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Direct-write diffracting tubular optical components using femtosecond lasers

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ABSTRACT

Over the last decade, femtosecond lasers have been used extensively for the fabrication of optical elements via direct writing and in combination with chemical etching. These processes have been an enabling technology for manufacturing a variety of devices such as waveguides, fluidic channels, and mechanical components.

Here, we present high quality micro-scale optical components buried inside various glass substrates such as soda-lime glass or fused silica. These components consist of high-precision, simple patterns with tubular shapes. Typical diameters range from a few microns to one hundred microns. With the aid of high-bandwidth, high acceleration flexure stages, we achieve highly symmetric pattern geometries, which are particularly important for achieving homogeneous stress distribution within the substrate.

We model the optical properties of these structures using beam propagation simulation techniques and experimentally demonstrate that such components can be used as cost-effective, low-numerical aperture lenses. Additionally, we investigate their capability for studying the stress-distribution induced by the laser-affected zones and possible related densification effects.

Keywords: ultrafast, diffraction, stress, birefringence, nanogratings, BPM, densification, silica

1. INTRODUCTION

Ultrafast lasers have become a ubiquitous tool for the production and modification of a wide variety of optical components and substrates. Ever increasing complexity and capability has led to the realization of various devices, including waveguides¹, monolithic direct-write lasers², exotic polarization converters³, microfluidic applications⁴, beam shaping components⁵, and even micro-mechanics⁶. As the direct-write technique becomes more prolific, research groups continually seek to exploit nonlinear interactions in dielectrics to produce new and unique devices. Here we present one such device, incorporating the direct-write technique to fabricate a new class of optical components.

It is well known that a side effect of the laser-writing process is the formation of nanogratings within the laser-affected zone⁷. Recently, our group has shown that these structures cause deformation of the substrate leading to stress buildup around the laser-affected zone⁸. This stress buildup has been shown to be very large in silica glass^{9,10}, and induces birefringence in the bulk of the substrate.

In this work, we combine the diffractive properties of laser-written tubes with the effect of stress-induced refractive index change in an effort to enhance their optical properties. Tubular structures benefit from simplicity and ease of fabrication using direct-write techniques, and give full control over the induced stress state, both in magnitude and orientation. In comparison to previous methods developed by our group¹⁰, tubular structures allow for the creation of stress anisotropy over a full range of angles. The inherent symmetry of these building blocks provides an efficient way to generate large anisotropy while keeping stress concentrations low, thereby reducing the possibility of material failure during loading. Additionally, tubes may be combined to produce higher stress states as well as complex field patterns and polarization states.

Previously, a rectilinear approach has been used to demonstrate the creation and modification of optical components. One such example employs linear stressors written in close proximity to a laser-written Bragg waveguide to control reflection peak splitting by modifying the inherent birefringence in the waveguide¹¹. Additionally, stress may also be used to create waveguides in crystalline materials by creating damage tracks that disrupt the regular crystalline lattice. The laser damage generates stress regions, producing a sufficient change in refractive index to allow for guided modes¹².

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This technique relies on lattice damage to create stress rather than the formation of nanogratings, yet still serves as an excellent example of the use of engineered stress.

2. FABRICATION

The structures presented in this work were fabricated using an ultrafast laser (Amplitude Systèmes) operating at 1030 nm with a repetition rate of 400 kHz and a pulse energy of 200 nJ. Laser light was focused into the bulk of a fused silica substrate using a 20x (0.4 NA) microscope objective. Sample translation was performed with a combination motion stage, incorporating traditional screw-driven stages for X-Y positioning as well as piezo-driven flexure stages for high-speed, high-precision positioning. Focus of the beam was performed using an independent stage, moving only in the Z direction.

Figure 1: Fabrication process for the construction of laser-written tube structures. A tube is composed of individual rings (A), fabricated by translating the substrate in a circular motion at a fixed velocity. Rings are then ‘stacked’ (B) to form a tube. Focal-plane separation was fixed at 5 μm .

Figure 1 shows the fabrication process for these tube structures. A tube starts with the basic building block of a single annular ring of index-modified material (Figure 1A), formed by translation of the substrate in a circular motion. The focus is then translated toward the surface of the substrate and the process repeated until the desired number of rings are written, forming a tube-like structure (Figure 1B). The lateral width of a single ring is defined by the width of the laser-affected zone with a height on the order of 8 – 10 μm . Focal plane separation between successive ring layers was set at 5 μm . The writing velocity was fixed at 1000 $\mu\text{m/s}$ at various diameters, with a maximum outer diameter of 100 μm , which is the travel limit for the flexure stages. For comparative purposes, tubes were fabricated in both fused silica and soda-lime substrates.

3. TUBES AS STRESSORS

Typically, nanograting induced stress has been utilized in a rectilinear fashion. This method has been applied to create stressors based on sheets or planes⁸, as well as single lines of laser-modified material¹¹. The application of these stressors is used to load the substrate with a finite amount of stress based on a measured deformation of $\sim 0.03\%$ per unit length⁸. In order to create anisotropic stress fields, one must either change the geometry of the nanograting structure, or introduce curvature to the laser-written pattern while keeping the writing polarization fixed. Here we accomplish both: curvature is introduced by fabricating rings to form tubes while the writing polarization may be rotated to change the orientation of the anisotropic stress field. Isotropic stress states are also possible through the use of exotic polarization states, such as radial or azimuthal polarization. While generation of anisotropic stress states is possible using a rectilinear approach (i.e. sheet or plane), this method has the disadvantage of creating regions of high stress concentration at the corners. Through

manipulation of the grating structure in a circular pattern, we effectively avoid creating these concentrated regions while still maintaining a directed anisotropic stress state.

Figure 2: Stress model (A) and resulting polariscope image showing retardance profile (B) for a 128 layer, 50 μm diameter tube. The evolution of the deformation profile displayed in (A) is determined by calculating the linear segment length along the direction of the +y axis that perpendicularly bisects the nanograting lamellae between the inner and outer ring radius. The color bar in (B) represents a maximum retardance of 100 nm.

A model for the developed deformation and corresponding retardance image for a 50 μm diameter tube with 128 layers is given in Figure 2. In this configuration, the writing polarization is oriented along the +y axis, forming nanogratings perpendicular to the polarization (Figure 2A). These nanogratings are responsible for the generated stress and lead to the unique field pattern shown in Figure 2B. In this model, individual lamellae undergo a volume expansion, possibly due to dissociation of elements within the substrate^{8,13}. This particular configuration of ring structures leads to a unique distribution of stress, as shown by the plot of the developed deformation along the x-direction of the ring radius. This deformation is calculated by computing the linear segment length along the direction of the +y axis that perpendicularly intersects the lamellae between the inner and outer radius as a function of distance along the +x axis. Previously, it was reported that these lamellae undergo a deformation of approximately $\sim 0.03\%$ ⁸. By calculating the intersecting segment length we estimate a total deformation (and hence stress buildup) over the radius of the ring. This distribution of deformation shows a strong correlation with the field pattern displayed in Figure 2B. The average developed stress in the center of the tube as calculated from the retardance measurements is ~ 11.3 MPa, with a maximum of ~ 30.8 MPa near the edges of the ring. Details of these calculations can be found elsewhere in the literature¹⁰.

The false-color retardance images displayed here were acquired using a liquid-crystal based polariscope (LC-Polscope, CRi Instruments). For the calculation of average retardance within the central region of the tube, image-processing techniques were used to create a circular mask, taking care to avoid sampling from the retardance region due to laser-modified material. As in previous studies, we are only interested in retardance resulting from nanograting-induced stress and not the form-birefringent retardance present in the nanogratings themselves¹⁰.

To investigate the developed stress further and to determine the controllability of the stress dipole, a series of tubes was written using the same conditions as previously mentioned, but with a varied number of layers, each having double the number of layers as the previous (i.e. 1, 2, 4, 8, etc.) and repeated multiple times for consistency.

Figure 3 shows the results of this experiment, where tubes were written in both fused silica (Figure 3A) and soda lime glass (Figure 3C) for comparison. The ring diameter was fixed at 100 μm , so that the central region could be used as a definable area to calculate an average developed retardance, again taking care to avoid sampling from the form-birefringent portion of the laser-modified zone.

High-resolution images were acquired of each tube structure, then cropped and arranged in the image arrays shown below each plot. Data acquisition consisted of multiple phases, the first acquiring a horizontal line scan across the central region of each row of tubes which is displayed as the black profile in each plot. Secondly, a circular mask is defined (as indicated by the colored markers in each image) for sampling of the image data. From this region an average retardance is computed along with the range (given as error bars) as shown by the blue markers in Figure 3A and 3C.

Figure 3: Retardance plots for multi-layered tubes in silica and soda lime glass. Ring diameter is 100 μm with a layer spacing of 5 μm . Upper row, left (A) line scan plot for increasing number of layers showing average retardance within each ring as well as range of max/min values above/below computed average. It should be noted that the sharp peaks on the plot represent retardance inherent in the form-birefringent regions of the laser-affected zone, and were excluded from the calculations. (B) Retardance profile within the tube containing 128 layers (C) line-scan plot for soda-lime glass and (D) retardance profile for the tube containing 128 layers. Here we see that, while the maximum developed retardance for the fused silica case is much larger (~ 50 nm), the 128-layer profile for soda lime indicates more material compaction within the center of the ring. The maximum retardance in this case however is an order of magnitude lower than for fused silica. Correspondingly, the calculated maximum difference in principle stress for fused silica and soda lime is 30.8 MPa and 2.42 MPa respectively. The colored markers inside each ring mark the positioning of the circular mask used for retardance calculations during image processing and analysis.

Qualitatively, the results in Figure 3 show that the induced retardance is anisotropic as suggested by the model, often oriented along the direction of the writing beam polarization (in this case, linear). The retardance profiles given in Figure 3B and 3D demonstrate that, while the total developed retardance in silica is much higher than that of soda-lime (~ 70 nm), the profile of soda lime indicates more homogeneous material compaction within the center of the ring, and has an overall convex shape. Here we find that the mechanism of volume change in soda lime glass is likely due more to melting within the laser-modified zone than the formation of nanogratings¹⁴. Despite this even profile, the total retardance is at least an order of magnitude lower than the fused silica case (~ 5 nm). We also find that the retardance profile for silica is concave, and nearly zero at the center of the tube, so any small-scale variations in this region will not be visible for the scale given.

Figure 4: (A) plot of total average retardance within the tube center in silica and soda lime glass for rings of 50 μm and 100 μm diameter. (B) Magnified view of the soda-lime tube data. Here we see a clear indication of increasing total average retardance with decreasing ring size.

Data from a series of tube structures is shown Figure 4A, where the total average retardance within the tube center is plotted as a function of the number of layers for both 50 μm and 100 μm diameter tubes. In general, the average retardance increases linearly with the number of layers and is overall higher for smaller ring diameter. This is to be expected, as each layer provides a finite amount of stress-induced retardance and should vary in a linear fashion with the number of layers. In Figure 4B we indeed find that the retardance per layer is relatively fixed and constant. When examining the data for soda lime, we again find that the total developed retardance in soda lime glass hardly changes over the full range of layers, further supporting focal-volume melting as a stress mechanism in this material. Note that the data presented here is for a fixed energy deposition, and the curves shown in Figure 4 may be shifted either up or down by varying the exposure conditions.

Figure 5: Plot of total average retardance vs diameter for tubes in fused silica with 128 layers. Retardance increases linearly down to a tube diameter of approximately 10 μm, at which point the resolution limit of the polariscope makes differentiation between stress-induced birefringence and the form-birefringence of the laser affected zone difficult. At a ring diameter of 10 μm, the average retardance is ~150 nm, corresponding to a difference principal stress of 55 MPa. Resulting values for maximum developed difference principle stress are also given for the other tube features.

It is also interesting to note that reducing the size of the tube, as indicated in Figure 4A, increases the slope of the retardance curve. As there is less material within the central region of the tube and the total deformation per unit length is the same, the developed stress is accordingly larger. To test this further, tubes were fabricated in fused silica with decreasing size from 50 μm down to 5 μm , each with 128 layers, the results of which can be found in Figure 5. We chose to exclude soda-lime glass due to the limited stress (and, hence retardance) generated. The total average retardance is found to increase almost linearly with decreasing diameter, up to a maximum of 150 nm at a tube diameter of 10 μm , corresponding to an average difference principal stress of ~ 15.9 MPa and 55 MPa respectively. Below a diameter of 10 μm , a maximum average stress of ~ 67 MPa is calculated, however it should be noted that differentiation between the stress-induced birefringence and form-birefringence inherent in the laser-affected zone becomes difficult due to the spatial resolution limits of the polariscope.

From this data, we find that relatively moderate amounts of stress can be generated using single-walled tubes, while combinations of multiple tubes, either concentric or in arrays, could be used to generate stress fields with larger magnitudes. The data presented here was given for a fixed set of writing conditions; therefore larger stresses are likely to be generated for higher values of total energy deposition. We find that this data gives evidence indicating a high degree of control over the magnitude of stress generated, however the question of orientation has not yet been addressed. In keeping with the nanograting orientation model, an experiment was designed in which a series of 128 layer tubes was written using a fixed energy deposition. To demonstrate control over orientation of the stress field, the writing polarization was rotated between successive sets of tubes. Representative retardance field plots for this experiment are shown in Figure 6, with fixed writing polarizations of (A) 90° , (C) 45° , and (E) 90° . To confirm the orientation of the resulting nanograting structure in comparison to our model, a second set of tubes was written using a z-displacement sufficient to breach the top surface of the substrate during each fabrication cycle. The substrate was then etched in a solution of 2.5% hydrofluoric acid for 5 minutes to expose the structure of the nanogratings. The resulting SEM images, corresponding to the writing polarization states displayed in A, C, and E, can be found in in Figure 6, sections B, D, and F.

Here, we see that the stress field can be oriented as desired based on the writing polarization, and that these images correlate well with our nanograting model of stress orientation in ring structures. For each feature, the nanograting period was consistent around the entire circumference of the tube and no variation with respect to the writing polarization. Our group has previously studied the role of nanograting orientation on stress, using analytical, finite-element method, and experimental analysis¹⁰. This study used an incrementally discrete method of writing a so-called ‘sun pattern’, in which a series of radial lines was written at angular increments of 15° , while keeping the writing polarization fixed. Each line segment written in the pattern then contained a different writing direction with respect to polarization, thereby creating orientation-dependent nanograting induced stress between each of the equally (angularly) spaced line segments. The model presented here demonstrates an extension of the sun-pattern approach while providing continuous information about the angular dependence of the nanograting orientation.

Following a similar approach of the nanograting model, it should be possible to create a stress state that is isotropic, showing no particular orientation of the stress field. Keeping in mind that nanogratings form perpendicular to the writing polarization then it is useful to consider polarization states such as circular, radial, and azimuthal polarization. These states should, given the unique orientation of the field vector that defines the beam polarization, yield grating structures that result in isotropic stress fields.

For comparison, tubes were fabricated using circular, radial, and azimuthal polarization, the latter two implemented using a vortex polarization converter¹⁵. Fabrication was performed in a similar manner to the previously mentioned liner case, with tubes being written through the surface, etched, and finally imaged under an SEM to reveal the resulting nanostructure. The stress-field patterns, along with their corresponding SEM nanograting images are shown in Figure 7.

Figure 7A, 7B show the resulting field pattern and nanostructure images for a tube written using circular polarization. The first thing we notice is that the resulting field is anisotropic, opposite of what was intended. Upon closer examination, we find that the nanogratings show a slight preferential orientation to the orientation of the quarter-waveplate used to induce the writing beam polarization state. The nanogratings formed in this feature mostly oriented perpendicular to the axis of orientation of the stress field. Between the sections of nearly parallel nanogratings, a ‘mixed’ orientation is found, suggesting a competition between the two vector components of the beam polarization. This is most likely due to anisotropy in the beam polarization.

Figure 6: Orientation of nanogratings with respect to writing polarization. Field plots for linear writing polarization with an orientation of (A) 0° , (B) 45° , and (C) 90° . The corresponding SEM images of the etched rings are shown in (D-F) respectively.

Figure 7: Retardance maps for 50 μm diameter tubes written with (A) circular polarization at 200 nJ/pulse, (B) radial polarization written at 1 $\mu\text{J}/\text{pulse}$, and (C) azimuthal polarization written at 1 $\mu\text{J}/\text{pulse}$. Translation speed for all features was 1000 $\mu\text{m}/\text{s}$. Due to a larger spot size radial and azimuthal writing case; larger pulse energy was used to ensure the focus intensity was above the threshold for nonlinear absorption.

Polarization anisotropy can arise due to several factors. Generation of circular polarization is often difficult since obtaining perfectly circular state is often difficult and results in a state that is slightly elliptical. Additionally, despite using achromatic waveplates, retardance is not fully compensated for broadband light (as in the case of ultrafast laser radiation), and slight differences in phase retardation over the full spectrum of the pulse will further contribute to the ellipticity of the polarization state. Lastly, variations in sample tilt (i.e. perpendicularity with respect to the writing beam propagation axis) can contribute to Fresnel reflections¹⁶, causing undue attenuation to the different polarization components of the writing beam. All of these factors lead to greater ellipticity in the polarization state, which ultimately alters and influences the process of nonlinear absorption and the formation of nanogratings.

Radial and azimuthal polarization states provide a beam polarization that is fully isotropic, and gives directionally independent material interaction¹⁷. In Figure 7C-F, we find that these polarization states do indeed produce a stress state that is almost perfectly isotropic. A slight anisotropy is still present for the radial polarization case, and closer examination of the SEM image of the nanograting structure again reveals the presence of ‘mixing’ of two types of nanograting structures at the upper and lower regions of the ring. Disruption of the regular nanograting pattern causes an unequal distribution of the generated stress, hence the anisotropic retardance profile found in Figure 7C. Better results are obtained when using azimuthal polarization, as the field pattern is nearly perfectly isotropic. In this case, the extent and magnitude of the retardance profile is smaller than that of the radial polarization case, suggesting that the generated stress is lower. The SEM image in Figure 7E shows a periodic grating structure, however the structure of the individual lamellae are again composed of a ‘mixed’ state, closely resembling a chevron. Stress distribution in this structure is split between the two halves of the chevron so that only half as much deformation is directed outward away from the ring structure. Comparing the retardance maps of both the radial and azimuthal structures, we find that the maximum retardance for azimuthal polarization is nearly half that of the radial case.

4. TUBES AS OPTICAL COMPONENTS

The ability to generate measurable amounts of retardance through induced stress opens up the possibility to enhance the optical properties of not only bulk silica substrates, but also the tube structures as well. It is well known that an annular aperture behaves like a lens due to diffraction. This phenomenon has been readily exploited using various techniques to fabricate diffractive optics, such as Fresnel zone plates. Such techniques are particularly attractive in applications where the use of conventional refractive optics is inefficient or impractical^{18,19}. Zone plates can be quite efficient in generating lens-like behavior, however they are also very complex often requiring hundreds of zones to achieve high diffraction efficiency. In some applications this may be necessary, however similar structures with a small number of zones have been used in wave front sensing applications where diffraction efficiency is not a major requirement²⁰. Here we make a comparison between low-zone count Fresnel zone plates and tube structures by treating the tube structures as a zone plate with only two zones. Using various configurations of tubes, it should be possible to generate unique field patterns using only a few basic structures.

In order to further our understanding of the diffractive properties of these tube structures, we first performed a basic simulation using the split-step beam propagation method²¹. Here a 2D simulation space was used for simplicity, taking into account differences of refractive index between the substrate, laser affected zone, and free space using a two-dimensional map of refractive index to define each interface. No account was made for the form birefringence inherent in the laser-modified volume.

Figure 8 shows several simulation results for various tube configurations. As expected, a single tube (Figure 8A) results in a focal spot in a matter similar to that of a Fresnel zone plate with only two zones²¹. Due to the low number of zones, the overall diffraction efficiency is quite low, which we estimate to be less than a few percent for the +1 diffracted order²². In Figure 8B, a nested or concentric ring configuration is used, yielding a focal intensity that is nearly twice that of the single ring case. We find that, not only is the focal intensity greater, but the extent of the focal volume in the z-direction has a uniform intensity over nearly 4 times the extent of the focal volume in the single ring case, closely resembling the focus produced by an axicon²³. Further explorations into ring configurations yield varied intensity distributions as demonstrated in Figures 8C and 8D. In Figure 9, a single tube with 10 layers has been imaged with 633 nm illumination to verify the simulation results.

Figure 8: 2D beam-propagation-method simulation results for various tube configurations. Here the substrate is 1 mm thick, and a ring thickness (width of laser-affected zone) of 2 μm . Right height (measured along beam propagation axis) could be varied in multiples of the length of the laser-affected zone (8 μm up to the thickness of the sample). Simulations were performed using an incident Gaussian beam width (full-width-half-maximum) of at least twice the largest ring diameter, which was set at 100 μm . (A) Single ring configuration showing a ‘standard’ diffraction pattern. (B) Multiple-ring configuration (concentric rings) showing axicon-like focal spot. (C – D) Variations of the nested-ring configuration.

Figure 9: Experimental plot of the diffractive focusing properties of a single ring with 100 μm diameter. Ring illumination was provided by a collimated 633 nm laser beam with a width of approximately 3 mm.

Our aim with these simulations is to demonstrate that, despite their simplicity, these tube structures can be quite versatile. The data presented in Figure 8 is given as an example to show that various complex field patterns can be easily generated, opening up the possibility for new aspects of material structuring and micromachining. We propose that further enhancement is possible through the introduction of stress-induced retardance within the substrate. Though focusing alone may not be heavily influenced, the generation and precise control of retardance allows for the generation of complex field patterns and polarizations. When tubes are arranged in regular lattice patterns, as shown in Figure 10A – 10C, the stress fields interact to form complex networks of retardance, which could be used for tailoring highly specialized polarization states¹⁵. Three lattice structures are shown, first a layout resembling a cubic lattice (Figure 10A), a face-centered lattice (Figure 10B), and a hexagonal lattice (Figure 10C). These patterns all contain tubes of 100 μm in diameter with 128 layers, all written using the same conditions as described in the beginning of this manuscript. Additionally, the transmission of these patterns varies strongly with orientation to linearly polarized light, as shown in Figure 10D where the square pattern is imaged on a standard white-light microscope between crossed polarizers.

Figure 10: Tube lattice patterns with a lattice constant of 250 μm . (A) Square or cubic, (B) face-centered, and (C) hexagonal patterns. (D) Standard white-light microscope illumination with crossed polarizers of the square pattern shown in (A).

We further demonstrate control of the retardance and resulting transmission / polarization state by changing the polarization orientation of the writing beam while writing. Figure 11 shows a tube structure with a 100 μm diameter and 128 layers in which the writing polarization has been rotated 11.25° every 8 layers, rotating through a full 180° over the length of the entire stack. Figure 8A gives an illustration of the polarization state for every 16 layers. The resulting retardance profile (Figure 11B) gives a characteristic vortex pattern, displaying the summation of the total retardance of the ‘twisted’ structure, not unlike that of the so-called vortex polarization converter¹⁵. With this technique, we have multiple variables with which to control the final state of the stress-induced retardance. The magnitude of the birefringence generated in each layer can be controlled by the total energy deposited (pulse energy and translation speed) as well as the ring diameter. This in combination with the number of layers and layer spacing allows for full control over the total retardance. Finally, orientation may be controlled by the direction of the writing polarization. It should be noted that the results presented here are for a relatively fixed set of parameters. No attempt has yet been made to characterize the induced stress and/or retardance as a function of pulse energy and writing speed (total deposited energy), or layer spacing.

Figure 11: Application example of laser-written tube structures. A tube of 128 layers was written while rotating the writing polarization (linear) 11.25° every 8 layers, for a total of 180° . The orientation of the writing polarization is shown in (B) for every 16 layers. The resulting retardance field (B) appears as a vortex-like pattern, suggesting that this device may be applicable to generating complex polarization states, such as radial or azimuthal polarization.

5. CONCLUSION

In summary, we have demonstrated the application of nanograting-induced stress as a means to enhance the mechanical and optical properties of direct laser-written tube structures. The unique combination of localized stress in conjunction with cylindrical structures yields a stress field that is highly controllable in both magnitude and orientation. By varying the exposure conditions, polarization, layer count, and layer spacing, one can achieve a fine level of control over both stress and localized induced optical retardance. As a basic building block, these tubes may be applied individually or in patterns to produce devices that are sensitive to polarized light, opening up the possibility for the generation of complex field patterns and polarization sensing applications.

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