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INVESTIGATING THE PRODUCTION OF GRADIENT INDEX OPTICS BY MODULATING TWO-PHOTON POLYMERISATION FABRICATION PARAMETERS

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Abstract

Two-photon polymerisation (TPP) is an additive manufacturing technique allowing the fabrication of arbitrary 3D geometries with sub-micron features. As such, TPP is a promising technique for fabricating optical metamaterials. The electromagnetic (EM) properties of metamaterials arise from their geometrical structure rather than their material constituents alone. By introducing variations across the unit cells of a metamaterial spatially varying EM properties can be created. In this way, gradient index (GRIN) optics can be produced which are useful for reducing coupling losses and creating compact optical systems. This work looks at modulating fabrication parameters to achieve geometrical variations. Line widths of IP-L 780 are measured on an array of lines fabricated at different laser powers and scan speeds. Proof of concept woodpile structures are also fabricated where laser power is changed for individual lines in the structure resulting in geometrical changes. Changing fabrication parameters along a single scan line is also investigated.

Introduction

The optical lens is a well understood tool whereby a curved surface focuses light in a way dictated by its refractive index. However arbitrary control of electromagnetic radiation is sought after and new approaches to optics are being discovered. One such discovery is that of the metamaterial [1]. Metamaterials provide electromagnetic properties that are not readily found in nature arising not just from their material constituents but from their geometrical structure [2]. The most widely known metamaterial response is that of the negative refractive index whereby for a finite range of frequencies both the permittivity (ε) and permeability (μ) are negative. This property resulted in the demonstration of “super lensing” [3].

Metamaterials are made up of unit cells known as the “meta-atom”. These must be much smaller than the wavelength being considered to result in a homogeneous averaged electromagnetic response. It is possible, however, to create spatially varying electromagnetic properties by introducing variations within each unit cell. In this way gradient index (GRIN) metamaterials are presented as an approach to developing GRIN optics [2]. From the 1850s GRIN optics have been of wide interest due to applications in lensing and filtering [4]. Conventional convex lenses can be replaced by an optical element where the refractive index increases from the centre to the outer edge allowing the light to be focused [5]. Since GRIN lenses are flat spherical aberrations are reduced decreasing coupling losses across optical systems, whilst also saving space and allowing more compact optical systems [6].

The manufacturing techniques for conventional GRIN lenses limit the shape and depth of the gradient thus limiting performance and design. However a wider range of fabrication technologies become available when starting to look at metamaterial GRIN lenses. One particular technique is two-photon polymerization (TPP) which writes structures in a photocurable resin using a tightly focused laser. By focusing and ultrashort pulse excitation, a high power density is achieved allowing polymerisation within regions smaller than the diffraction limit. Since the cured photopolymer is supported by the polymer bulk TPP allows the fabrication of structures of arbitrary geometry with feature sizes close to 100 nm [7].

In this work, line widths of commercial resin IP-L 780 are measured for different TPP processing parameters via atomic force microscopy (AFM). Proof of concept woodpile structures are fabricated where the line width is changed for each log within the woodpile. Additionally, work is presented on changing the line width along a single scan line to introduce further ways to alter metamaterial geometry.

Fabrication Method

The commercial Nanoscribe GmbH Photonic Professional GT was used to fabricate the structures in this work. It has a 780 nm fibre laser with an 80 MHz repetition rate and 120 fs pulse duration. An oil immersion objective lens (1.4 NA, 63X, 190 µm WD) focuses the laser beam. The galvo writing mode was used where the laser beam is moved relative to the sample using a high speed XY galvo-scanner and a piezo stage moves the sample in the Z direction.

A glass coverslip was cleaned in Acetone (VWR Chemicals, UK), then 2-propanol (Sigma-Aldrich, Dorset UK) and subsequently blow dried in air. The coverslip was then secured to the sample holder where a drop of Zeiss Immersol^{TM} 518F was applied to the centre of one side and the IP-L 780 resin (Nanoscribe, Germany) was drop-cast on the other. Following this, the sample holder was placed into the Nanoscribe for writing. A .gwl file is required to write structures which is created via Nanoscribe's software "DeScribe". The designs were hard coded in DeScribe allowing greater flexibility to change processing parameters across a design compared with importing a CAD model. Post writing, samples were developed in propylene glycol monomethyl ether acetate (PGMEA; Sigma-Aldrich, Dorset UK) for 15 minutes and cleaned in 2-propanol for a further 2 minutes then blow dried in air.

Results

Line Width Measurements

Many parameters affect the feature sizes in TPP including the resin used and the processing parameters. The main processing parameters affecting the line widths are the laser scan speed and power; the combination of these is referred to as the laser dose [7]. To measure the line widths of IP-L 780, lines were printed at increasing offset from the substrate for different laser doses. This is known as the "ascending scan" method [8]. Lines with smaller offsets adhere to the substrate and can be used to measure line width. Due to the elliptical focal point lines at larger offsets fall over since the surface area at the tip is small which can be used to measure line height.

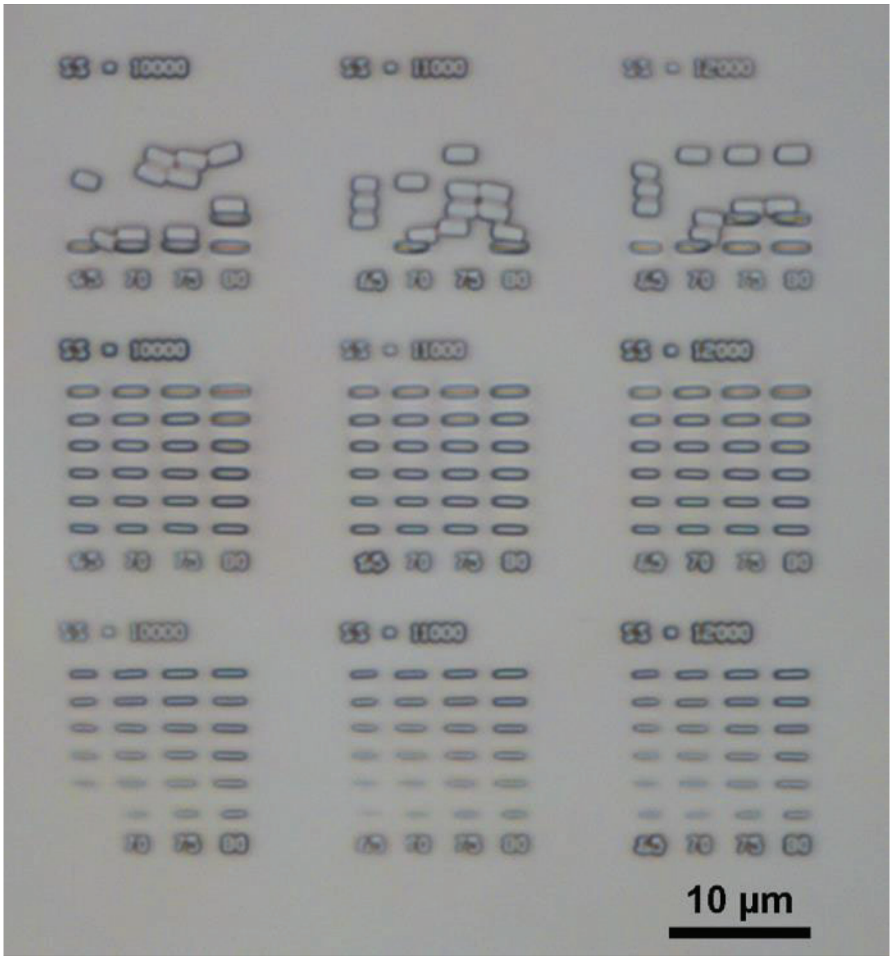

Figure 1: Optical image of the ascending scan array written in IP-L 780. The print was split into blocks to allow an AFM scan area of 15 x 15 μm2 to tradeoff between resolution and scan time. Each column of three blocks is fabricated at scan speeds of 10, 11 and 12 mm s^{-1}. Each line is written with increasing offset from the substrate with the bottom row of blocks having the lowest offset increasing by 0.1 μm continuously across the three blocks for each scan speed. The columns of lines within a block are fabricated at different laser powers.

Using this method each line array was written with an increasing offset of 0.1 μm from the substrate. A set of arrays were written at laser powers between 22.5 and 40 mW in steps of 2.5 mW and for scan speeds of 10, 11 and 12 mm s^{-1}. This range of values were selected based on a previous laser dose test which highlights the processing range of the resin. An example ascending scan array is shown in Fig. 1. The top row blocks with the highest line offsets were intended to be used to measure line height. However since they are highly scattered and overlapping line heights could not be measured; this will be considered further in future work.

The line widths of the arrays were measured using AFM (Bruker Dimension FastScan Bio^{TM}) and analysed in ImageJ [9]. Three patterns were printed within the same run and line widths were taken as the average of 5 lines within a line set. Fig. 2 shows the results of this

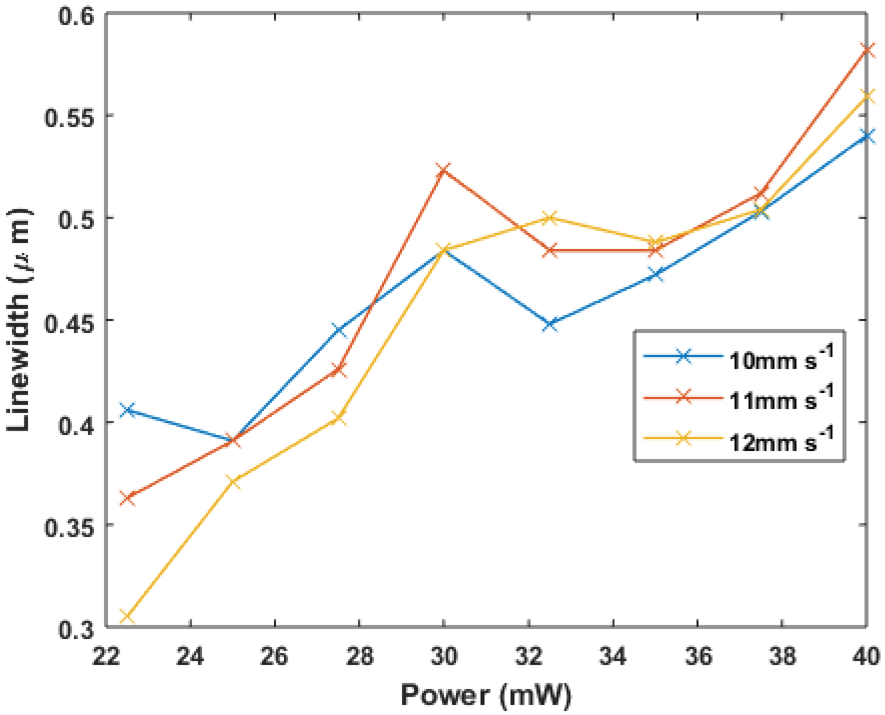

Figure 2: Graph showing relationship between laser power and resulting line width for different laser scan speeds.

where the in-run standard deviation was found to be 44 nm. This variation represents inhomogeneities within the photoresist as well as variations in the scan speed and power. Line width increases with laser power as expected, but the relationship of increasing line width with decreasing scan speed is less evident across the whole power range. In [8] line widths are seen to overlap for scan speeds of 10 and 20 mm s^{-1} indicating the range used here may not be wide enough for distinguishable line widths in part due to in-run variations.

This investigation will be extended to a larger range of scan speeds allowing the creation of a catalogue of scan speed and power combinations resulting in particular line widths. From this the fastest scan speed can be picked for the required line width increasing the through-put of this fabrication method. Further investigation into the variance of these lines should also be undertaken in particular the run-to-run repeatability as differences in ambient conditions could affect results.

Changing Line Width Across a Device

Metamaterial geometry can be altered across a device by changing the laser dose. This was explored by fabricating woodpile structures where laser power differed for each log in the woodpile. Fig. 3 shows optical images of woodpiles where each line orientated in either the x-direction or both the x- and y-directions is fabricated at powers from 15 to 35 mW in steps of 0.5 mW.

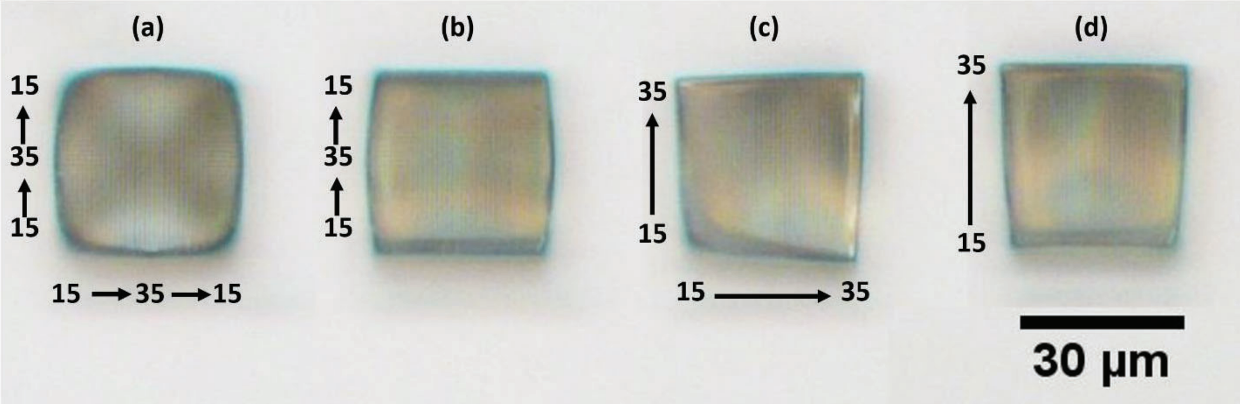

Figure 3: Woodpile structures printed at a scan speed of 10 mm s^{-1}. The annotations show the minimum and maximum laser powers in milliwatts which changes with an increment of 0.5 mW in the direction shown. For (a) and (c) the power is changed across both the x- and y-parallel lines. Whereas (b) and (d) powers change for just the x-parallel lines.

The resulting shapes of the woodpiles are in line with what was expected. Where lines are fabricated at higher powers the woodpile bulges due to the larger line widths, but taper where lines are fabricated at the lower powers where the lines are thinner. No optical effects were considered when designing these structures however they will be investigated through further experimental and computational work in the future.

Changing Line Width Along a Single Line

Altering the line width along a single line by changing the laser power has also been investigated. The power can be changed linearly using an inbuilt function within DeScribe. However a manual approach must be taken for non-linear power profiles. This is done by dividing the lines into sections and using a mathematical function to determine the power at each point/section along the line. Fig. 4 shows lines fabricated using both of these methods of changing laser power at a scan speed of 10 mm s^{-1}.

Fig. 5(a) shows lines fabricated at a constant 25 mW so that line widths do not change. In Fig. 5(b) the lines are fabricated with a linearly increasing power from 20 to 35 mW from the bottom to the top. Lines increase in thickness in a uniform way. Fig. 5(c) shows lines fabricated with a hyperbolic secant power profile using the manual approach. There is a clear distinction between each of the line divisions however a smoother line can be achieved by decreasing the division length thus having a smaller power difference between each division. It should be noted that length of a division should be in line with the size of the metamaterial unit cell which will be investigated in future work.

Conclusions

Line widths of IP-L 780 fabricated at different laser doses have been measured by AFM. These results will be used when programming future metamaterial structures where specific line widths are required. Further work in this area will look at a large range of scan speeds as well as looking further into the in-run and run-to-run variances. A method of working out line height for different laser doses should also be investigated.

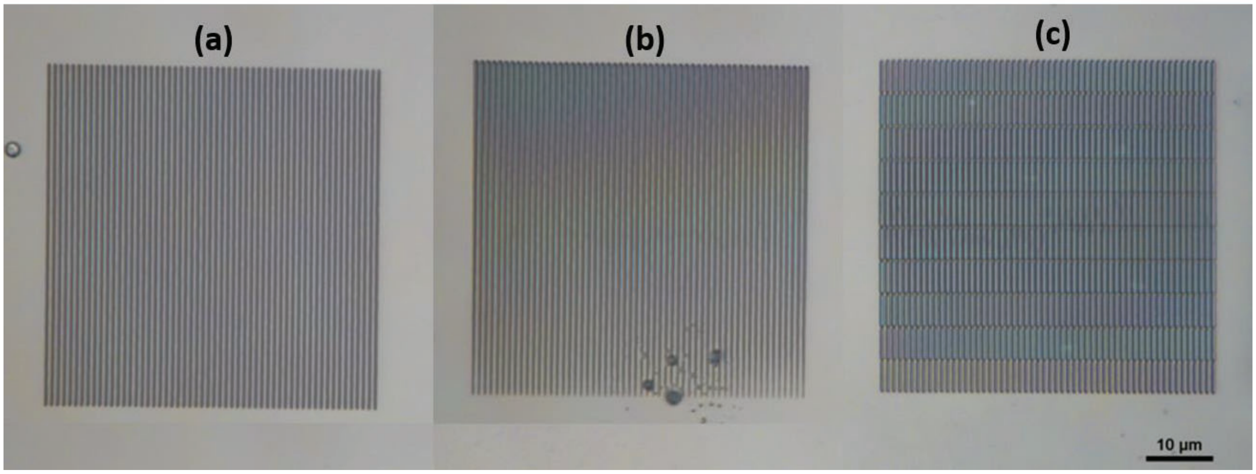

Figure 4: Optical image of lines fabricated at 10 mm s^{-1} for (a) constant laser power of 25 mW (b) linear increase in power from 20 to 35 mW using inbuild DeScribe function and (c) a hyperbolic secant power profile with a minimum power of 20 mW at the outer edge rising to 35 mW at the centre.

Proof of concept graded woodpile structures were fabricated where geometry was altered by incrementally changing the laser power across each rod in the woodpile. Additionally methods to change the power across a single line was investigated and shown to be successful. The geometry was altered as expected.

One of the main tasks going forward is to design an optic with the desired functionality and look into geometries and materials that can achieve this. However this current work has demonstrated that TPP is a useful tool towards creating GRIN metamaterial optics. It allows relatively simple fabrication of complex geometries and enables geometry changes to be implemented simply by changing the processing parameters at different points in space.

Acknowledgements

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