Note: Automated Maskless Micro-Multidomain Photoalignment

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Note: Automated maskless micro-multidomain photoalignment

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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 2 mm × 2 mm area with a resolution of 2.2 μm. 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. © 2011 American Institute of Physics. [doi:10.1063/1.3669528]

Patterning alignment surfaces into microscopic domains with features much smaller than the conventional pixel size has attracted considerable attention for the last ten years as a new approach to generate additional functionalities for the liquid crystal-based electro-optic devices. One early example is that of an alignment surface arranged as a checkerboard pattern, consisting of alternating square domains with mutually orthogonal alignment directions; these orthogonally aligned domains induce a truly bistable alignment surface irrespective of the properties of the specific liquid crystal or the alignment layer material. Orientational patterned alignment surfaces have been effectively applied in the construction of switchable optical phase gratings, a Fresnel lens, and a Pancharatnam phase-based tunable lens. In all these early studies, the orientational surface patterns were fabricated by a local rubbing process using the sharp stylus of an atomic force microscope or a profilometer. While these processes effectively demonstrate a concept, they rely on serially scanning the entire patterned surface and are too slow to provide a practical means of alignment surface fabrication.

As a non-mechanical alternative, photoalignment has been shown to be an effective method for fabricating alignment surfaces. Photoalignment materials assume an alignment direction when exposed to polarized UV light. An alignment surface is created parallel to, or perpendicular to, the polarization direction of the incident UV light, depending on the photoalignment mechanism of the surface material. We have successfully utilized photoalignment technology in the fabrication of the aforementioned checkerboard surface structure. We patterned orthogonally aligned 1 μm × 1 μm unit domains over the size of 4 cm × 4 cm glass panel. For relatively simple alignment patterns, the conventional photoalignment process which requires sequential exposures for each polarization direction through individually positioned masks, can be used without much difficulty. However, the fabrication and precise positioning of each photomask is an arduous and often expensive task, especially for patterns involving many alignment angles or continuous angular distributions, such as a Pancharatnam lens device. In order to alleviate this difficulty and to advance research in micro patterned surface alignment, we designed and implemented a fully automated maskless polarized UV exposure system.

Figure 1 shows the schematic diagram of the maskless machine. The key component is the digital micromirror device (DMD) (Discovery 4100, Digital Light Innovations) which is used as an UV spatial light modulator. The DMD is made of 1024×768, 13.7 μm-square MEMS mirrors. The image generated by the DMD is projected through an infinity corrected UV objective (Zeiss Plan-Neofluar 10×/0.30) at approximately 1/10 its real size onto the substrate, which is coated with a photoalignment material. With this system, we have expanded the functionality of conventional maskless lithography technology by the inclusion of motorized polarizer which allows us to choose dynamically 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 photolithography. The intensity of the UV light at the image plane was directly measured to be approximately 11 mW/cm². 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 × 2 cm.

We have directly confirmed the resolution of the exposure 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 (Figure 2) 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.

To insure accurate and repeatable focus, the maskless system is equipped with an in-line autofocus mechanism. A schematic representation of the autofocus system is shown in Figure 3. 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 (confocal) focusing detector, and a closed-loop stepper system is used to move the objective. On the DMD, a checker pattern is used to create an array of finite detector regions (white squares), and the substrate reflection is projected through the DMD onto the focusing detector. When the objective is defocused, the light imaged onto the detector is blurred, i.e., it spread out in space. Since the detector is of finite size, not all of the defocused signal reaches the detector, and the intensity of the measured signal drops. This geometric argument is shown by the rays illustrated in Figure 3. Using this principle, we expect a linear correspondence between detector size and the width of the focus peak, and the best focus discrimination for the smallest detector size. The measured intensity of the reflection is shown as a function of objective position for a number of aperture sizes in Figure 5. As anticipated, the width of the focus peak narrows for smaller apertures, and the position of the peak remains constant for all apertures. This is in agreement with previous theoretical results. While the width of the one pixel checker peak is the smallest, corresponding to an objective travel of 14 μm, it was not chosen as the configuration to provide the most accurate focus. With our checkerboard aperture and image scheme, smaller apertures mean smaller checkers, which have higher spatial frequencies. As we approach the limit of the smallest (one and two pixel) checker sizes, the expected high frequency roll-off in the modulation transfer function of our optical system causes a reduction in the intensity of these peaks. This resolution limitation results in a poor signal to noise ratio for the smallest checkers, so the four pixel checker was chosen as the optimal configuration.

The maskless photoalignment exposure system has been first applied to fabrication of a fairly complicated four-domain pattern. The photoalignment material is an azo-based polymer, a perpendicular type photoalignment material, generously provided by DIC, Corp. The exposure time was 60 s for each domain, so the whole process completed in 4 min.

FIG. 2. (a) Normalized intensity profile of a single DMD pixel and projected on to a CMOS camera mounted in the image plane. This signal is a convolution of a one-pixel DMD line, and the translated step response of the camera pixel. (b) Intensity profile of a single line on-off-on pattern projected on to a camera in the image plane.
We established by observation of a nematic liquid crystal (5 CB) micrograph, that the orientation pattern could be faithfully generated over the entire active area of DMD without any noticeable defect. The more technically demanding pattern of the Pancharatnam lens device (Figure 4) highlights the utility of our maskless system. Figure 4(a) depicts the orientational profile required for a Pancharatnam phase liquid crystal lens. Although it looks similar to the ordinary Fresnel lens, the necessary optical phase shift in the Pancharatnam phase lens associated with the azimuthal angle of the liquid crystal director, not with the optical phase retardation. 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. Figure 4(b) depicts a polarizing micrograph of the liquid crystal texture on the photo aligned processed substrate, a six lens array. While of significant functional interest, it should be noted that the features in this pattern are larger than a single pixel, and therefore are not inherently suitable for the evaluation of machine resolution. This sample was prepared by a sequence of 60 exposure patterns. The success of this fabrication technique is experimentally demonstrated in Figures 6 and 4(c). We experimentally confirm the functionality of the Pancharatnam lens by measuring the output intensity of the focus of one of the lenses in the array. Figure 6 shows a clear correspondence between focus intensity and applied cell voltage. The Pancharatnam effect does not rely on spatially varying the optical retardation, instead the effect is maximized at a uniform retardation of $\lambda/2$. By varying the voltage across the liquid crystal cell, we tune the effective birefringence and consequently the retardation. As the retardation approaches $\lambda/2$, we obtain peak focus.

These initial results demonstrate the effectiveness and efficiency of our automated maskless system. While the current feature resolution of 2.2 $\mu$m is acceptable for our present applications, our future plans include the installation of a higher magnification objective lens, which would provide a simple means to improve resolution and extend the functionality of the system.