In these types of applications, the TAG lens can withstand high intensities and can be used to change laser spot size and shape at rates in excess of 1 MHz [4].

In a variety of applications, it is useful or even necessary to have feedback between the characteristics of an incident laser light source and the materials processes that are induced or the imaging conditions that are required. A classical example is the use of a telescope to image distant objects through the atmosphere. In this case, the motion of the atmosphere causes constant perturbations in the wavefront of the light. One can measure the fluctuations and, using adaptive elements, adjust the wavefront to cancel out these effects [5]. Still other, atmospheric based applications such as remote chemical sensing or long range imaging, or laboratory-based, imaging applications such as ophthalmologic scanning, confocal microscopy or multiphoton microscopy, would benefit greatly from the use of direct feedback to rapidly correct for aberrations or rapidly vary focusing conditions for the sample under investigation.

Variable and adjustable optics allowing for focal length variation, field of view tuning, and aberration correction have traditionally been achieved through mechanical systems of lenses and other optical components. Such assemblies can be susceptible to excessive noise, wear and fatigue of mechanical parts, and can be limited in range or require substantial power to adjust. Adaptive optical elements attempt to replace these optical systems with a single lens or optical component with variable optical properties. These adaptive optics elements often attempt to mimic the human eye which can vary its focal length through physical deformations of its lens. There are a variety of technologies that have traditionally been used in adaptive optics applications. These include addressable mirror surfaces, fluid-deformable, and liquid crystal phase shifting elements. Addressable mirror devices include large area single surface mirrors containing actuators to modulate the height of the surface, or digital micromirror arrays where the angle of each pixel can be independently controlled [6]. In fluid deformable lenses, pressure, electrostatic, and other forces can be used to modulate the curvature of a surface or interface leading to a change in focal point [7]. Finally, liquid crystal based devices such as spatial light modulators (SLMs) allow for digital control of the phase shift as a function of position across the device due to electric field variations [8].

Although current adaptive optical technologies have been successful in many applications, they suffer from limitations that prevent their use under more extreme conditions. For instance, one of the major limitations of spatial light modulators and deformable liquid lenses is the slow switching speed, typically on the order of only 50-100 Hz for SLMs and even slower for deformable liquid lenses. Digital mirror arrays can be faster, but their cost can be prohibitive. Also, while these devices are good for small scale applications, larger scale devices require either larger pixels, leading to pixelation errors, or they

require an untenable number of pixels to cover the area, decreasing the overall speed and significantly increasing the cost. Finally, many of the currently available adaptive optic technologies tend to have relatively low damage thresholds, making them suitable for imaging applications, but less suitable for high energy/high power laser processing. These limitations and others can be overcome with the TAG Lens.

The TAG lens is a resonant cavity for acoustic waves that modulates the density of a refractive filling fluid and thereby creates a gradient in index of refraction. As light passes through this index gradient, it will acquire a phase shift and therefore become focused or redirected into an alternative pattern. In the case of a cylindrical geometry as shown in figure 1, the waves are generated at the circumference of the chamber by a hollow tube piezoelectric driven with an AC voltage and frequency that depends on the geometry of the lens and the index profile desired. Typical frequencies are in the 100-1000 kHz range with amplitudes ranging from 0-10 V for the experiments discussed here. The optical damage threshold of the TAG lens is primarily determined by the filling fluid, which may be any refractive fluid and can be easily emptied and replaced from the cell. In our experiments, we fill the lens with silicone oil of variable viscosity and use a CW 532 nm laser to illuminate the time-averaged patterns generated by the TAG lens. The output of the lens is imaged directly on to a CCD camera to acquire these images. For rapid imaging and characterization, we employ a pulsed 355 nm, 15ns laser at up to 200 kHz for observing high-frequency variations in the beam. In these cases, we synchronize the phase of the TAG lens with the occurrence of the laser pulse by adding a user controlled phase shift to the AC driving signal and a digital delay generator for the laser trigger. Although in the experiments described here we focus on a cylindrical geometry, other geometries are possible. For instance, a square chamber with actuators in both x and y directions, enables the production of two-dimensional patterns with square instead of cylindrical symmetry.

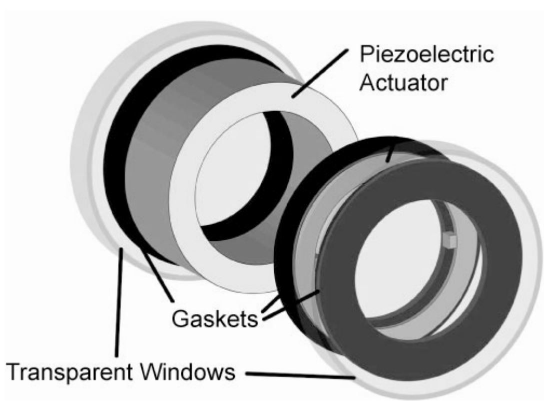

Figure 1. Schematic of TAG lens assembly. Geometry can be modified to include arbitrary shapes and sizes.

The intensity profile for CW illumination of a single frequency driving signal is shown in figure 2. In this case, we see the appearance of bright major rings surrounded by smaller scale, minor rings. This effect has been explained in the literature [1,9,10] and is caused by the combination of the periodicity in the index of refraction for a cylindrically confined geometry and the refraction of light through local maxima and minima in the index function. The resulting beams maintain the unique properties of Bessel beams including nondiffracting and self-healing behavior. In essence, the central focused region will maintain its spatial extent over long distances (on the order of meters and larger) and due to the multiply interfering beams can reconstruct the focused point behind partially blocking obstacles. These effects can be quite beneficial in a variety of laser-based applications such as optical trapping, deep hole drilling, waveguide fabrication, texturing non-planar substrates and 3-d manufacturing among others [11,12]. Under this type of CW operation, the central spot size, the number of rings, lens working distance, and ring spacing in the Bessel beam are all tunable by simply varying the TAG driving voltage frequency and amplitude [10].

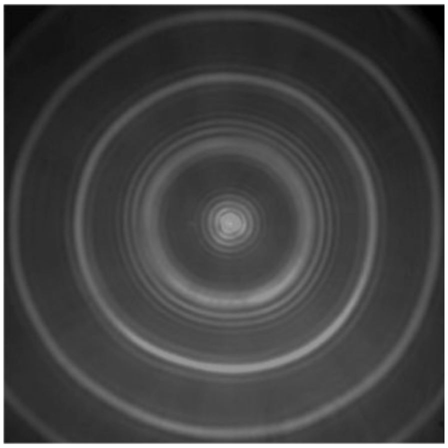

Figure 2: Optical output under CW 532 nm illumination and single driving frequency. The pattern can be described as a multiscale Bessel beam with bright major rings surrounded by dimmer, minor rings. The diameter of the first ring in the pattern is 3 mm.

In order to determine the pattern of light that will develop from the lens, it is necessary to calculate the index of refraction function in the lens. For a cylinder, this problem can be solved in a 1-d linear, inviscid regime, resulting in an index function that varies as a Bessel function in space and a Sine function in time [9]. Due to linearity, it is possible to reconstruct any arbitrary index of refraction function subject to the overall boundary conditions at the walls by performing a Fourier or Bessel transform of the desired pattern and driving the lens with the appropriate combination of frequencies, amplitudes, and phase shifts [3]. Such a result has important implications for square geometries where the additional degrees of freedom in the driving parameters lead to further complexity in the patterns that can be constructed.

Some of the most interesting and technological important behavior occurs when the lens is illuminated with a pulsed light source. Since the index of refraction is constantly changing in time, the phase difference between the pulsed laser and the driving frequency of the TAG will select a specific instantaneous pattern. In the case of a single frequency driving signal, one can select patterns with either bright intensity at the center of the pattern, or intensity distributed around a ring. As shown in figure 3, these patterns develop due to the refraction of light as it passes through the central region of the lens. In the first state (upper left and right), the center of the lens is a global maximum in index of refraction. As light passes through this region, it will get focused toward the center resulting in bright central spot. The minor rings that appear around this spot are caused by the interference that occurs from rays emerging near the inflection points where the index approximates a linear function. Here, the rays do not focus to a single point and rather approximate the behavior of an axicon lens, resulting in a Bessel beam of light. Subsequent maxima result in major rings that surround this central spot. In the lower two images, the index function reaches its global minimum at the center and in this case, the rays of light are directed away from the center resulting in a dark central region surrounded by a ring of illumination. Rapid switching between rings and spots enables many important applications in imaging or materials processing, for instance, multiphoton microscopy or laser micromachining [13]

This same effect that allows lens to produce a bright central spot or a dark central spot can be applied to imaging applications. If one uses an aperture to reduce the diameter of the incident light such that it is smaller than the width of the central maxima in the index function, the index of refraction can be approximated with a parabolic function. In the case of a local maximum, this will be equivalent to a converging lens where the focal length is determined by the curvature of the index. Since the amplitude of this index is constantly changing, the curvature is also constantly changing and therefore, the focal length of this device is constantly changing. Thus, by synchronizing the lens at a desired amplitude in the index of refraction, it is possible to select any given focal length within the range of the device. This includes both positive and negative values.

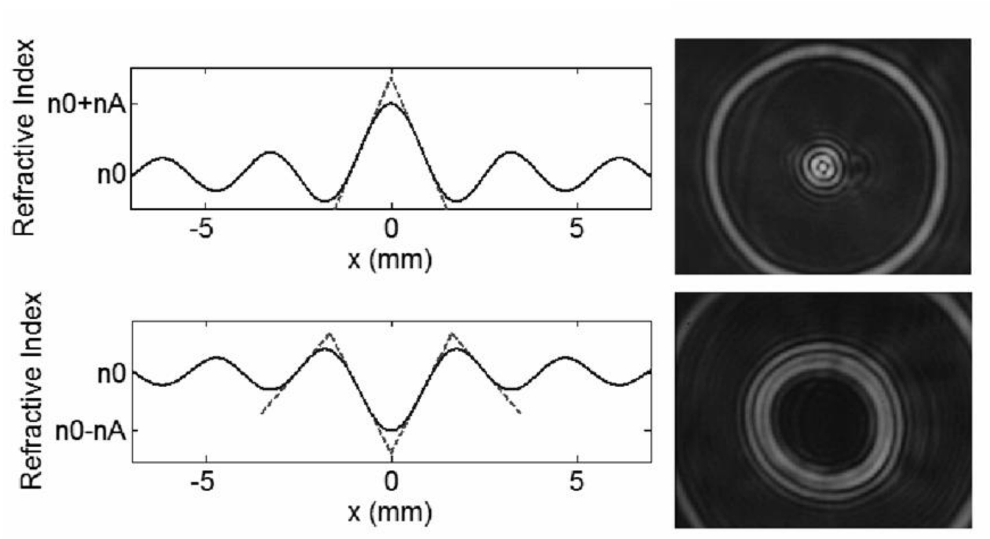

Figure 3: Upper left: Azimuthally averaged index of refraction profile for cylindrical TAG lens at one instant of time. The resulting pattern with bright central spot is shown in the upper right. Lower left: Azimuthally averaged index of refraction profile for cylindrical TAG lens one half-period later. The image on the lower right shows the resulting pattern exhibiting dark center with annulus illumination.

In Figure 4, one can see this situation for a simple case of three wires spaced at distances of 10, 45, and 80 cm away from the TAG lens along the optical axis. By synchronizing the TAG with the illumination source and using a phase shift to determine the selected focal length, it is possible to bring each wire into focus independently starting from the closest to furthest away.

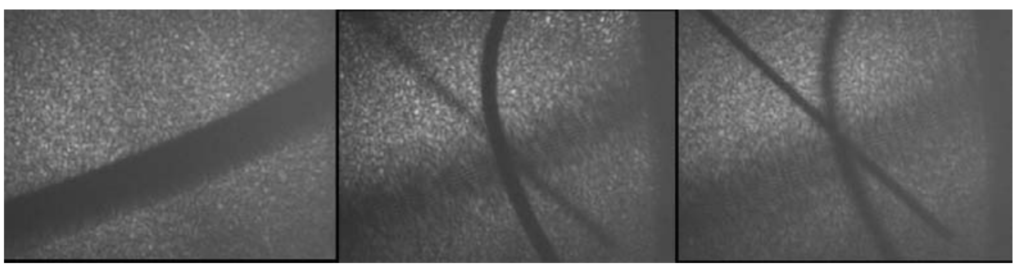

Figure 4: Images of objects at different locations along the z-axis. In the left-most image, a wire (~1.5 mm width) is located at 10 cm away from the TAG lens and brought into focus. In the middle image, the wire in focus (vertical wire) is at 45 cm away from the lens. In the right-most image, the wire in focus (left-right diagonal) is located 80 cm away from the lens. The total amount of time to switch between the first and third image is a total of 2.2 μs.

One of the biggest advantages of the TAG lens is its speed. Since we are only changing the phase and not the driving frequency or amplitude, the amount of time it takes to switch between different focal planes is only portions of the oscillation period. For figure 4, it took only 2.2 μs to change from the leftmost to the right-most image (70 cm) at the driving frequency of 370 kHz. In general, one can increase the frequency of the driving signal further, giving one the ability to change focus at rates over 1 MHz depending on the amount of focal length change that is desired. This is many orders of magnitude greater than competing technologies.

Another important advantage of the TAG lens for extreme conditions is that the damage threshold and energy throughput can be quite high. One can design the geometry that is needed for a given

application and use appropriate refractive media for the desired wavelengths or amplitudes required thereby limiting absorption and maximizing refractive changes. In fact, if the fluid or glass end plates do become accidentally damaged, a simple refilling operation or replacement of the glass plates can be performed in the field and will return the lens to new.

The TAG lens represents a new direction in adaptive optics with the ability to rapidly change focus and modulate patterns of high repetition, high power lasers without many of the limitations of existing adaptive optic technologies. The technology is scalable and can be designed to work over large wavelength or power regimes with different geometries. We expect the TAG lens to find many applications across consumer, industrial, and defense platforms.

References

[1] E. McLeod, A. B. Hopkins, and C. B. Arnold, “Multiscale Bessel Beams Generated by a Tunable Acoustic Gradient Index of Refraction Lens,“ Opt. Lett., v 31, pp 3155-3157 (2006)

[2] C. B. Arnold and E. McLeod, “A new approach to adaptive optics for materials processing,” Photonics Spectra, v 41, pp 78-84 (2007)

[3] E. McLeod and C. B. Arnold, “Complex Beam Sculpting with Tunable Acoustic Gradient Index Lenses,” Proc. of SPIE, v 6483, p 64830I (2007)

[4] T. Tsai, E. McLeod, and C. B. Arnold, “Generating Bessel Beams with a Tunable Acoustic Gradient Index of Refraction Lens,” Proc of SPIE, v 6326, p. 63261F (2006)

[5] A. Greenway, “Adaptive optics: Astronomy and Beyond,” *Optics and Photonics News*, v 17,pp 22-27 (2006)

[6] E. J. Fernandez, “Membrane Deformable Mirror for Adaptive Optics: Performance Limits in Visual Optics,” Opt. Exp. v 11 p. 1056 (2003)

[7] H. Jiang and L. Dong, “Smart Lenses,” Physics World, v 19, pp 29-31 (2006)

[8] S. T. Kowel, “Focusing by Electrical Modulation of Refraction in a Liquid Crystal Cell,” Appl. Opt. v 23, p278 (1984)

[9] C. B. Arnold and E. McLeod “Mechanics and Refractive Power Optimization of Tunable Acoustic Gradient Lenses,” J. Appl. Phys. v 102, p 033104 (2007)

[10] E. McLeod and C. B. Arnold, “Optical Analysis of Time-Averaged Multiscale Bessel Beams Generated by a Tunable Acoustic Gradient Index of Refraction Lens,“ In press, Appl. Opt. (2008)

[11] J. Amako, D. Sawaki, and E. Fujii, “Microstructuring Transparent Materials by Use of Nondiffracting Ultrashort Pulse Beams Generated by Diffractive Optics, “J. Opt. Soc. Am. B., v 20, pp. 2562-2568 (2003)

[12] Y. Matsuoka, Y. Kizuka, and T. Inoue, “The Characteristics of Laser Micro Drilling Using a Bessel Beam,“ Appl. Phys. A, v 84, pp. 423-430 (2006)

[13] A. Mermillod-Blondin, E. McLeod, and C. B. Arnold, “Dynamic pulsed-beam shaping using a TAG lens in the near UV,” In press, Appl. Phys. A, (2008)