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Direct laser writing of micrograting arrays using a spatial light modulator

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ABSTRACT

Surface micrograting arrays have applications ranging from diffractive optics to bioengineered surfaces. We report a versatile fabrication platform for the maskless photofabrication of these arrays based on structured polarized light and photoresponsive azopolymer films. The films are patterned using a spatial light modulator (SLM) configured as a polarization modulator. The light source is a 488 nm laser with exposure times of order 5 sec or less. Structured polarized light from the SLM is imaged onto the film, writing a 120 µm x 80 µm surface relief pattern with amplitudes and periods controllable from 25 nm to 1 µm and 700 nm- 10 µm respectively. These are stitched into larger area patterns via XY translation. The versatility is demonstrated through a variety of micrograting patterns, including diffractive optical elements, multiplexed surface grating arrays, and diffractive optically variable image devices for optical security applications. In a different application, the biocompatibility of the polymeric film can be leveraged since cellular interaction with synthetic microscale structures influences a wide array of cell responses. We demonstrate this by showing directed cell growth mediated by the micrograting array. In all examples, the surface gratings required no post-exposure processing, are stable in ambient conditions, and can be replicated using nanoimprint lithography.

Keywords: dot-matrix hologram, diffractive optical element, diffractive optically variable image device, photopolymer, optical microstructure

1. INTRODUCTION

Surface relief micrograting arrays are utilized in multiple applications, including as diffractive optical elements and as templates for bioengineered surfaces. As diffractive components, such arrays are integrated in LED backlight systems, automotive illumination, and optical security devices[1-5]. In bioengineering, synthetic microscale surface gratings are used to influence cell response, included directed cell growth[6-8]. Here we report a versatile fabrication platform for micrograting arrays based on thin-film photoresponsive azopolymers and structured polarized light. The azopolymer films were fabricated using commercially available components and were spin-coated on glass. They were photopatterned with a spatial light modulator (SLM) configured as a polarization modulator. Using a programmable XY stage with micron-scale resolution, micrograting arrays of order 100 x 100 elements each with unique period, amplitude, and orientation can be patterned with a 488 nm laser source with exposure times of 5 sec or less per element.

The photomechanical response of azopolymers enables the considerable versatility of this system. When illuminated with a spatially periodic distribution of linearly polarized light, the orientational response of the azobenzene ultimately exerts a periodic torque on the polymer, mediated by the azo-polymer coupling interaction. This distorts the originally flat film surface into a topographical surface relief grating with the same period as the illumination. Because the film response is photomechanical, and not photochemical, the surface relief appears immediately in response to polarized light, allowing the growth to be viewed in real time and in ambient lighting. The films are available for use directly after exposure, and can be replicated using nanoimprint lithography.

While the photomechanical response of azopolymers has been studied extensively[9-15], it has only recently been exploited using SLM-based light sources[16-18]. The SLM can project user-defined spatial distributions of polarized light, which when combined with XY-raster movement of the film result in a system capable of tiling a surface with microgratings. The period, amplitude, and orientation of each micrograting element can be uniquely defined and requires no optomechanical

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realignment between exposures. Perhaps most interesting, the micrograting elements can be optically erased and reconfigured[19-21], making this system particularly useful in dynamic diffractive optics and bioengineering applications.

2. EXPERIMENT

The experimental setup is shown in Figure 1. The film is the azopolymer 4-hydroxy-40-dimethylaminoazobenzene and poly(4-vinylpyridine) and is more fully described in ref. 19. Films of order 1 µm thickness were spin coated on glass substrates and were used for all results reported here. The laser is a continuous wave 488 nm diode-pumped solid state laser, and the SLM is a reflective liquid crystal on silicon device with 1920 × 1152 pixels. A 40X objective focuses light from the SLM, forming a 120 µm x 80 µm image at the film surface. The film is mounted in an XY motor stage capable of translational movement with sub-micron accuracy. The incoherent light source, dichroic mirror, and camera combination allows the surface relief grating evolution to be viewed in real time.

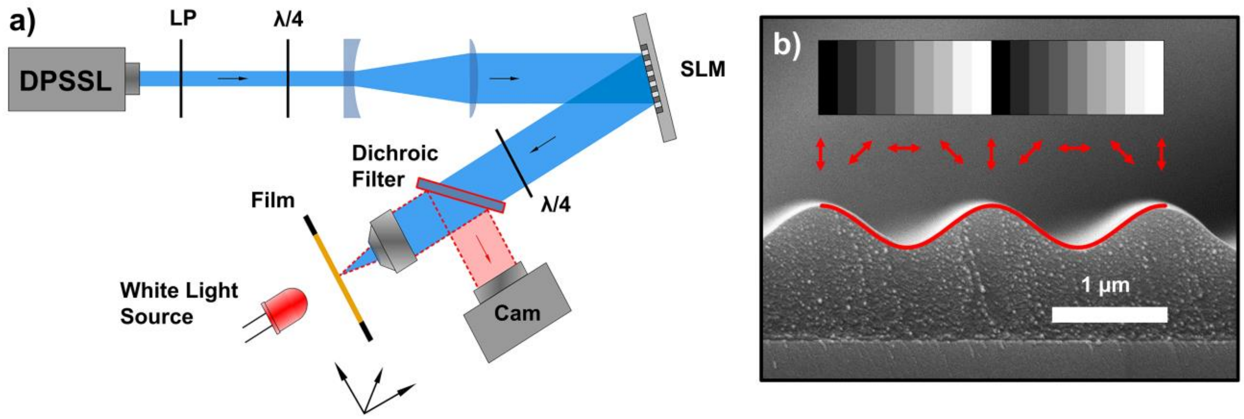


Figure 1. Experimental setup for optical microstructure fabrication. (a) Diode-pumped solid state laser (DPSSL) illuminates reflective spatial light modulator (SLM). SLM is between crossed quarter wave plates (λ/4), forming optical rotator. Structured polarized light is focused on film surface with 40X objective. White light source, dichroic filter and camera enable realtime viewing of film surface. (b) Grayscale addressed to SLM (top) generates linear polarization distribution (red) at film surface, driving sinusoidal surface relief pattern as shown in SEM image.

The SLM is between crossed quarter-wave plates, which rotates the polarization plane of an incident laser beam at each pixel according to the optical retardation of the SLM. Addressing the SLM with an appropriate gray scale pattern will therefore illuminate the film surface with the periodic linear optical polarization shown in Figure 1b. This will in turn activate the photomechanical film response, resulting in a surface relief grating of the same period and with an approximately sinusoidal depth profile. By programming the SLM, optical exposure time, and the XY stages, the film surface can be tiled with a 2D matrix of surface relief gratings, where the period, amplitude, and orientation of each SRG element can be defined by the user. In practice, feature sizes (i.e. spatial periods) of 700 nm – 10 µm and amplitudes up to 1 µm can be fabricated using exposures no longer than 5 s, at constant optical intensity of 89 x 10^3 mW/cm^2

3. APPLICATIONS TO DIFFRACTIVE OPTICAL ELEMENTS

One application of the system shown in Figure 1 is the fabrication of simple diffractive optical elements. Conventional DOEs are fabricated by first taking the inverse Fourier transform of a user-designated image and mapping that to a complex surface relief pattern. That pattern is then realized on a surface via electron-beam lithography or photolithography. To construct a DOE from the 2D tiled arrangement of gratings produced by the setup in Figure 1 requires a different approach as shown in Figure 2a.

Here, the period, orientation, and amplitude of each matrix element on the film surface is defined to generate the +1 diffracted mode of a single pixel in the image plane. Using this approach, simple DOEs can be fabricated rather quickly (of order minutes to a few hours, depending on number of matrix elements) and are available immediately after exposure for replication via nanoimprint lithography. As an example, Figure 2b shows the image from a DOE fabricated from 100

SRG elements, which together comprise a roughly 1 mm² area on the film surface. The image is shown at 0.5 m from the film, and the entire fabrication process took 15 minutes.

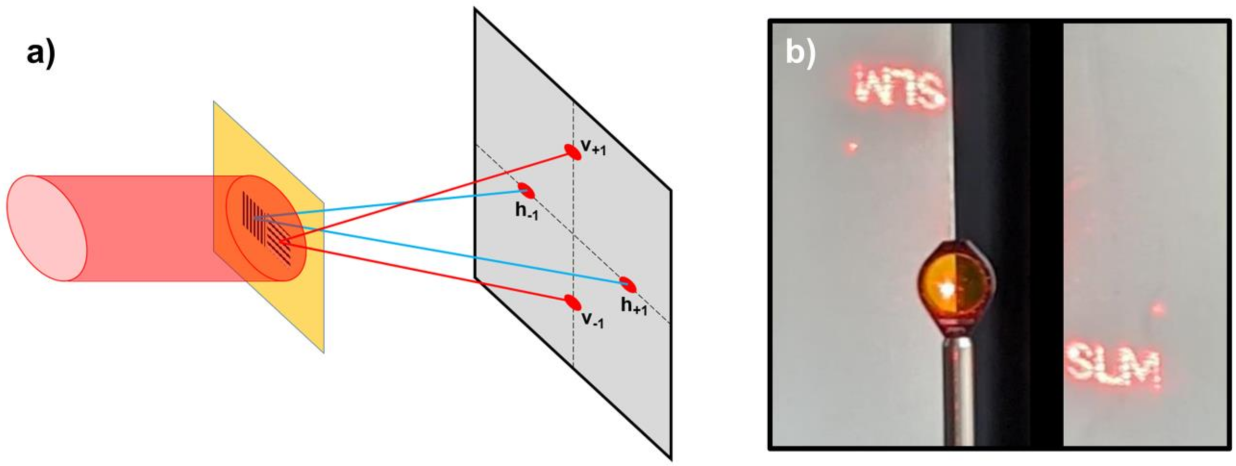


Figure 2. Diffractive optical element (DOE) using SLM patterning of micrograting arrays (a) Graphical representation of simplified DOE architecture. First-order diffraction modes, defined by period and orientation of each micrograting pixel on film surface, generate one pixel of desired projected image. (b) 100 element DOE micrograting array fabricated on azopolymer film designed to project letters "SLM". Film is illuminated at normal incidence with 5 mW HeNe laser and image is shown at 0.5 m. Zero order mode is not visible due to angle of photo.

In a more advanced application, simple DOE's as described above can be embedded in larger SRG grating arrays to create for example sophisticated optical security elements more generally referred to as diffractive optically variable image devices (DOVID). Consider that we can define the amplitude, period Λ, and orientation of each 120 μm x 80 μm SRG element on the film surface. Normally incident light of wavelength λ will scatter preferentially at angles defined by λ/Λ, giving rise to a brightly colored appearance as the film is viewed at different angles. There are many approaches for mapping information to this structure, including complex optomechanical techniques [22,23]. However, the SLM-based approach here is considerably more versatile in that all grating parameters can be electronically varied pixel-by-pixel, enabling a rather broad range of mappings. For example, the pixel value of a JPEG image can be scaled to exposure time. This maps pixel value to diffraction efficiency, which essentially transforms pixel value to the image brightness perceived by the observer. As an additional layer of security, an independent DOE can also be embedded in the SRG matrix, which can generate a far-field image in transmission that is completely different from the JPEG-mapped image perceived by the observer in reflection.

Figure 3a shows an example film photopatterned with a 62 x 106 array of surface relief gratings, each of area 120 μm x 80 μm. This array contains a diffractive optical element designed to generate an image in transmission of atomic orbitals while presenting an observer in reflected white light with an image of a light bulb surrounded with spectral colors. In the photo foreground, the rectangular glass substrate with the film is visible, showing the brightly colored light bulb image in reflection. Simultaneously, a HeNe laser beam of approximately 0.5 mm diameter is directed at normal incidence through the center of the light bulb, revealing the atomic orbital image in the far field. Figure 3b is an optical micrograph of the film surface, showing a representative sample of some of the SRG matrix elements. The fabrication of these kinds of DOVIDs with the setup of Figure 1 is entirely computer-automated, with the user designating the desired DOE far-field image, the desired reflected image, and the number of SRG grating elements on the film, which determines the total fabrication time. The SRG matrix in figure 4 required 11.5 hours to fabricate and was viewed immediately upon completion.

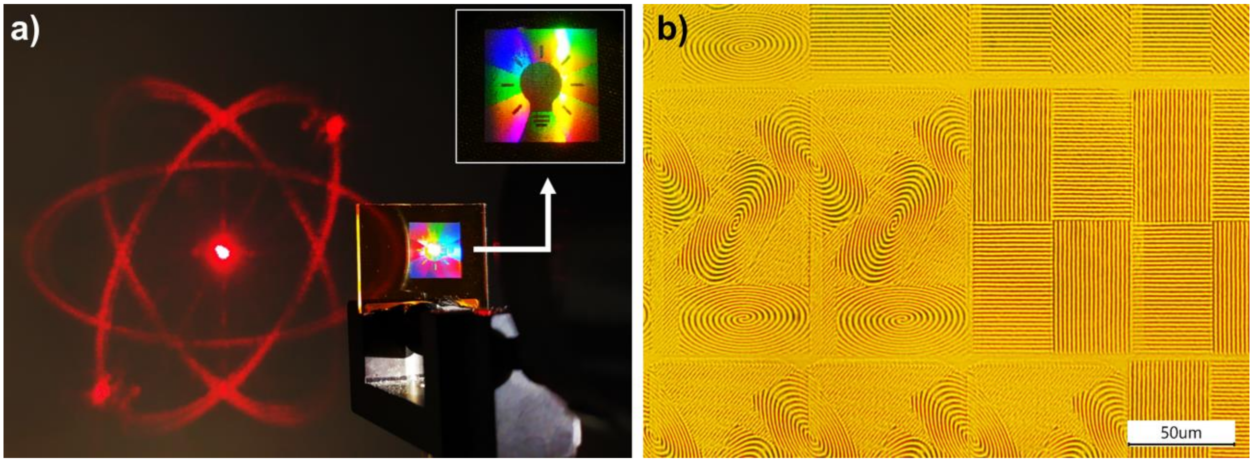


Figure 3. Combined DOE and DOVID written with SLM system. (a) 62 x 106 micrograting array on azopolymer film designed to show colored light bulb in reflected light. Top right image is a magnified view of the reflection. Center is illuminated at normal incidence with HeNe laser, revealing DOE of atomic orbitals, visible in transmission at 0.5 m from film. (b) Optical micrograph of a portion of film surface, showing individual micrograting elements.

4. APPLICATIONS TO MULTIPLEXED IMAGES FOR MOTION SIMULATION

Light incident on a SRG element is preferentially diffracted parallel to the grating wavevector. This angular selectivity can be leveraged to multiplex SRG matrices on the film surface such that when the image from each matrix is viewed in succession, the observer perceives the image to be in motion. For example, consider Figure 4a, which shows diffracted light in reflection from a 100 x 70 SRG array mapped from the image of a bird in flight. The figures show the array viewed at four different angles. Equivalently, the observer can remain at a fixed perspective and rotate the film as shown in Video 1. In both cases, the viewer perceives a bird flapping its wings.

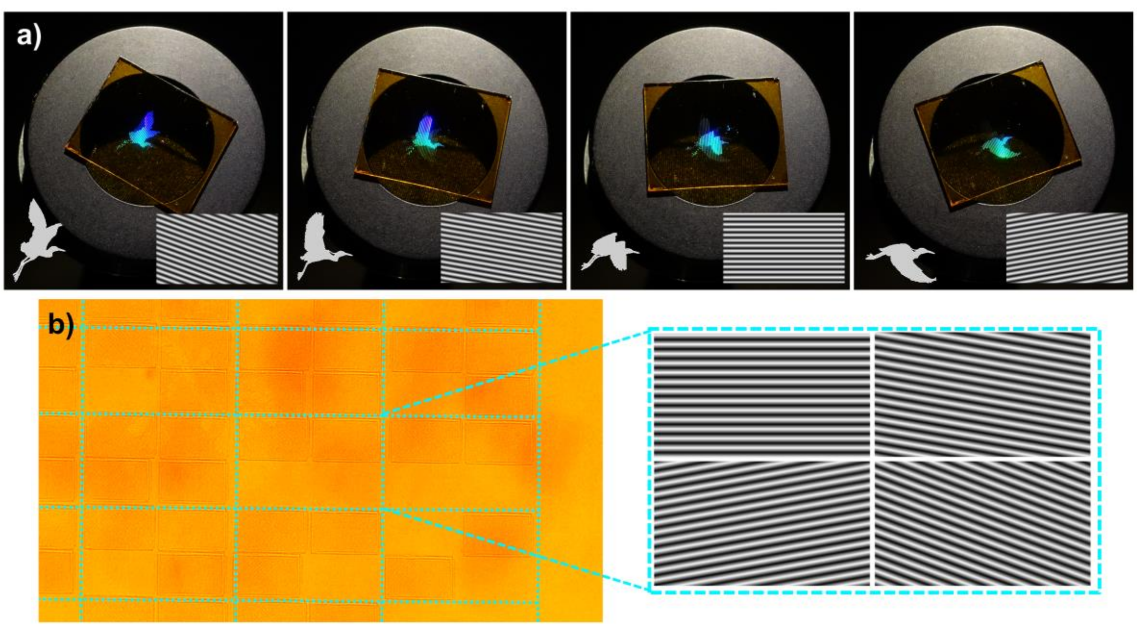
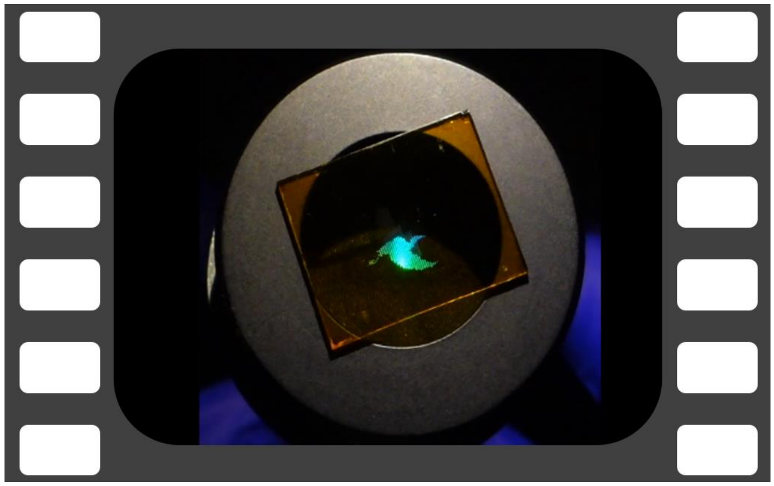


Figure 4. Micrograting arrays to display simulated motion. (a) Four interspersed micrograting arrays, each with a unique orientation (bottom right of each frame) that directs diffracted light to viewer as film is rotated. (b) Optical micrograph (left) of film surface. (right) Schematic representation of the four grating orientations.



Video 1. Video of bird in motion, simulated by successive diffraction from interspersed surface grating arrays. http://dx.doi.org/10.1117/12.2647393.1

The total SRG array is composed of 4 subarrays, with the grating wavevector of all elements in a particular subarray oriented such that the viewer perceives the appropriate image sequence as the film is rotated (or as the viewer's observing angle is varied). The four subarrays are interweaved as shown in the Figure 4b inset.

5. APPLICATIONS TO BIOENGINEERING- DIRECTED CELL GROWTH

In an application quite different from diffractive optics, the SLM-based system described here can photopattern surfaces for use in bioengineering research. It is well known that cellular interaction with synthetic microscale structures influences a range of cell responses. In cell-culture-technology, they can influence the adhesion capabilities of cells to the substrate, act as templates for directed cell growth, and influence the differentiation of stem cells.

For example, simple microstructures such as scratches on a 2D surface induce cells to align along these scratches and to migrate along them. Directed microstructures can thus contribute to the targeted growth of cells. In addition, microstructuring can force cell growth and also cell morphology into morphologies dictated by the microstructure. The external shape of the microstructure then forces the cells to adopt certain morphologies[24].

To assess the potential of the photofabrication system reported here for use in these bioengineering applications, consider the results shown in Figure 5. Here, HeLa cells in a liquid suspension were poured on top of the azopolymer thin film surface (see Fig. 5 top right) and stored in an incubator at 37 degrees Celsius. Using the SLM system, the film surface was previously patterned with a variety of SRGs of various profiles, including circular and linear patterns.

The left microscope image shows the system after 4.5h in the incubator. Most cells have not adhered yet to the surface, visible due to their round shape with some individual cells starting to spread out (compare Fig. 5 top left). After 18.5h in the incubator, almost all cells have completely adhered to the film surface, which is indicated by their extended linear shape (middle microscope image).

This demonstrates the biocompatibility of this azopolymer material system. Furthermore, a preferential alignment parallel to the crests and troughs of the surface relief grating can be observed (red markings in right microscope image).

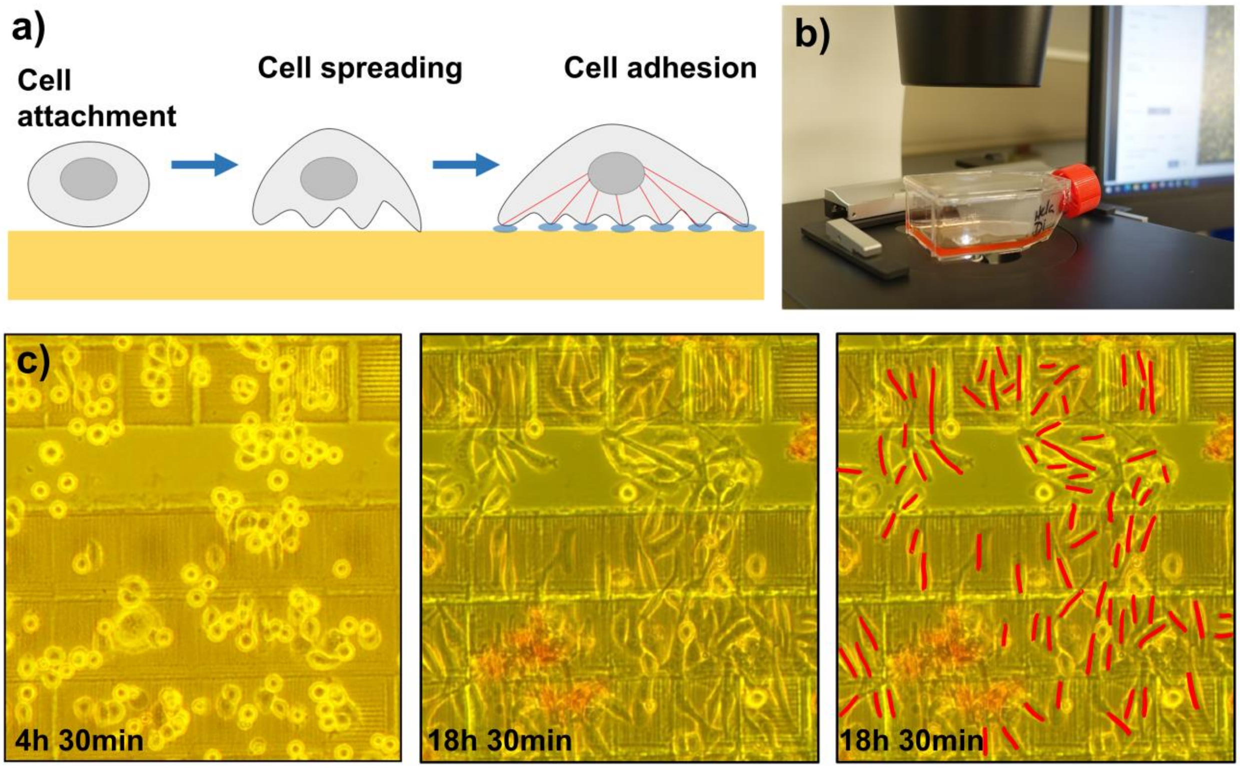


Figure 5. Micrograting arrays as templates for directed cell growth. (a) Schematic representation of cell attachment, spreading, and adhesion processes. (b) Incubator containing HeLa cells in liquid suspension deposited on top of pre-patterned azopolymer film. (c) Micrographs of incubator showing time-series of cell attachment, spreading, and adhesion.

This is a proof-of-concept demonstration that the azopolymer film is biocompatible and that surface relief structures photopatterned on the film can indeed act as templates for directed cell growth. A powerful advantage of this system is that it can be operated in a write-erase-rewrite configuration in which the SLM is programmed to phase-shift the SRG by one-half period, effectively erasing it and restoring the film surface to a flat configuration. A new SRG with different amplitude, period, and orientation can then be written on the film, all in situ with the cell suspension. To avoid direct illumination of the cells with the 488 nm laser, the film-substrate combination can be illuminated through the glass substrate side.

6. CONCLUSIONS

A system for the maskless photofabrication of surface relief micrograting arrays is reported. This new platform is based on the projection of 488 nm structured polarized light from a spatial light modulator onto a photoresponsive azopolymer film. The SLM generates surface relief patterns over a 120 μm x 80 μm area, with a sinusoidal amplitude controllable from 25 nm to 1 μm and periods 700 nm- 10 μm, with exposure times of 5 sec or less. The versatility is demonstrated through a variety of micrograting patterns including diffractive optical elements and synthetic microscale templates for directed cell growth in bioengineering applications.

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