Automated maskless photoalignment

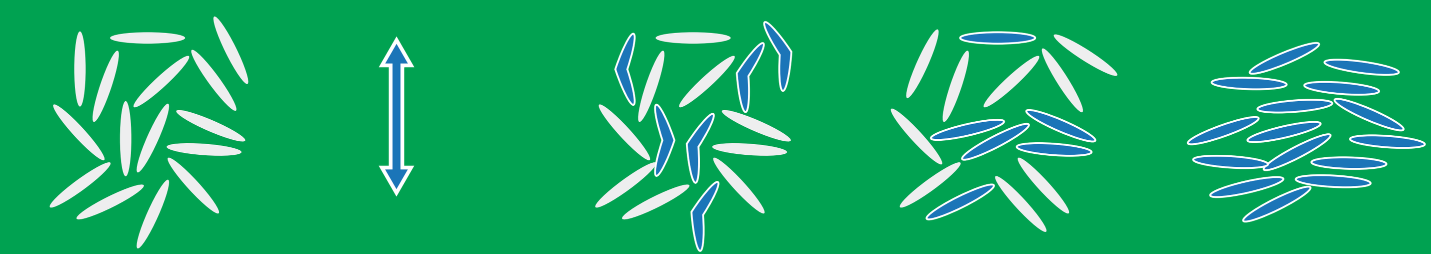
Christopher Culbreath Nik Glazar Hiroshi Yokoyama
Liquid Crystal Institute. Kent State University. Kent, Ohio.

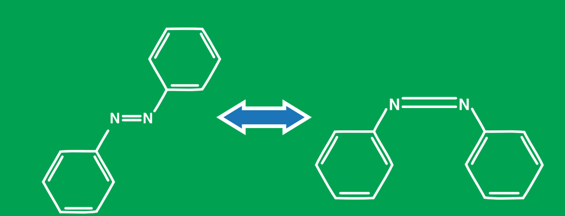
Abstract

We present a fully automated maskless exposure system for the fabrication of microscopic orientational surface alignment patterns. The maskless system allows us to fabricate arbitrary surface patterns over a 2mm x 2mm area with a resolution of 2.2µm. A confocal autofocus system insures accurate and repeatable focus.
Microscopic orientational surface patterns have been demonstrated to exhibit a variety of novel functionalities, such as surface alignment multi-stability.

Photoalignment

Photoalignment is a non-contact fabrication method for liquid crystal orientational alignment patterns. Conventionally, liquid crystal alignment surfaces are fabricated through mechancial means such as rubbing. Photoalignment promises a fast and clean non-mechanical alterative. Photoalignment materials work through many mechanisms: photochemical crosslinking, photodegradation of polyimides, and through the reversible *cis-trans* photoisomerization (see left). The maskless photoalignment system is well suited for the preparation of azopolymer (cis-trans) photoalignment materials. In the dark, azos assume the lower energy trans form. Upon the absorption of a photon (in our case, UV) the azo converts to its cis form. The molecules then thermally convert back to trans, and assume a random molecular orientation. Azos preferentially absorb light polarized along their long axis (with a probability proportional to $\cos^2\Theta$). Therefore, over time, exposure to polarized light drives those molecules oriented along the polarization direction into new randomized directions (via a cis-trans transition) while those molecules perpendicular to the polarization direction remain aligned with the polarization axis. The result is a net orientation perpendicular to the polarization axis[8].

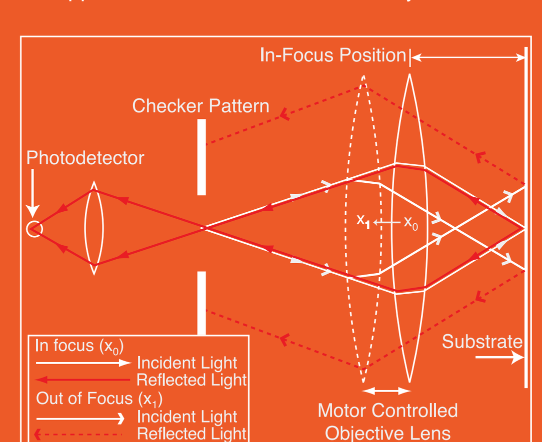


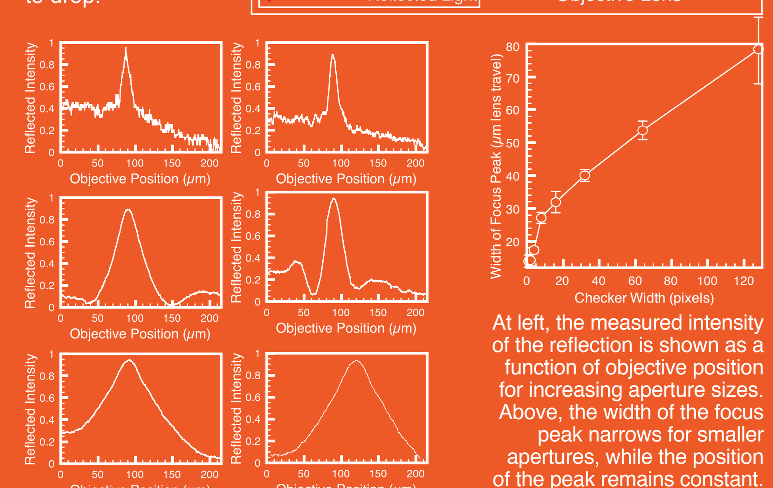


cis-trans isomerization

Confocal autofocus

To insure accurate and repeatable focus, the maskless system is equipped with an in-line autofocus mechanism. The autofocus system works much like a confocal microscope: the observed signal is a reflection from the substrate, imaged onto a finite sized detector. In our system, the DMD is used as a digitally controlled aperture to limit the extent of the focusing detector, and a stepper motor is used to move the objective. As shown in the figure on the right, an image of the substrate is projected onto the focusing photo detector. As the objective is moved out of the focus position, the image is blurred and partially obscured by the checker pattern loaded on the DMD, causing the signal intensity to drop.





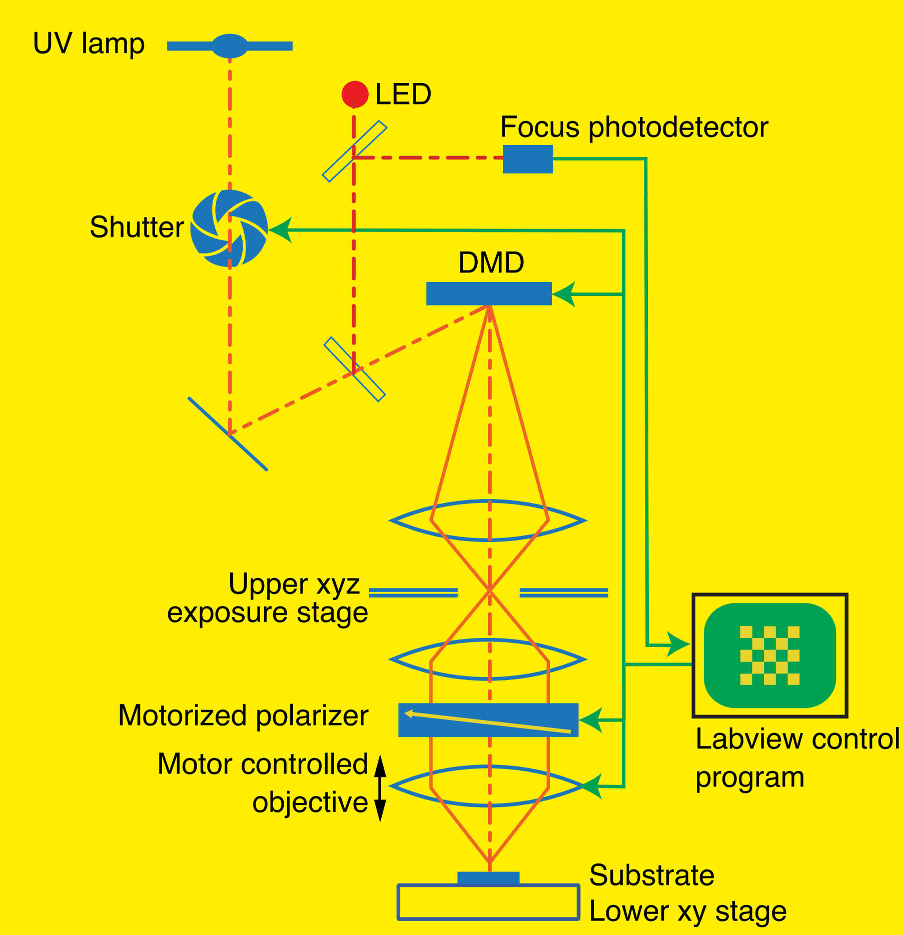
At left, the measured intensity of the reflection is shown as a function of objective position for increasing aperture sizes. Above, the width of the focus peak narrows for smaller apertures, while the position of the peak remains constant.

Automated maskless exposure system

System description

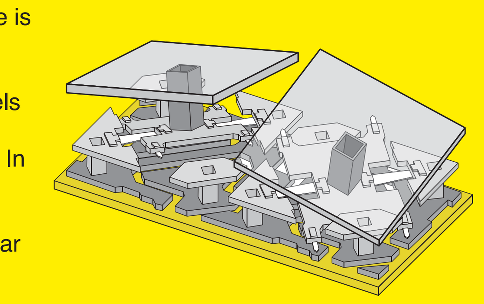
The key component to the automated maskless exposure system is a digial mirror device (DMD) which is used as an UV spatial light modulator (See "Digital micromirror device"). The DMD is made of 1024x768 pixels. The image generated by the DMD is projected through an infinity corrected UV objective (Zeiss Plan-Neofluar 10x/0.30) at approximately 1/10 its real size onto the substrate, which is coated with a photoalignment material. The system is equipped with a confocal autofocul system (see "Confocal autofocus"). With this system, we have expanded the functionality of conventional maskless lithography technology by the inclusion of motorized polarizer stage which allows dynamic selection of the polarization direction of the exposing UV light and consequently the alignment direction written onto the photoalignment material.
In order to create an orientational alignment pattern on the substrate, the desired pattern is decomposed into a set of black-and-white bitmap masks, each designed to illuminate the portion of the image that corresponds to a particular orientation angle. The pattern image data is sequentially fed from the control computer to the DMD, while synchronized with the rotation of the polarizer, and the UV shutter. A red light-emitting diode provides a safelight for positioning and focusing the pattern without exposing the photoalignment material.
The maskless system is equipped with two exposure stages. The lower stage has a total image width of 2 mm, and provides an exposure to polarized light for orientational pho- toalignment. The intensity of the UV light at the image plane was directly measured to be approximately 11 mW/cm^2. The system is also equipped with a translation-rotation-tilt stage located at the first image in the optical path (the upper stage), which can be used for conventional (non-polarized) photolithography. On the upper stage the DMD image is magnified to 1.5 times its original size, resulting in an approximate exposure area of 1.5 cm x 2 cm.

Schematic overview



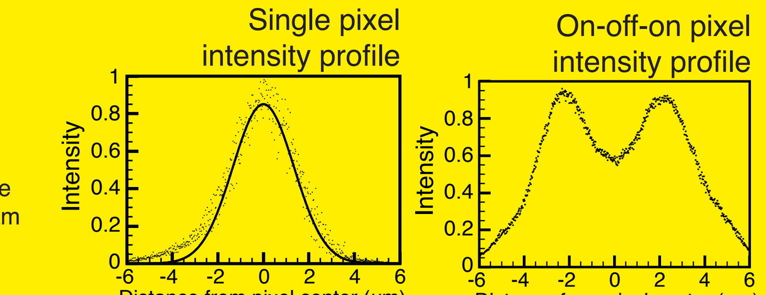
Digital micromirror device

The heart of our maskless photoalignment device is a digital micromirror device (DMD). A DMD chip has on its surface several hundred thousand microscopic mirrors which correspond to the pixels in the image to be displayed. The mirrors can be individually rotated ±10-12°, to an on or off state. In the on state, light from the UV light source is reflected onto the substrate. In the off state, the light is directed elsewhere making the pixel appear dark. Shown at left, the mirrors themselves are made out of aluminum and are around 13.7 micrometres across. Each one is mounted on a yoke which in turn is connected to two support posts by compliant torsion hinges[11].


Two pixel micromirror detail[10]

Resolution characterization

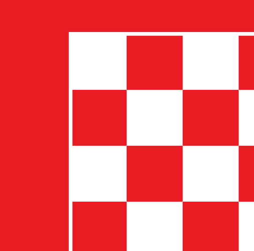
We have directly confirmed the resolution of the ex- posure system to a single DMD pixel level by placing a high resolution CMOS camera (Edmund Optics EO-5012C, 2.2 µm-square pixels) at the image plane. The resolution was measured by translating the camera using a piezoelectric stage under a one DMD pixel line. The resulting signal (below) is a convolution of the gaussian beam profile and the translated step response of the camera pixel. By taking the appropriate deconvolution, we calculate the beam width (2σ) to be 2.2 µm.

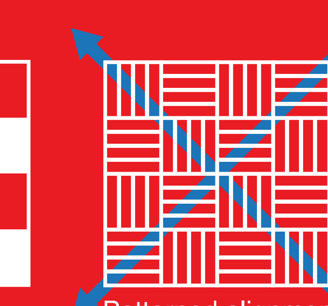


Applications

Bistable surface alignment

With an appropriate choice of surface alignment pattern, liquid crystal cells exhibiting nematic bistability and tristability have be achieved[2,3,4]. A layer of azo-based photoalignment material is deposited on a glass substrate by way of spin coating, while the opposing substrate has uniform planar alignment. The photoalignment layer is exposed using a checker patterned mask, with adjacent regions receiving orthogonal polarizations of UV light. The result is a patterned alignment surface as shown in the diagram above right. The blue arrows represent the bulk alignment direction for the two stable configurations, homogeneous planar and twisted planar, for which switching occurs via orthogonal in-plane electric fields. The maskless photoalignment method can further be used to fabricate flexible bistable displays which are attractive due to their low-power consumption, low cost, and ease of manufacturing.


Bitmap checker mask pattern


Patterned alignment surface

Pancharatnam Frensel lens array

In contrast to many lenses and liquid crystal devices in which optical retardation is used as a means to control the wavefront, it is possible to make a liquid crystal based lens[5] with a *fixed* retardation in which a Pancharatnam phase[7] shift is induced solely by the azimuthal director orientation. Jones calculus analysis of circularly polarized light incident on a uniform, planar aligned, liquid crystal cell with a fixed retardation of λ/2 and an arbitrary azimuthal orientation ϕ provides an illuminating example of this Pancharatnam phase principle. Starting with the incident electric field vector:

$$\vec{E}_{\mathrm{out}} = R(\phi)^{-1}.L.R(\phi).\vec{E}_{\mathrm{in}}$$

$$\begin{bmatrix} E_{ox} \\ E_{oy} \end{bmatrix} = \begin{bmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} -i & 0 \\ 0 & i \end{bmatrix} \begin{bmatrix} \cos\phi & -\sin\phi \\ -\sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} E_{ix} \\ E_{iy} \end{bmatrix}$$

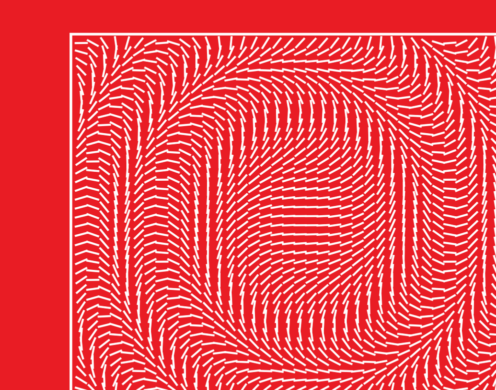
We require that our incident light be circularly polarized,

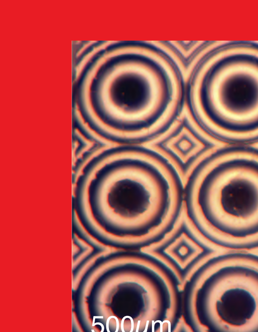
$$\begin{bmatrix} E_{ix} \\ E_{iy} \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -i \end{bmatrix}$$

and our expression for the transmitted light becomes

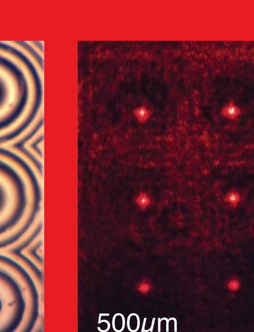
$$\begin{bmatrix} E_{ox} \\ E_{oy} \end{bmatrix} = \frac{-i}{\sqrt{2}} e^{-i2\phi} \begin{bmatrix} 1 \\ -i \end{bmatrix}$$

The incident RHC light is transformed to LHC as expected from a half-wave plate, however, we also gain a phase shift that depends not on the optical path length, but exclusively on the azimuthal orientation of the liquid crystal director ϕ. By building an array of half-wave plates in space, each with a different azimuthal orientation, we can tune the phase difference in each region. For a Fresnel type lens, the orientational pattern consists of a continuously winding azimuthal orientation in the plane of the surface from the center toward the edge with an increasing periodicity, as seen in the upper diagram to the right. The center right diagram depicts a polarizing micrograph of the liquid crystal texture on the photoaligned processed substrate, a six lens array. This sample was prepared by a sequence of 60 exposure patterns. The exposure images were generated by decomposing the Fresnel lens pattern into a series of spatial masks, each designed to illuminate the regions of the substrate that correspond to a specific angular range. Each exposure pattern provides for the alignment of the substrate each taking care of a sufficiently narrow range of orientation angle. The success of this fabrication technique is experimentally demonstrated by using the Pancharatnam lens array to focus light to an array of points, as depicted in the picture above right.


Fresnel surface alignment pattern



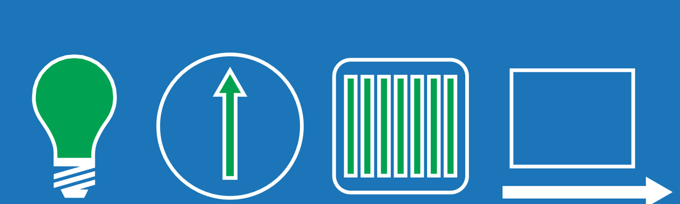
LC lens array



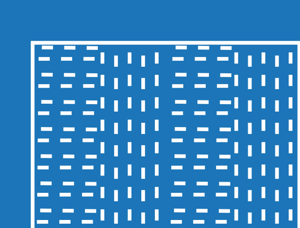
Focused light

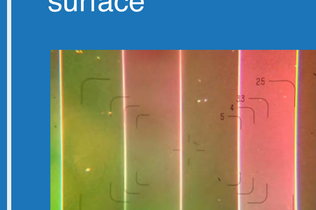
Related work

Pre-tilt photoalignment



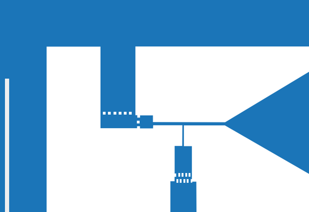
Photorubbing is a process in which a cross-linking type photoalignment material is irradiated with periodically modulated polarized UV light. These polarized UV stripes are translated across the substrate to yield a stable pretilt angle in the resulting alignment surface[1]. Our maskless photoalignment system has been equipped with a motorized translating platform at the lower exposure stage. The speed and direction of the translation are integrated into the system Labview control. This functionality make the rapid fabrication of photorubbed surfaces possible, with control of the scan rate, mask perodicity and exposure time.

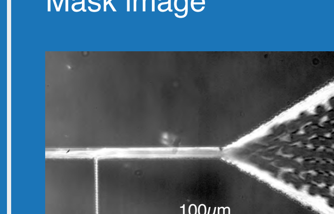

Patterned alignment surface


Polarizing micrograph

Pancharatnam phase mask

Pancharatnam phase devices (see "Applications") are optical devices that impart an optical phase shift by varying the azimuthal surface anchoring of the liquid crystal director. A straightforward application of the Pancharatnam device principle is a four-region phase mask (shown at right). By orienting the azimuthal anchoring in neighboring regions at 90˚, the light emerges from the Pancharatnam phase device 180˚ out-of-phase. Any overlap between the regions results in phase cancellation and increased edge acutance. A phase mask can be used to improve the resolution of photolithographic optics. Resolution limiting diffraction results in a blurring of the image across the phase boundary, where it is phase cancelled. This cancellation serves to improve the resolution of the optical system. With the two exposure stages of the automated maskless system, a phase mask can be created *in situ* on the top stage, where it remains aligned to act as a resolution-improving phase mask for lower stage exposures.


Mask image



Smectic bubble generation

Microfluidic photolithography

Shuojia Shi and Hiroshi Yokoyama

The two exposure stages on the maskless system are both readily used for conventional (non polarized) photolithography. The upper stage has an exposure area of 2cmx1cm. The upper stage has been used in the fabrication of microfluidic devices. With the maskless system, changes to the exposure mask can been made readily, facilitating the rapid development and troubleshooting of microscale devices. At left, a generating mask and miscroscale microfluidic device are shown. The maskless machine was used to fabricate this microfluidic chip. The chip is designed to form bubbles in smectic liquid crystals utilizing a t-junction geometry.

1. Masayuki Kimura, Shoichi Nakata, Yutaka Makita, Yasuo Matsuki, Atsushi Kumano, Yasumasa Takeuchi and Hiroshi Yokoyama. Jpn. J. Appl. Phys. 41 (2002) 2.Jong-Hyun Kim, Makoto Yoneya, Jun Yamamoto, and Hiroshi Yokoyama, Appl. Phys. Lett. 78, 3055 (2001) 3. Jun-ichi Niitsuma, Makoto Yoneya, and Hiroshi Yokoyama, Appl. Phys. Lett. 92, 241120 (2008) 4. J.-H. Kim, M. Yoneya, and H. Yokoyama, Nature (London), 420, 159 (2002). 6. Michinori Honma and Toshiaki Nose. Jpn. J. Appl. Phys. 44 (2005) 2877. S. Pancharatnam, The Proceedings of the Indian Academy of Sciences, Vol. XLIV, No. 5, Sec. A, 1956. 8. Y. Zhao, T. Ikeda. *Smart Light Responsive Materials.* Wiley 2009. 10. L. Hornbeck. "Current Status and Future Applications for DMD-Based Projection Displays." Texas Instruments Digital Imaging. 1998.
11. √Wikipedia contributors, "Digital micromirror device," Wikipedia, The Free Encyclopedia, http://en.wikipedia.org/w/index.php?title=Digital_micromirror_device&oldid=507192346 (accessed September 26, 2012).

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