Materials processing with superposed Bessel beams

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Abstract

We report experimental results of femtosecond laser processing on the surface of glass and metal thin film using superposed Bessel beams. These beams are generated by a combination of a spatial light modulator (SLM) and an axicon with >50% efficiency, and they possess the long depth-of-focus (propagation-invariant) property as found in ordinary Bessel beams. Through micromachining experiments using femtosecond laser pulses, we show that multiple craters can be fabricated on glass with single-shot exposure, and the 1+(-1) superposed beam can reduce collateral damage caused by the rings in zero-order Bessel beams in the scribing of metal thin film.

1. Introduction

Spatial laser beam shaping provides the possibility of designing beam shapes that are optimized for specific applications [1]. Bessel beams, among these engineered beam shapes, have attracted attention lately due to their interesting properties such as long depth-of-focus (propagation invariance), “self-healing”, and the possession of orbital angular momentum [2]. For materials processing, zero- and high-order Bessel beams have been used to drill high-aspect-ratio nanochannels [3,4], produce structures inside silicon and glass [5-9], fabricate circular and ring-shaped surface structures [10-12], scribe narrow grooves [13], and form three-dimensional patterns [14]. One can refer to Ref. 15 for a review on this subject. Other applications with beam shaping techniques include particle manipulation [16], optical microscopy [17], etc. However, materials processing with Bessel beams still lacks the flexibility demonstrated with Gaussian beams. For example, it is demonstrated that complex damage patterns can be fabricated simultaneously by applying beam-shaping techniques to Gaussian beams [18], thus dramatically reducing processing time. It is desirable to have similar capabilities for Bessel beams. Another

1 problem regarding the use of zero-order Bessel beams is the collateral damage resulting from
2 concentric rings in these beams [6,19]. While such damage can be avoided by lowering input
3 laser power (pulse energy) so that only the intensity of the central lobe exceeds damage threshold
4 [13], these rings cause quality issues when high laser power is required, such as in scribing deep
5 grooves [19].

6
7 There currently exist two approaches to the generation of Bessel beam patterns consisting of
8 distinct bright spots. The first approach is an extension of Durnin's ring-slit-and-lens setup [20],
9 where an azimuthal phase modulation with opposite handedness is applied to the ring slit [21].
10 The limitation is that, in order to obtain superposed modes with high quality, the width of the
11 ring slit should be small (150 μm as reported in [21]). This narrow slit introduces a huge loss ($>$
12 90%, estimated by us) to the laser power. One could reduce this loss by transforming the input
13 beam into a ring-shaped beam and focusing it through the ring slit. This, however, would greatly
14 increase the intensity on the phase mask (spatial light modulator) and the risk of damaging it.
15 Another limitation of this approach is that the resultant beam patterns constantly rotate as they
16 propagate, due to the mismatched wave vectors. This rotation impairs the key advantage of
17 Bessel beams in micromachining applications, which is the ability of maintaining the same beam
18 shape over a long distance. In another setup based on a similar idea, two phase masks and two
19 axicons are used to generate a superposition of two first-order Bessel beams [22]. This setup still
20 suffers from high energy loss (76% as reported in [22]) and reduction in depth-of-focus due to
21 pattern rotation. In the second approach, superpositions of Bessel modes are generated by
22 passing Laguerre–Gaussian beams with opposite orders through an axicon [23]. This is a
23 preferred method for micromachining since the resultant beam patterns do not rotate. However,
24 in the previous study, the interfering Laguerre–Gaussian beams are generated in an
25 interferometer, and further demagnification is required to obtain the final, μm -sized patterns,
26 both involving complex optical systems. Furthermore, the usefulness of these superposed Bessel
27 beams for micromachining applications has not been reported.

28
29 In this paper, we use a spatial light modulator (SLM) to generate superpositions of Laguerre–
30 Gaussian beams, which then go through an axicon with a large base angle to form superposed
31 Bessel beam patterns with μm -sized spots. This simple setup, compared with previous work

[21,23,24], has high ($> 50\%$) energy efficiency, generates non-diffracting, non-rotating patterns over mm-level range, and shows the capability of forming new beam patterns other than superposed Bessel modes with opposite orders. We use this setup to conduct micromachining experiments with glass and metal thin films, and show that multiple craters can be fabricated on glass with single-shot exposure, and the $1+(-1)$ superposed beam can reduce collateral damage caused by the rings in the zero-order Bessel beams. Our work shows that the use of superposed Bessel beams, and of spatial beam shaping in general, can lead to improved performance in terms of processing speed, quality and robustness compared to commonly-used Gaussian beams.

2. Experimental

Fig. 1. (a) Experimental setup. Insets are calculated beam shapes (b) in front of SLM, (c) 1.2 m after SLM, and (d) 9 mm after axicon, respectively, for the $1+(-1)$ superposition.

The experimental setup is shown in Fig. 1. We use a Ti:Sapphire femtosecond laser system as our laser source. This system delivers 45 fs (full-width-at-half-maximum, FWHM) laser pulses at a center wavelength of 790 nm and a repetition rate of 2 kHz. At the laser output, the beam has a Gaussian shape with $1/e^2$ diameter of 9.8 mm, and the maximum pulse energy is 2 mJ. A

1 combination of a half-wave plate and a polarizer is used to control pulse energy. The polarizer is
2 oriented along the X-axis, ensuring that the beam is *p*-polarized when shining on the SLM
3 (Hamamatsu X10468-02). The angle between the beam into and out from the SLM is about 1°.
4 The beam coming from the SLM is focused by an axicon (Doric Lenses) with 25° base angle and
5 25.4-mm diameter. The samples are mounted on a motorized XYZ-stage and move at either high
6 speed (50 mm/s) for single-shot irradiation on borosilicate glass (BK-7) or low speed (1 mm/s)
7 for continuous scribing on molybdenum (Mo) thin film (200-nm thickness). Phase mask images
8 are calculated with Matlab and then loaded onto the SLM. Generated beam patterns are observed
9 with a CMOS camera (Mightex SME-B050-U) with a constant exposure time (25 ms) and a 30×
10 objective lens mounted in front of the image sensor. During the observation the incoming beam
11 is attenuated by a neutral density filter (ND=4.0) placed after the polarizer. Scanning electron
12 (SEM) and atomic force microscopy (AFM) are used to observe the morphology of resultant
13 damage.

3. Results and discussion

3.1 Fabrication of multiple craters on glass with single-shot exposure

Fig. 2. Center portions of (a0)-(a4) designed and (b0)-(b4) applied SLM phase masks, (c0)-(c4) calculated patterns and (d0)-(d4) observed patterns. The pixelation in (b0)-(b4) is due to the finite size of SLM pixels. All columns represent Bessel beams of increasing superposed orders denoted on the left of the

figures. (e0)-(e4) SEM images of damage generated by the corresponding beam patterns on borosilicate glass. The size of phase masks shown in (a0)-(a4) and (b0)-(b4) is $800\text{ }\mu\text{m} \times 800\text{ }\mu\text{m}$, and the width of each ring is $40\text{ }\mu\text{m}$. The size of full masks is $16\text{ mm} \times 12\text{ mm}$. The size of all the other images is $10\text{ }\mu\text{m} \times 10\text{ }\mu\text{m}$. All the damage is obtained at about $Z=9\text{ mm}$ and with single-pulse exposure. Pulse energies (measured in front of SLM) used to generate damage (e0)-(e4) are $100\text{ }\mu\text{J}$, $300\text{ }\mu\text{J}$, $500\text{ }\mu\text{J}$, $600\text{ }\mu\text{J}$ and $900\text{ }\mu\text{J}$, respectively.

The center portions of designed phase masks are shown in Fig. 2 (a0)-(a4) and the masks actually applied on the SLM are shown in Fig. 2 (b0)-(b4). The pixelation in (b0)-(b4) is due to the finite size of SLM pixels ($20\text{ }\mu\text{m} \times 20\text{ }\mu\text{m}$). The full size of these masks is $16\text{ mm} \times 12\text{ mm}$. The first mask (a0) is simply a flat phase mask (replicating a flat mirror), and introduces no phase modulation to the input Gaussian beam. The beam after the axicon is a zero-order Bessel (Bessel-Gaussian) beam. The calculated beam pattern is shown in Fig. 2(c0), and the experimentally measured pattern is shown in Fig. 2(d0). This beam generates a single damage spot on borosilicate glass, as shown in Fig. 2(e0).

The next three masks (a1)-(a3) are used to generate superpositions of Bessel beams with opposite orders of 1 and -1, 2 and -2, and 3 and -3, respectively. The transmission function for these masks, $T_{l,-l}(r, \theta)$, is

$$T_{l,-l}(r, \theta) = \exp \left[i(-1)^{\lfloor \frac{x}{\Delta} \rfloor} l \theta \right], \quad (1)$$

where l (1, 2 or 3) is the superposed order, r and θ are the radial and azimuthal coordinate, respectively, Δ is the width of each ring, and $\lfloor x \rfloor$ denotes the integer part of the number x . The phase angle of T is then calculated at each pixel location, phase-wrapped between 0 and 2π , and linearly mapped to an 8-bit bitmap image. This image is loaded onto the SLM. These masks are composed of concentric rings with continuous azimuthal modulation from 0 (black) to 2π (white). The radial coordinate r is used only to determine the handedness of the azimuthal modulation. Every two neighboring rings have opposite modulation directions (handedness), and the number of modulation cycles (l) along each ring is $l=1$ for (a-1), $l=2$ for (a-2) and $l=3$ for (a3). Similar phase masks have been used to generate high-order Laguerre-Gaussian beams [25] and superpositions of Bessel beams when combined with a lens [21]. In this study, these rings with opposite modulation are stacked together to ensure that the generated patterns do not rotate as

they propagate (shown later). These masks generate superpositions of Laguerre-Gaussian beams (e.g., Fig. 1(c)) after the SLM, and these Laguerre-Gaussian beams are focused by the axicon to generate superpositions of Bessel beams with opposite orders, an extension of the work reported previously [26,27].

The electric field in between the SLM and the axicon, and after the axicon, can be obtained by numerically solving the Fresnel diffraction equation using the fast Fourier transform (FFT) method [28]. Formally, the field between the SLM and the axicon is

$$E_1(x, y, z) = \frac{e^{ikz}}{i\lambda z} \iint T_{l,-l}(x', y') T_G(x', y') \exp\left\{\frac{ik}{2z}[(x - x')^2 + (y - y')^2]\right\} dx' dy', \quad (2)$$

and the field after the axicon is

$$E_2(x, y, z) = \frac{e^{ik(z-L)}}{i\lambda(z-L)} \iint E_1(x'', y'', L) T_A(x'', y'') \exp\left\{\frac{ik}{2(z-L)}[(x - x'')^2 + (y - y'')^2]\right\} dx'' dy''. \quad (3)$$

In Eqs. (2) and (3), (x, y, z) is the Cartesian coordinate with the origin at the center of the phase mask; (x', y') and (x'', y'') are the coordinates on the phase mask and the axicon plane, respectively; $T_{l,-l}(x', y')$ is the transmission function of the phase mask (Eq.(1)) in the Cartesian coordinate; $T_G(x', y') = \exp\left(-\frac{x'^2 + y'^2}{w_0^2}\right)$ is the amplitude modification for Gaussian beams, where w_0 is the waist radius of the input beam; $k=2\pi/\lambda$ is the wavenumber, where λ is the wavelength; L is the distance between the SLM and the axicon; and $T_A(x'', y'') = \exp\left(-\frac{i2\pi n \tan \gamma}{\lambda} \sqrt{x''^2 + y''^2}\right)$ is the transmission function of the axicon, where n and γ are the refractive index and base angle of the axicon, respectively.

While the intensity at each location can be obtained by numerically solving the Fresnel integrals (Eqs. (2) and (3)), a closed-form equation based on Ref. [27] can be used to approximate the intensity after the axicon:

$$I_{l,-l}(r, \theta, z) \propto z^{2l+1} \exp\left[\frac{-2(n-1)^2 \gamma^2 z^2}{w_0'^2}\right] \times J_l^2[k(n-1)\gamma r] \cos^2\left[l\left(\theta + \frac{\pi}{2}\right)\right], \quad (4)$$

where r and z are the radial and axial coordinate, respectively; n and γ are the refractive index and base angle of the axicon, respectively; $w_0'^2$ is the radius of the beam on the axicon; J_l is the l -th order Bessel function of the first kind; and $k=2\pi/\lambda$ is the wavenumber, where λ is the wavelength. The last term in Eq.

(4), $\cos^2[l(\theta + \frac{\pi}{2})]$, is the azimuthal modulation resulting from the interference of superposed orders.

One should note that the beam radius on the axicon (w'_0) differs from the original waist radius (w_0) in our setup. This is because the beam profile on the axicon is no longer Gaussian (Fig. 1(c)), but instead has complex structures. The radius w'_0 is therefore an “effective” radius characterizing the overall intensity distribution on the axicon. This parameter determines the z-position of peak intensity and the range of non-diffracting propagation. In our simulation, we find that $w'_0=2.2$ mm gives good agreement with the experimental results. From Eq. (4) we can estimate the contrast between the peak of central bright spots and the peak of the structures surrounding them. This contrast is $J_0^2(0)/J_0^2(3.8)=6.2$ for the zero-order Bessel beam ($l=0$), $J_1^2(1.8)/J_1^2(5.3)=2.8$ for $l=1$, $J_2^2(3.1)/J_2^2(6.7)=2.4$ for $l=2$, and $J_3^2(4.2)/J_3^2(8)=2.2$ for $l=3$. Due to this reduction of contrast with increasing l , input laser power should be chosen so that only the central lobes exceed material’s damage threshold in order to avoid collateral damage from other parts of the patterns.

Figures 2(d1)-(d3) show the experimentally observed patterns, which in general match the calculations (Figs. 2(c1)-(c3)). Small differences, such as the elongated shape and unequal brightness of the six spots in (d3), are attributed to slight wavefront distortion originating from the input beam and optical elements. In particular, it should be noted that the manufacturing of high-optical-quality axicons is still a challenge for most optics companies. Damage patterns (Figs. 2(e1)-(e3)) are generated with single-pulse exposure. It should be noted that, while all the bright spots in Figs. 2 (d1)-(d3) have similar intensities – in fact they should have the same intensity distribution according to Eq. (4) – the phases of the electric fields in neighboring spots, however, are in π -phase shift, i.e, every two neighboring spots along the azimuthal direction have the opposite signs in the electric-field amplitude, due to the azimuthal modulation term in Eq. (4).

In Fig. 2(a4), we insert a flat-phase ring between every pair of oppositely-modulated rings. This mask can be seen as a combination of (a0) and (a3), and generates a beam pattern similar to (d3) but with the addition of a central lobe. This new pattern can be considered as a combination of the zero-order Bessel beam and the $3+(-3)$ superposition. The resultant damage is shown in Fig. 2(e4), where an added damage spot at the center can be seen.

In obtaining Fig. 2 (and following Figs. 3 and 4), the width of each ring (Δ in Eq. (1)) in the phase masks is $40\text{ }\mu\text{m}$ (corresponding to the size of 2 pixels on the SLM), and the beam path (L) from the SLM to the axicon is fixed at 2.5 m. First, regarding the ring width, we find that nearly identical beam shapes can be generated when Δ is between $20\text{ }\mu\text{m}$ (1 pixel) and $160\text{ }\mu\text{m}$ (8 pixels). The resultant patterns become distorted when Δ is larger than $180\text{ }\mu\text{m}$ (9 pixels). Surprisingly, despite the heavy pixelation of the 1-pixel-width phase masks, high-quality patterns can still be generated. We use 2-pixel-width masks in this study to reduce unknown effects arising from heavy pixelation. Second, regarding the beam path L , there is no noticeable difference in the generated patterns when L is changed between 1.5 and 4.5 m, which is the range we can conveniently achieve with the current setup. Our computer simulation confirms that similar beam patterns can be generated from $L\sim 0$ (if using a transmission SLM immediately followed by an axicon) to $L=110\text{ m}$. While we do not observe significant change in the beam profile when L is between 1.5 and 4.5 m, one should check this and verify that it meets one's requirement when working at long L .

The energy efficiency of this “SLM + axicon” method is defined as the ratio of output pulse energy (measured in front of the axicon) to input pulse energy (measured after the polarizer). The energy after the axicon is not measured to avoid damaging the power meter sensor with the intense beam patterns. Since our axicon is made of fused silica with high transmission at the laser wavelength, the energy loss (estimated $<10\%$) from the axicon is mainly due to reflection on the uncoated surfaces, and can be reduced with anti-reflective coatings. Therefore such loss is not included in this measurement. Furthermore, the focus of our paper is to show that the inclusion of an SLM does not introduce large additional losses, and the axicon would be equivalent to a focusing lens in the “ring-aperture and convex lens” setup. Our results show that the efficiency for generating the zero-order beam (Fig. 2(d0)) is 97%, and the efficiencies for other beam patterns (Figs. 2(d1)–(d4)) are 60%, 55%, 54% and 52%, respectively. The energy loss is caused by diffraction on the SLM due to the complex phase masks. It should be noted that, even if the efficiencies for generating the superposed beams are almost the same, more input pulse energies, increasing from $100\text{ }\mu\text{J}$ for Fig. 2(e1) to $900\text{ }\mu\text{J}$ for Fig. 2(e4), are required to produce more damage spots. We use large pulse energies (especially for more complex patterns) to ensure that all of the damage spots can be observed. When working with large pulse energies,

one should choose appropriate laser parameters (beam diameter, pulse duration, repetition rate, etc.) to avoid damaging SLMs due to excessive heating in the liquid-crystal. In this experiment, these parameters are chosen so that our SLM can output stable phase modulation for 10-hour continuous irradiation at the maximum load.

To estimate the peak intensities of the beam patterns relative to that of the zeroth-order beam, we take images of these patterns together with the zeroth-order pattern with the same input power. The power is checked after the polarizer, and then attenuated by an ND=4.0 filter. Our imaging system has been checked to be linear in the range of values of interest. We find that, relative to the zeroth-order beam, the peak intensities are 46% for the $1+(-1)$ pattern, 37% for $2+(-2)$, 27% for $3+(-3)$, and 15% for $3+(-3)+0$. This reduction in peak intensities is the reason that more pulse energies are required to generate multiple craters shown in Fig. 2.

3.2 The long depth-of-focus (propagation-invariant) property of generated beams

Fig. 3. Propagation of the +1(-1) superposed Bessel beam. (a) Observed and (b) calculated beam profiles in YZ (X=0) and XZ (Y=0) planes. (c-g) Observed and (h-l) calculated beam shapes at Z=6.5, 7.5, 8.5, 9.5 and 10.5 mm, respectively.

The propagation-invariant property of these superposed Bessel beams is demonstrated in Fig. 3, using the 1+(-1) superposition as an example. We take images of beam patterns from Z=6.5 mm to 10.5 mm (Z=0 is at the axicon tip), with 0.1-mm step size and 25-ms camera exposure time, and plot YZ and XZ profiles in Fig. 3(a). Beam shapes at five locations (Z=6.5, 7.5, 8.5, 9.5 and 10.5 mm) are shown in Fig. 3(c-g). For comparison, simulation results based on Eq. (2) are shown in Fig. 3(b) and (h-l). In the YZ-plane, we can see that measured profiles show two strong lobes, spanning across the entire Z-range, in consistence with the simulation data. In the XZ-plane, weak intensity distribution is observed at the beam's trailing portion, while simulation shows nearly zero intensity in this entire region. From Fig. 3(c-g), we observe almost unchanged beam shapes from Z=7.5 to 9.5 mm, resulting in a 2-mm depth-of-focus. For comparison, a focused Gaussian beam with a waist diameter of 2 μm (similar to the size of one lobe in the superposed beam) has a confocal length of only 8 μm . At Z=6.5 mm and 10.5 mm, the intensity of one of the lobes becomes higher than the other, while simulation shows equal intensities at each Z location. This discrepancy, together with the weak intensity distribution in the XZ-plane, is attributed to the imperfect input beam and optical elements. The non-diffracting length of a zero-order Bessel beam can be estimated geometrically as $D = w_0 / [(n - 1)\gamma] = 25.5 \text{ mm}$. For the 1+(-1) superposed beam, w'_0 instead of w_0 should be used, and this gives $D' = w'_0 / [(n - 1)\gamma] = 11.2 \text{ mm}$. Other superposed beams have similar, mm-order depth-of-focus (results not shown). It is worth pointing out that these superposed beam patterns do not rotate as they propagate, in contrast to previous results [21,22]. This “nonrotating” feature ensures that similar damage patterns can be generated within a long depth-of-focus, which is convenient for the fabrication of microstructures on uneven surfaces, such as moving rolls of solar thin film (which will be used later in this study).

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10 *3.3 Scribing of Mo thin film with the $1+(-1)$ superposed beam*

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Fig. 4. Comparison of groove scribing with (a, b) zero-order and (c, d) 1+(-1) superposed Bessel beams.

(a) and (c) are calculated beam shapes, and (b) and (d) are AFM images of grooves scribed with corresponding beams. A pair of damage tracks is indicated with red arrows in (b), and is believed to be caused by sections of rings indicated by blue arrows in (a). In both cases, the scanning speed is 1 mm/s, and the samples are placed at $Z=9$ mm. Pulse energies (estimated peak fluences) are $10 \mu\text{J}$ (0.42 J/cm^2) for (b) and $20 \mu\text{J}$ (0.38 J/cm^2) for (d) (e) shows a comparison of intensities integrated along the scanning direction between two cases. The integrated intensities are normalized to their peak values.

It has been reported that, while zero-order Bessel beams offer substantial increase in depth-of-focus compared to Gaussian beams, the concentric rings in the zero-order beams can cause

undesired damage [6,19]. Shown in Fig. 4(b) is an AFM image of a narrow groove scribed on Mo thin film with a zero-order Bessel beam (illustrated in Fig. 4(a)). The groove width is 1.3~1.4 μm and the depth is about 200 nm. A pair of damage tracks (indicated with red arrows in Fig. 4(b)) parallel to the central groove can be seen. A single track on the right-hand side is also visible. It is further found that the distances between these tracks and the center of the groove coincide with the radii of the first and the second rings (2 and 4 μm , respectively) in our zero-order beam. Therefore, we conclude that these tracks are caused by sections of these rings, the sections (indicated by blue arrows in Fig. 2(a)) that are located at about 90° angle to the scribing direction. This is because these sections overlap more on the sample than the other sections along the ring, and therefore can cause damage more easily. The missing track in the second pair is attributed to uneven intensity distribution of the second ring, as can be seen in Fig. 2(d0).

These results suggest that, if the $1+(-1)$ superposed beam is used and aligned such that the scanning direction is parallel to the two lobes, such collateral damage can be reduced, since there is nearly zero intensity in those sections. To demonstrate this, we scribe a groove with similar width and depth using the $1+(-1)$ beam, and the result is shown in Fig. 4(c) and (d). We observe a clean groove without any damage tracks, in consistence with the analysis above. Small bumps observed in Fig. 4(d) are random debris and defects on the surface, and are not damage from the beam. Comparing Fig. 4(b) and (d), we also observe reduced roughness at the groove walls when the superposed beam is used. This is perhaps due to the fact that, with the superposed beam, every location on the sample is scribed twice by the two lobes, and the second scribing can smooth the rough surface after the first scribing. The peak fluence for the zero-order beam is estimated from our previous study [19] to be 0.42 J/cm^2 , and that for the $1+(-1)$ beam is calculated to be 0.38 J/cm^2 using the results of relative intensities from Section 3.1.

The improved quality from the superposed beam can also be explained by calculating the intensity profiles integrated along the scanning (Y) direction, as shown in Fig. 4(e). These integrated intensity profiles represent the total power delivered to the sample per unit distance along the X -direction, under the condition that shot-to-shot overlapping is high ($> 75\%$ in our case). One can see from Fig. 4(e) that, when the same amount of power is delivered at the center, at locations away from the center ($|X| > 1 \text{ } \mu\text{m}$), the $1+(-1)$ beam introduces less power than the

1 zero-order beam. More importantly, the curve for the superposed beam increases monotonically
2 from either side of the X -axis, as opposed to the zero-order beam for which local maxima exist.
3 This is the reason that a distinct groove can be generated with the superposed beam, whereas
4 multiple damage tracks appear for the zero-order beam.

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6 We also find that, with the $1+(-1)$ beam, the width of scribed grooves is $1.7\sim 1.8\text{ }\mu\text{m}$, larger than
7 that ($1.3\sim 1.4\text{ }\mu\text{m}$) with the zero-order beam. We attribute this to the slightly larger beam size for
8 the $1+(-1)$ beam. Specifically, the groove width with the $1+(-1)$ beam is determined by the
9 maximum width of one of the two central spots, measured perpendicularly to the writing
10 direction. From Eq. (2) we can calculate that the full-width-at-half-maximum (FWHM) is $1.8\text{ }\mu\text{m}$,
11 whereas the FWHM for the zero-order is $1.3\text{ }\mu\text{m}$. These numbers agree well with measured
12 groove widths. To reduce the widths, one can focus the $1+(1)$ beam more tightly with a sharper
13 axicon. For example, our calculation based on Eq. (2) shows that to get the same width as the
14 zero-order beam ($1.3\text{ }\mu\text{m}$), the base angle should be increased to 30° .

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16 In writing complex structures with the $1+(-1)$ pattern, another factor one should take into account
17 is that the orientation of this pattern should be constantly adjusted so that the two central lobes
18 are always parallel to the writing direction. This can be achieved by rotating the phase mask on
19 the SLM (and consequently changing the pattern's orientation) in synchronization with the XYZ-
20 stages.

21 22 **4. Conclusion**

23 We use the "SLM + axicon" setup to generate superposed Bessel beams with opposite orders
24 with high efficiency. Designing new beam patterns is possible by tweaking phase masks on the
25 SLM. These beams can be used to fabricate micro-scale structures with the advantages of
26 increased depth-of-focus, programmable patterns and reduced processing time. We also
27 demonstrate that the $1+(-1)$ superposition can reduce collateral damage caused by ordinary zero-
28 order Bessel beams.

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