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Enhanced depth of field laser processing using an ultra-high-speed axial scanner

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Lasers are ubiquitous in materials processing, but the requirement of precise control of the focal plane in order to ensure optimal performance constitutes a time limiting step for high-throughput laser manufacturing. Here, we overcome this limitation by axially scanning the focus at high speeds using an acoustically driven liquid lens. We demonstrate this approach by processing silicon surfaces, and we find it is possible to enhance the depth-of-field by an order of magnitude without loss in lateral resolution. These results open the door to a fundamental change in the paradigm for laser processing by eliminating the need in z-focus control. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4791593]

When focusing a pulsed or continuous wave laser onto a workpiece, it is critical to know the precise z-axis location of the surface in order to deliver the desired energy and power density for proper processing to occur. The accurate control of the focal plane constitutes a classic problem in laser processing: most real-world surfaces are non-flat, and the presence of roughness, complex 3D shapes, texture, warping, or other surface features requires methods capable of adjusting the surface position relative to the focal plane.[1] The standard solution consists of using proximity sensors that map the surface and mechanical translation stages that adjust the focal plane accordingly.[2,3] However, the speed limitation of the stages and the need for controls and feedback can slow down the process and drastically reduce the throughput.[4]

A different strategy to relax the critical positioning of the focal plane consists in extending the depth-of-field (DOF) of the laser system. This can be accomplished using low power optics, but at expenses of lateral resolution. Recently, other methods have appeared based on using structured light. This includes the use of quasi non-diffracting beams, such as Bessel beams[5,6] or Airy beams,[7,8] that enable the increase of DOF by orders of magnitude with little loss in lateral resolution. However, non-desired properties of these beam shapes including the ring structure for Bessel beams or the curve pathway for Airy beams can constitute drawbacks for many applications.[9]

Here, we present an alternative method to extend the DOF of a conventional laser system without significantly affecting lateral resolution. Our approach consists of axially scanning the focus at speeds of 300 m/s or above using a resonating high speed optical element known as a TAG lens (TAG Optics Inc.). By firing multiple shots while automatically scanning over different focal planes, we create an extended DOF that ensures that the surface is always in focus without having to mechanically translate either the sample or optics. The TAG lens is a varifocal device that consists in a fluid-filled cylindrical cavity that is radially excited causing a periodic modulation of the refractive index.[10,11] As such, the lens is continuously varying its focal length, and when combined with standard beam delivery systems produces a periodically varying axial displacement of the system focus.[12] The varifocal capabilities of the TAG had been previously demonstrated in imaging,[12,13] but have not been used to increase the DOF for laser materials processing. In this manuscript, we demonstrate the feasibility of high-speed axial scanning and we find that under appropriate laser fluences it is possible to obtain a user-controllable increase in DOF that can be one order of magnitude longer than the DOF of the initial system without loss in lateral resolution.

In this experiment, the TAG lens is driven at a frequency of 144 kHz using a function generator (Syscomp, Inc.). At this frequency, the TAG lens focal length oscillates between −1000 mm and +1000 mm for the given voltage amplitude of 10 V_{pp}. This range can be further increased or decreased by controlling the driving amplitude. We perform laser processing with a $Nd:YVO_4$ laser (Coherent Inc., 355 nm, 15 ns pulse duration) which is passed through the TAG lens and further focused onto the substrate using a ultraviolet-coated microscope objective (5×, N.A. 0.13) placed 10 cm away after the TAG lens. By placing the TAG lens at this location, we achieve the highest scanning range, in good agreement with the previous experiments.[13] The substrates for this study are standard silicon wafers.

We first characterize the effects of axial scanning on beam propagation using a charge-coupled device camera placed at different distances after the objective (Fig. 1). At each axial position, we record multiple firing events using long exposure times, thereby obtaining an average intensity. Fig. 1 shows the change in the axial extent of the focal volume caused by scanning. Since the TAG lens creates a sinusoidal translation of the focus,[13] the dwell time in the edges of the scanning range is longer than in any other position resulting in a higher average intensity in these points (Fig. 1). Using the Rayleigh criterion, we can define the DOF as the Rayleigh range (z_R) or the axial distance where the intensity drops a factor of 2. In this case, axial-scanning produces an enhancement in DOF of about a factor of 6. Notably, this change in DOF is just the result of adding the scanning range (Δz) to the initial z_R. In the particular case of the TAG lens, the Δz is linearly related to the amplitude of

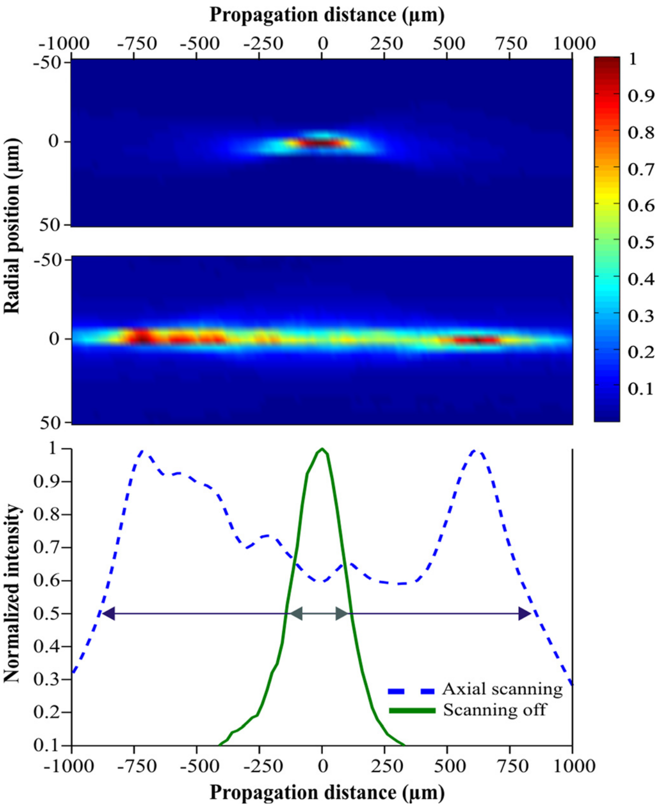

FIG. 1. Top: Laser beam propagation after the microscope objective (5×, N.A. = 0.13) without axial scanning and with axial scanning using a TAG lens at 10 V_{pp}. Bottom: Corresponding intensity profiles along the axial direction in the beam center.

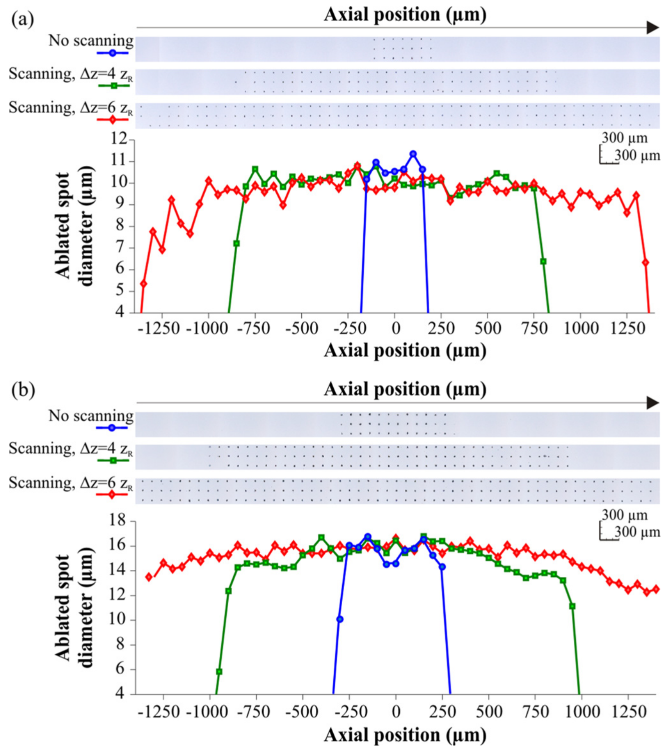

FIG. 2. Optical micrographs of different arrays in silicon prepared by firing 100 shots per spot at a fluence of (a) 2.3 J/cm^2 and (b) 5.5 J/cm^2. For each column, we vary the relative position of sample and objective in 50 μm steps. The axial scanning extends the region over which ablation occurs. The plots show the diameter of the ablated spots versus the axial distance. At a fluence of 2.2 J/cm^2, the spot size remains the same, indicating that the resolution is preserved. At a fluence of 5.5 J/cm^2, scanning produces a slight loss in lateral resolution.

the driving signal[12,13] thus increasing the amplitude above 10 V_{pp} enables one to easily obtain DOF increases of over an order of magnitude. We can also estimate the scanning speed of the TAG lens from Fig. 1. By considering the period of a scanning cycle to be given by the TAG oscillation time, which in this experiment is about 7 μs, the translation of the focal position over a distance of 2 mm takes place at a scanning speed of about 300 m/s.

The effects of axial scanning on laser processing are presented in Fig. 2. In this case, we prepare arrays using 100 shots per spot and repeat that 15 times in a single column (note the Fig. 2 shows only 3 of the 15 shots per column). For each column, we vary the relative position of sample and objective in 50 μm steps. Based on this figure comparing the results with and without axial scanning, we can see a clear difference. At a fluence of 2.3 J/cm^2 (Fig. 2(a)), with no axial scanning the DOF of the focusing objective gives us a range of $\pm 200\,\mu$m in which we can achieve ablation. By axially scanning using $\Delta z = 4z_R$, which corresponds to driving the TAG lens at 6 V_{pp} amplitude, we obtain an increase in the ablation range by a factor of 4. By extending scanning over $\Delta z = 6z_R$ (amplitude to 10 V_{pp}), we can further increase the ablation range to $\pm 1250\,\mu$m, an improvement by more than a factor of 6 in the DOF. Looking at the plot, we also notice that the width of the ablation spots in this fluence regime does not change significantly over the entire scanning range of the TAG lens. This result demonstrates that by axially scanning, it is possible to perform laser processing on surfaces with variations in the z-position as large as 2.5 mm without any moving parts and without any active feedback, sensing, or positional control. The same trends are observed at a fluence of 5.5 J/cm^2 (Fig. 2(b)), where scanning enables the extension of the axial range of ablation by a factor of 4 and a factor of 6 for the two Δz tested. In this case, though, the plot reveals a small increase in the size of the ablated spots when scanning as compared to the minimum spot size obtained without scanning.

We construct a model in order to account for the potential loss in lateral resolution caused by scanning. Our model assumes that the minimum feature size achieved during scanning is limited by the largest ablated spot at the surface. For a given substrate position within the scanning range (Δz), there is a superposition of pulses, all with the same energy but different beam sizes and consequently different fluences. If we define the beam size as the radius at which the intensity is 1/e^2 of its maximum and consider a Gaussian beam, the ablation spot size (r_m) depends on the beam size (ω) at the surface as[14]

$$r_m(\omega) = \frac{\omega}{\sqrt{2}}\sqrt{\ln\left(\frac{2E}{\pi\omega^2 F_{th}}\right)}, \tag{1}$$

where E is the laser pulse energy and F_{th} is the fluence threshold for material modification. According to our model, the measured feature radius is given by the beam size that maximizes r_m, named ω_s. We can find ω_s by solving $dr_m(\omega)/d\omega = 0$, and we can determine the feature radius by substituting this value back into Eq. (1). This approach yields a solution,

$$\omega_s = \sqrt{\frac{2E}{\pi e F_{th}}}. \quad (2)$$

However, there are limits on the values for ω_s that are physically possible. At the lower limit, ω_s must be larger than the diffraction limited beam waist ω_0 of the beam delivery system.

At the upper boundary, the largest physically possible beam size is limited by the maximum scanning range of the TAG lens. In other words, although a value for ω_s is determined by Eq. (2), it might not be possible to scan the focus position far enough to achieve this beam size. In that case, the maximum experimentally measured beam size will be limited by the actual size at the end of the scanning range, ω_{max}. This leads to the condition

$$\omega_0 = \frac{\lambda}{NA} \le \omega_s \le \omega_{max} = \omega_0\sqrt{1 + \left(\frac{\Delta z}{z_R}\right)^2}, \quad (3)$$

with λ being the laser wavelength, NA the numerical aperture of the focusing objective assuming the beam fills the lens aperture, and z_R the Rayleigh range.

In order to understand the results of this model and thus the effects of adding TAG lens scanning to laser micromachining, we define a non-dimensional feature size, $\mathscr{W}$, as the measured feature size with scanning divided by the minimum feature size without scanning, and the non-dimensional fluence $\mathscr{F}$, defined as $\mathscr{F} = F/F_{th} = 2E/(\pi\omega_0^2 F_{th})$. Fig. 3 plots these variables and shows no change in the feature size due to scanning up to $\mathscr{F} = e$. This point corresponds to the condition where $\omega_s = \omega_0$. Notably, within this fluence regime the DOF could be, in principle, extended up to infinity without sacrificing lateral resolution. This model is in good agreement with Fig. 2. Considering that the ablation threshold for silicon is 1 J/cm^2, the fluence of 2.3 J/cm^2 used in Fig. 2(a) lies within this regime where no loss in lateral resolution

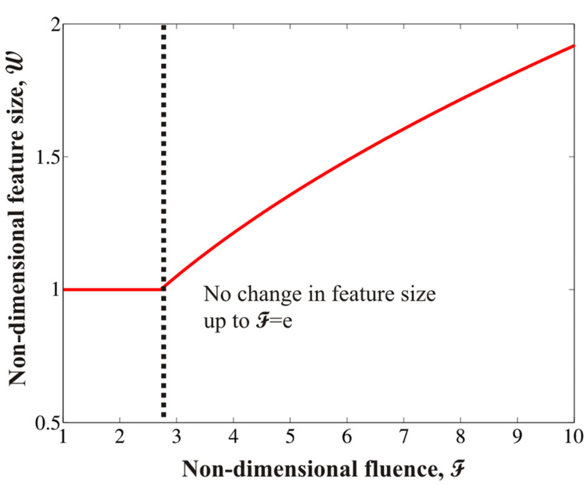

FIG. 3. Simulated dependence of the non-dimensional feature size $\mathscr{W}$ (feature size with scanning divided by minimum feature size without scanning) versus non-dimensional fluence $\mathscr{F}$ (fluence divided by ablation threshold). The region to the left of the dashed line corresponds to the fluence range where the TAG lens scanning does not induce any loss in lateral resolution.

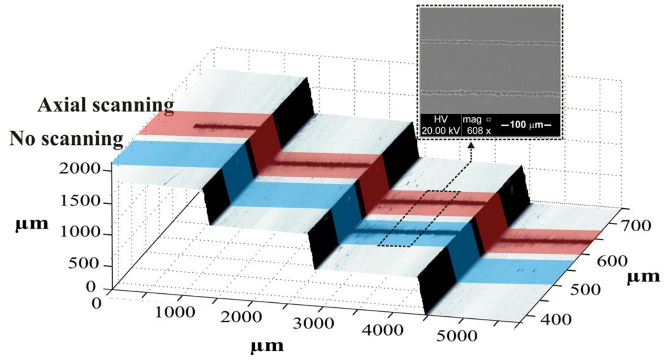

FIG. 4. Laser machining silicon on stepped surface with 500 μm steps. With the TAG lens off, it is only possible to write a line at the specific surface height for which the beam is in focus. By turning the TAG lens on, we extend the depth of field and we can write lines in each of the 4 silicon surfaces accounting for a total scanning of 2 mm. The inset corresponds to a scanning electron microscope (SEM) image that shows no significant differences between the lines written with the TAG lens on and off.

is observed, as experimentally demonstrated. On the contrary, the fluence of 5.5 J/cm^2 used in Fig. 2(b) is above this regime and, consequently, a slight loss in resolution is expected, in good agreement with the experiment. It is also important to note that the model results also apply to non-ablative laser processing.

Finally, we demonstrate the potential of axial scanning for laser processing by writing lines on a stack of 4 silicon wafers, each with a thickness of 500 μm arranged in a step-wise surface (Fig. 4). We observe that with the TAG lens off the limited DOF of the optical system enables us to write a line on only one of the silicon wafers at the specific surface height for which the beam is in focus. In contrast, using axial scanning provided by the TAG lens without any movement of the sample in the z-direction, we can mark a line in each of the 4 silicon wafers which accounts for a total axial extent of 2 mm. Notably, the cross-section profile of the lines in the 4 wafers is preserved along the entire sample, which proves the feasibility of axial scanning for uniform machining of uneven samples.

The high-speed axial scanning of the focal plane demonstrated in this letter enables the extension of the depth of field of optical systems, and provides an interesting approach towards uniform laser processing of uneven substrates. Our method does not require movable optics and enables axial scanning speeds as high as 300 m/s. By appropriate selection of laser fluence and scanning range, it is possible to preserve the lateral resolution associated with the fixed optics and yet extend its corresponding DOF by over an order of magnitude. This extended DOF approach obviates the need for mechanical z focus control during laser processing, opening the door to more efficient and higher throughput operations.

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