

Dynamic pulsed-beam shaping using a TAG lens in the near UV

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Abstract The ability to dynamically shape the spatial intensity profile of an incident laser beam enables new ways to modify and structure surfaces through pulsed laser processing. Here we describe a method to generate doughnut-shaped beams from an input Gaussian source using a tunable acoustic gradient index (TAG) lens. The TAG lens is capable of modulating between focused beams and annular rings of variable size, using sinusoidal driving frequencies. Laser micromachining is accomplished by synchronizing the TAG lens to a 355 nm pulsed nanosecond laser. Results in polyimide demonstrate the ability to generate adjacent surface features with different shapes and sizes.

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42.79.Jq

1 Introduction

The spatial intensity distribution of a laser beam plays a crucial role in determining the light-matter interactions that occur. Controlling the magnitude and distribution of the laser beam intensity, beyond simple focusing optics, is important for advanced materials processing where detailed control over local properties is required [1]. Being able to change these laser parameters on the fly is essential to many processes such as high-throughput industrial control of cutting and welding [2], ultrafast laser pulse shaping for micromachining [3], and optical trapping [4, 6]. For micromachin-

ing, being able to rapidly shape the beam reduces the downtime required to retool or reposition fixed optical elements. Until now, the needs for dynamic beam shaping have been met with spatial light modulators [3], galvanometric scanners, acousto-optic modulators, or deformable mirrors [7]. Spatial light modulators are generally limited to refresh rates of less than 100 Hz, while galvanometers and acousto-optic modulators are primarily capable of deflecting and not shaping beams. Mirror arrays can be fast and effective, however they are expensive and subject to pixelation effects.

Tunable acoustic gradient index (TAG) lenses are a new form of adaptive optic that uses sound to modulate the wavefront of an incident light beam [8, 9]. As the sound propagates through the fluid, it establishes a density oscillation in the lens that corresponds to a spatiotemporal index of refraction variation. For a cylindrically symmetric lens, this index takes the form of a standing wave Bessel function. As light propagates through this lens, it is bent according to this function leading to the observed patterns. Since the index is oscillating in time, such a system produces an average pattern that can be observed using a CW laser and a continuum of instantaneous patterns that can be selected using pulsed lasers. In comparison with conventional beam shaping devices, the TAG lens is fast [10], scalable, nonpixelated, and inexpensive to produce.

Using single frequency sinusoidal driving signals, the TAG lens produces multiscale Bessel beams [8]. Beyond their potential interest for microprocessing [11], doughnut shaped beams are important for optical trapping [5, 6] or as a light source for super resolution microscopy [12, 13]. More recently, researchers have begun to apply doughnut beams for high aspect ratio laser micromachining of metal foils [16]. Additionally, those beams have been employed to produce attosecond duration bursts of light [14] due to their ability for high harmonic generation [15].

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In this paper, we use a TAG lens to produce a doughnut-shaped beam with a variable size that can be rapidly changed. These patterns are used to micromachine polyimide films enabling spot-to-spot control of the surface structure.

2 Experimental setup

The experimental setup is shown in Fig. 1. The light source is an Nd:YVO₄ laser (Coherent AVIA) delivering 15 ns duration pulses at a 355 nm wavelength and maximum repetition rate of 250 kHz. The output beam has a Gaussian profile, with a measured diameter of about 3.5 mm at $1/e^2$ and an M^2 approximately 1.3. We direct the beam into a 3.5 cm radius TAG lens filled with silicone oil (0.65 cS Dow Corning 200 Fluids). A wavefunction generator (Stanford Research Systems Model DS 345) provides a radio frequency (RF) sinusoidal signal between 0.33 and 1.20 MHz to drive the piezoelectric crystal, generating vibrations inside the silicone oil. The refractive index of the TAG lens cavity continuously changes with the instantaneous value of the AC signal.

Synchronization of the laser and TAG lens is accomplished using a pulse delay generator triggered off the same AC signal. The pulse delay generator (Stanford Research Systems Model DG 535) is programmed to provide a specific phase shift from the trigger signal that can be much greater than 2π . In this way, it is possible to synchronize the laser pulses with the TAG lens so that each pulse meets the lens in the same state of vibration. Because the phase shift is greater than one period, the effective repetition rate of the laser pulse can be arbitrarily controlled within the specifications of the laser source.

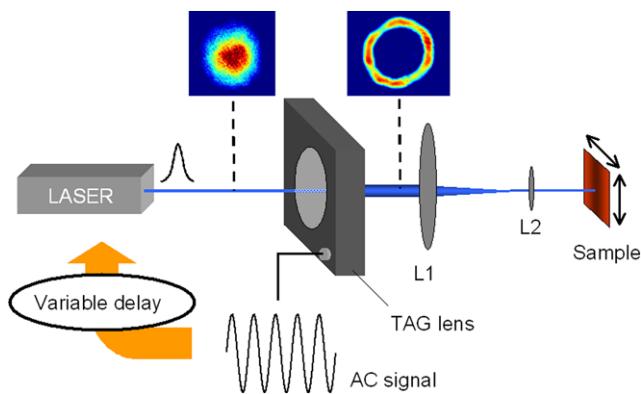


Fig. 1 Experimental setup (color). The pair of lenses L₁ and L₂ form a telescope to reduce the size of the beam for micromachining. The delay between the AC signal and the laser pulse is set by a pulse delay generator. The inset image on the left shows the spatial profile of the incident Gaussian beam and the inset image on the right shows the resulting annular beam after passing through the TAG lens

For micromachining, the size of the shaped laser beam is reduced by a pair of lenses (L₁ and L₂) with focal lengths of 500 mm and 6 mm, respectively. The demagnified laser beam illuminates the surface of a thin layer (about 4.7 μm) of polyimide coated on a glass plate. This substrate is mounted on an x - y - z translation system. Photomodified samples are then observed under an optical microscope and characterized by profilometry.

3 Results and discussion

3.1 Basis

There are three main parameters of the TAG lens that affect the dimensions and shapes of the patterns we can generate: the driving amplitude, the driving frequency, and the phase shift between the driving signal and the laser trigger. For this study, we have focused our attention on simple shapes including annuli and single spots, although the TAG lens is capable of more complex patterns [17]. We denote these instantaneous patterns as our “basis.” In general, the frequency affects the diameter of the ring, while the amplitude affects the sharpness and width of the rings. The phase selects the nature of the instantaneous pattern. For instance, when the index of refraction is at a global maximum in the center, the instantaneous pattern is a spot, but at half a period later when it becomes a global minimum, the instantaneous pattern is doughnut-shaped.

In Fig. 2, a few elements of the basis are presented. These patterns are acquired 50 cm away from the TAG lens but without the reducing telescope. Rings with various diameters, ranging over an order of magnitude from a single bright spot to about 4 mm dimension are obtained. Different driving frequencies ranging from 0.33 to 1.29 MHz are used to generate the annular shapes shown in the figure with fixed amplitude (9.8 V peak to peak) and phase angle chosen to optimize the ring shape. For high throughput micromachining, one would use this basis to define a lookup table



Fig. 2 Intensity image of instantaneous patterns obtained by changing the TAG lens driving frequency. Pictures were taken at a distance of 50 cm away from the lens. Frequencies from left to right are: 719 (bright spot), 980, 730, 457, 367, 337 kHz. The amplitude of the driving signal is fixed at 9.8 V peak to peak. The ring diameter is provided at the bottom of the picture. There is a half a period phase shift between the spot and the ring pattern

that establishes the correspondence between driving amplitude, frequency, phase shift, and the observed instantaneous intensity distribution. We note a slight eccentricity in the micromachined rings due to minor imperfections and nonuniformities in fabricating the piezoelectric electrodes. Furthermore, these asymmetries depend on the driving frequency due to resonance behavior in the cell [9]. A new TAG lens design is currently being developed in order to cancel this unwanted effect.

3.2 Sample micromachining

The TAG lens is capable of high energy throughput without damage and can therefore be used for pulsed laser micromachining. Figure 3 demonstrates this point for a polyimide film. In this case, the incident laser energy on the sample is 8.2 μJ , and the driving frequency is 700 kHz, resulting

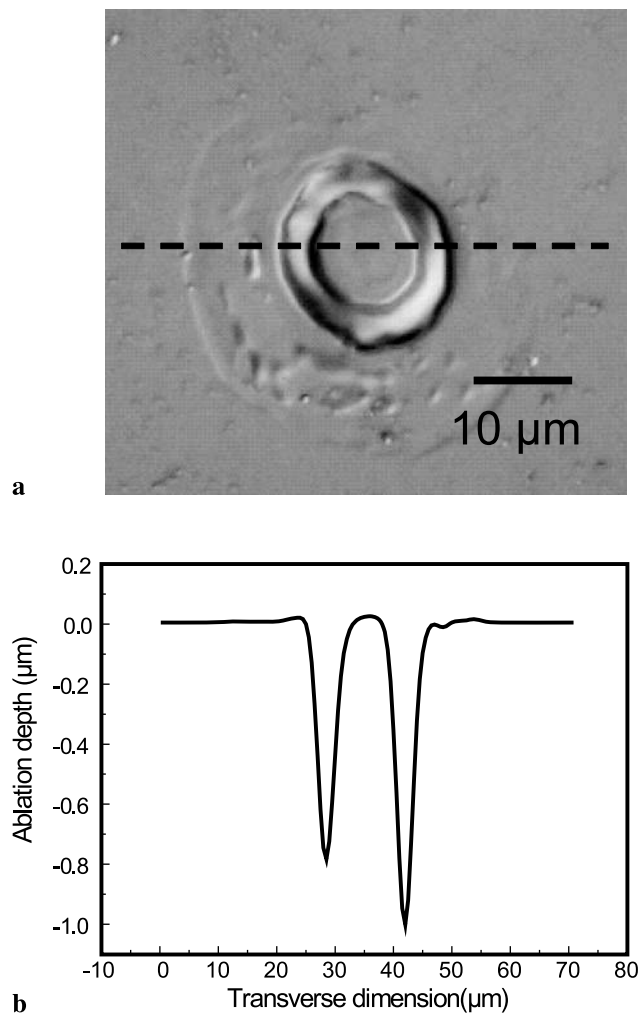


Fig. 3 Micromachined ring on the surface of a polyimide sample. (a) Optical micrograph of micromachined ring structure. (b) The profilometry analysis through the *dashed line* of part (a) shows that material is removed over a depth of approximately 0.9 μm with little recast material

in a 15 μm diameter ring in the film. Calculating the actual fluence is difficult because the background of the beam, although subthreshold, still carries significant energy as expected. A profilometry analysis of the irradiated polyimide thin film shows a well-defined annular structure with depth of 0.9 μm and a width of approximately 3.5 μm . Additional studies are needed to assess the heat affected zone surrounding the laser-induced structures using these non-traditional intensity profiles.

In contrast to many other methods of producing annular beams, the TAG lens gives the added ability to rapidly change the pattern according to the structure or pattern required. To demonstrate this effect, Fig. 4 gives examples of adjacent laser-induced surface structures that alternate between a central spot and an annular beam. For this figure, the two basis elements are selected by varying the phase shift such that the index function is at either a maximum or minimum, while the substrate is manually translated. In the upper image of the figure, a driving frequency of 989 kHz is used. Here we see that the bright central spot shows indication of a second ring that causes damage to the polyimide film. However, when driven at lower frequencies as in the lower image (531 kHz), we are able to obtain single spots in the image. This effect can be ameliorated by better optimization of the phase shift and amplitude in order to maximize the energy difference between the central spot and the outer rings. Furthermore, aperturing or reducing the size of the beam incident on the TAG lens can be used to remove unwanted outer rings.

3.3 Switching time of the TAG lens

The ability to switch rapidly between two distinct intensity distributions is a key parameter in evaluating the relevance of a beam shaping strategy for micromachining or laser marking purposes. When using a TAG lens, two situations have to be considered. Either the elements of the basis

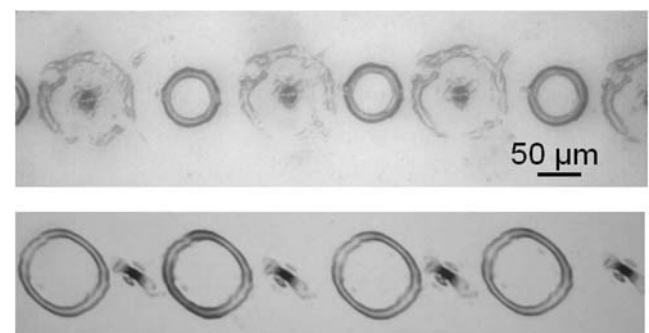


Fig. 4 Different intensity distribution at each laser spot. For this image, a two pattern basis is used and the demagnification is 50 \times . The TAG lens is capable of switching between these two patterns at twice the driving frequency. In the *upper image*, the lens is driven at 989 kHz and in the *lower one*, it is driven at 531 kHz

can be reached by driving the TAG lens at a single frequency (Fig. 4), or it is necessary to run the lens at different frequencies, as illustrated in Fig. 2.

When all the desired shapes can be generated by using the same lens driving frequency, the theoretical minimum switching time is given by half of the driving signal period. In Fig. 4, the TAG lens was driven at a frequency of 989 kHz (upper picture) and 531 kHz (lower picture) implying that toggling times between two adjacent patterns are theoretically as short as 0.5 and 0.9 μs , respectively. This converts to a switching frequency of approximately 1–2 MHz. Although these values are too low for optical communication and switching requirements, these rates are more than sufficient for pulsed laser processing.

In the case that frequency changes are needed, the minimum amount of time required to switch the pattern is equal to the amount of time it takes to propagate the sound wave from the piezoelectric to the center of the lens. We denote this as the TAG lens response time. The instantaneous pattern is established at this time, followed by a transient to reach steady state [10]. In the context of pulsed laser processing, it is the response time that is the relevant test of lens speed. As an example, considering the sound velocity in the silicone oil to be about 900 m s^{-1} and a radius of 3.5 cm for the lens, the response time is as short as 40 μs . This time corresponds to a frequency modulation rate of 25 kHz. However, by changing temperature or the refractive filling fluid, the speed of sound can be increased, and the response time can be significantly decreased.

4 Conclusion

We demonstrate the applicability of the tunable acoustic gradient index of refraction (TAG) lens for efficient beam shaping of pulsed UV sources. By synchronizing the laser with

the TAG lens, it is possible to generate annular rings of programmable size from an incident Gaussian beam. High energy throughput of this adaptive optical element enables us to use these different spatial intensity distribution functions for pulsed laser micromachining. High switching speeds, limited only by the driving frequency, size, and the speed of sound in the refractive fluid, allow for real-time changes in beam shape and the possibility to write different preselected basis elements at each laser spot in laboratory and industrial processes.

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