Fabrication of high-resolution micropolarizer arrays

Junpeng Guo
David J. Brady, MEMBER SPIE
University of Illinois at Urbana-Champaign
Beckman Institute for Advanced Science and Technology
Department of Electrical and Computer Engineering
405 North Mathews Avenue
Urbana, Illinois 61801
E-mail: jguo@echo.phs.uiuc.edu

Abstract. Procedures for creating high-resolution polarization filter arrays using multilayer polyvinyl alcohol (PVA) films are described. Two state polarization filter arrays with 25 μm resolution and three state polarization filter arrays with 48 μm resolution are demonstrated. [S0091-3286(97)01608-5]

Subject terms: micropolarizer array; polarization optics.

Paper 05017 received Jan. 6, 1997; revised manuscript received Mar. 7, 1997; accepted for publication Mar. 11, 1997.

1 Introduction

Spatially varying polarization elements are desirable for a number of applications in 3-D display and optical data storage.[1–3] Ideally, one would like to make polarizer arrays in which each polarizing element can be arbitrarily oriented across a 2-D plane to resolution of 10 μm or less. Polarization filter arrays fabricated to such resolution are called micropolarizers. In practice, the fabrication of high-resolution polarization filter arrays presents a number of challenges.

Optical polarizers can be constructed using the following effects:

1. anisotropic reflection and transmission from high spatial frequency metal wires
2. birefringence in anisotropic crystals
3. Brewster reflection at surfaces
4. dichroic molecular absorption in stretched polymer matrices
5. form polarization by high-resolution structures on dielectric surfaces.

Approach 1, while satisfactory at IR wavelengths, has not been successful in the visible because it is difficult to fabricate metal wires with sufficiently high spatial resolution. Approaches 2 and 3 yield high quality polarizers but are not amenable to high-resolution fabrication. Approach 5 has shown promise, but is not yet fully developed and, with presently available fabrication technologies, is expensive on a per element basis.[4]

The most common methods for fabricating inexpensive polarization elements rely on the orientation of dichroic absorbers in stretched polymer matrices, as in iodide-doped polyvinyl alcohol (PVA) films. For example, potassium iodide (KI_3) diffusion into stretched PVA films produces polarizers for the visible wavelength range.[5,6] Sheet polarizers for different spectral regions can be made by diffusing different dyes into stretched PVA films.[7–9] For mechanical stability, the stretched polymer sheets for these polarizers are made in large sizes and then cut to suit different applications. Recent advances in 3-D display, data storage and optical interconnections require polarizer arrays with micrometer level dimensions. To our knowledge, the concept of patterned polarizers was first reported in 1972 by Dreyer.[10] More recently, methods for making micropolarizer arrays in PVA films involving selective bleaching, selective iodine/potassium iodide indiffusion, or selective etching were proposed by Faris.[11] High-resolution polarizing elements have been reported using strong laser beam bleaching of polarization film.[12] A focused laser beam can bleach the dichroic dye molecules in the polymer matrix to make individual polarizing elements. Using laser beam bleaching to transfer a high-resolution pattern on a mask to a polarizing film was tried in our lab, but it failed since it was difficult to characterize the exposure and also too much heat was delivered to the polymer film during the exposure. Here we report the fabrication of high-resolution micropolarizers with the techniques of photolithography and selective iodide indiffusion. Multiaxis polarizing elements as small as 25 μm have been fabricated using multiple polymer layers. To our knowledge, this paper represents the highest resolution experimental result using the selective indiffusion method. We also report the fabrication of three state micropolarizer arrays.

2 Micropolarizer Fabrication

Polarizers based on stretched polymer matrices are not particularly amenable to high resolution because one cannot independently stretch each element in a different direction. One can address this problem in two ways:

1. One can create an independent layer for each target polarization state. Dichroic dye is diffused into the layer in regions where one wishes to absorb the target polarization. Regions where one wishes the layer to transmit all polarization are kept free of dyes. This approach is easy to implement but has two drawbacks: the thickness of multilayer devices limits the spatial resolution of the micropolarizer and birefringence in the clear regions of a layer can reduce the contrast ratio of succeeding layers.
2. One can fabricate layers for each target polarization state on a substrate, etch away unused elements and transfer etched patterns between substrates, interleav-

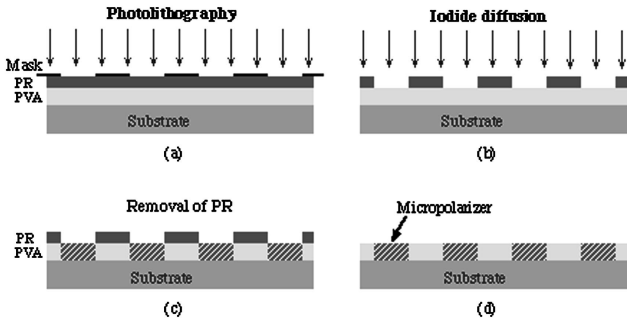

Fig. 1 Fabrication of one layer of a PVA film micropolarizer: PR; photoresist.

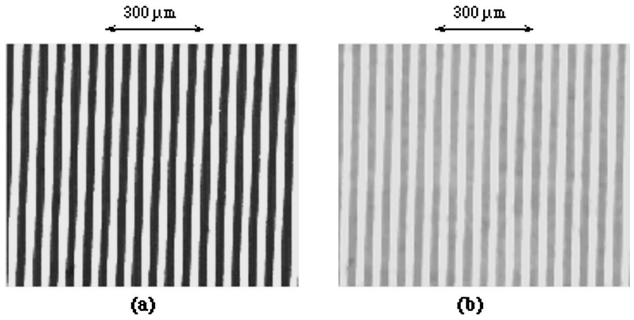

Fig. 2 Transmission photographs of the micropolarizer strips. The width of each strip is 25 μm. (a) The illuminating light is polarized (a) orthogonally and (b) parallel to the micropolarizer polarization orientation.

ing the two polarization states. This approach avoids the disadvantages of approach 1 at a cost of much higher fabrication complexity.

This paper describes micropolarizers fabricated under approach 1.

Fig. 1 illustrates the procedures used to fabricate a layer for the micropolarizer array. The process begins with a stretched PVA layer bonded to a rigid transparent substrate. The PVA is coated with photoresist and the photoresist is patterned using standard photolithography techniques. Iodide is diffused into the PVA through the patterned photoresist layer. In areas where the photoresist has been etched away, micropolarizers are formed. In areas covered by photoresist, no iodide reaches the PVA layer. After iodide diffusion, the photoresist pattern is etched off the PVA. The resulting micropolarizer layer can be used as a substrate for subsequent layers or transferred to another substrate to form a multilayer device.

In our experiments, stretched PVA films were obtained commercially from International Polarizer, Inc. We dissolved the cellulose acetobutyrate (CAB) coatings with methane dichloride. The PVA film was mounted on the transparent thin glass slide with wax around the edges. The surface of the PVA films were well cleaned with acetone while spinning to remove CAB residues, which would otherwise inhibit iodide diffusion in the following process. The stretched films have a thickness of about 25 μm and a stretching ratio of 3. AZ5214, a standard novolak based photoresist (PR) was spin coated on the surface of the PVA film at a speed of 5000 rpm for the following UV optical lithography exposure. Chromium (Cr) masks with desired micropolarizer patterns were made by e-beam lithography. The e-beam patterns on the mask were transferred to a photoresist pattern on the surface of stretched PVA film by standard UV optical lithography. Since the host substrate is PVA film, which has low melting point and is soluble in water, care must be taken in the soft baking and developing processes. We softbaked the photoresist twice on hot plate at the temperature of 65°C, each time for 30 s. We used the CASPAR™ mask aligner to do the UV exposure (*I*-line, 365 nm). The UV intensity in the mask aligner is 2.0 mW/cm^2. The UV exposure time is critically related to the softbaking conditions. The exposure time we used was 60 s. After exposure the PR pattern was developed in the developer (AZ327-MIF) for 20 s, rinsed briefly with water and dried immediately. The patterned film was then dipped in the potassium iodide (KI_3) water solution (I_2: 1.8 g; KI: 1.43 g, water: 350 cm^3) for iodide diffusion. The diffusion time is related to the concentration of the iodine molecules and affects the transmittance and the extinction ratio of the polarizers. Since PVA is soluble in water, the diffusion time can not be long. The diffusion time was about 1 s in our experiments. Then the film was immersed in a boric acid solution (2.0 g boric acid dissolved in 150 cm^3 water) about 1 s for stabilization. The film was dried immediately. Finally, the photoresist was stripped off, leaving the UV-exposed regions as polarizers.

3 Experimental Results

Fig. 2 presents photographs of the microscopic transmission through patterned single layer samples of stretched PVA film indiffused with iodide. The clear microstrips are 25 μm wide regions of undoped PVA. The dark microstrips are 25 μm wide regions of iodide doped PVA film. In Fig. 2(a), the illuminating light is polarized orthogonally to the polarizer orientation. In Fig. 2(b) the illuminating light polarization is parallel to the polarizer orientation and the transmission through the doped regions is increased. The micropolarizer film is 25 μm thick and is mounted on a 150 μm thick glass slide. The illumination source is a tungsten light for which most of the spectrum is in the visible range.

For a simple demonstration of multiaxis micropolarizers, we used two of the Fig. 2 style devices that were electrostatically joined by slightly heating them around 50 °C. A photograph of this device under unpolarized illumination is shown in Fig. 3(a). The darkest elements are covered by crossed polarizers. The gray elements are covered by linear polarizers. The transparent parts are elements where only transparent PVA films exist. The polarization orientations of the polarizing elements are illustrated by the arrows in Fig. 3(b). Transmission photographs under linearly polarized illumination are shown in Figs. 3(c) and 3(d).

The transmission versus incident polarization angle for an individual polarizing element has been measured at the specific wavelength of 632.8 nm with a He-Ne laser source. To perform this measurement, we imaged a specific micropolarizer element using a micro-objective lens (25×), and then measured the intensity of the image of that element as a function of the polarization of a back-illuminating plane wave. The result is shown in Fig. 4, which gives the normalized transmission of a micropolar-

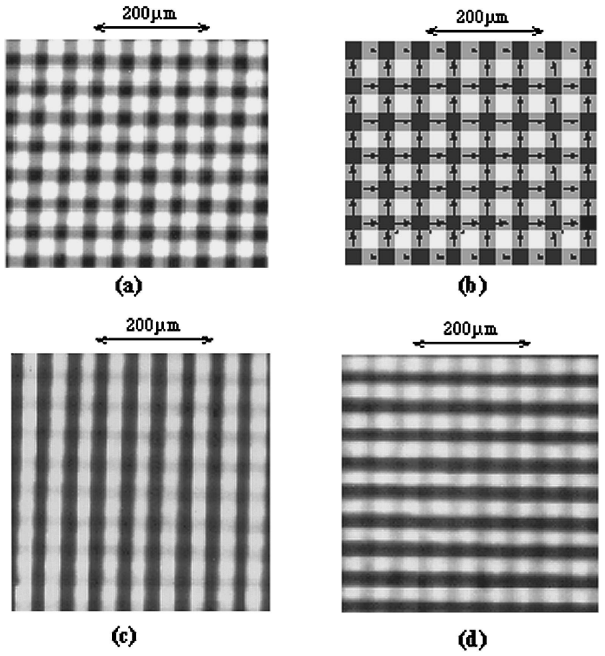

Fig. 3 (a) Transmission photograph of the crossed micropolarizer arrays under unpolarized illumination, each polarizing element is 25×25 μm; (b) Polarization orientation pattern in the micropolarizer arrays; (c) transmission photograph under horizontally polarized illumination; and (d) transmission photograph under vertically polarized illumination.

izing element versus the incident light polarization orientation. The absolute parallel transmittance is 50% and the perpendicular transmittance is about 2.5%. The extinction ratio is about 20. We believe this limited extinction ratio is due to the limited stretching ratio of the PVA films. The stretching ratio of the high quality commercial available polarizer film is between 5 and 6. The stretching ratio of the PVA films we used was about 3. The polarization extinction ratio can be increased by using further stretched PVA films. Also the concentration of iodide molecules and the diffusion condition might affect the extinction ratio of the micropolarizers. Further experiments must be carried to optimize the fabrication process.

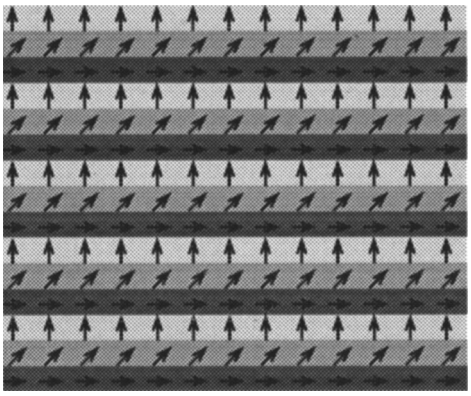

Fig. 5 Polarization pattern of the three-state micropolarizer arrays.

The fabrication of complex micropolarizer arrays is a principal objective of this work. We have constructed three state arrays in which the polarizer consists of cycles of 0, 45, and 90-deg polarization orientations. The polarization pattern in one cycle is shown in Fig. 5. A transmission photograph of a fabricated device under polarized illumination is shown as Fig. 6. The width of each polarization state was 48 μm. Each line is approximately 1 cm long. The polarization pattern was repeated over 40 cycles. The photograph was taken with linear polarized light in one polarization direction. The device shown in Fig. 6 was formed as three layers of micropolarizer film. Each layer was patterned with different polarization state, which has the polarization strips of 48 μm width and unpolarized transparent strips of 96 μm width. Three patterned polarizer films were horizontally displaced and electrostatically joined together by slightly heating them around 50 °C. Since each polarization state has a thickness of 25 μm, the three-state device is about 75 μm thick.

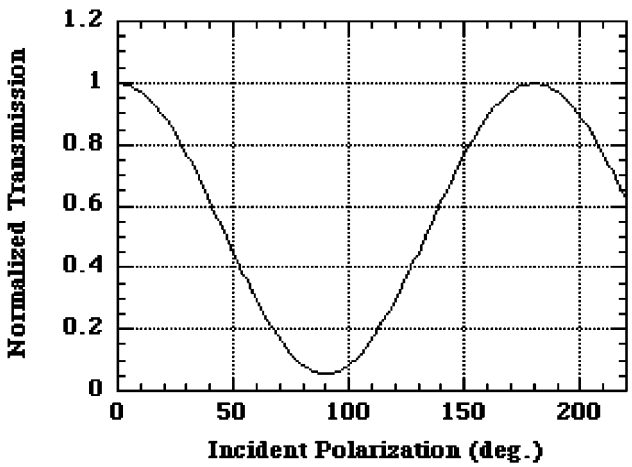

Fig. 4 Normalized transmission of a micropolarizer element versus the incident polarization angle with respect to the polarizer polarization axis. The transmission extinction ratio is about 20.

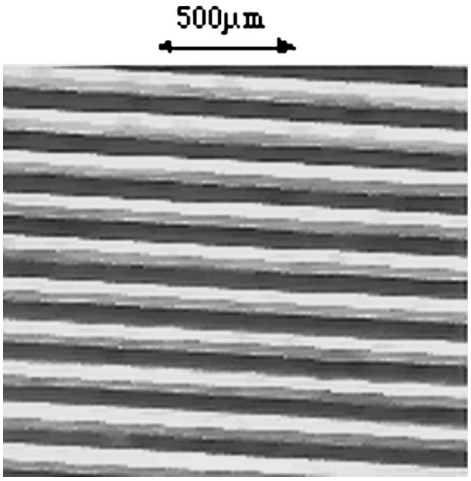

Fig. 6 Photograph of the three-state (0, 45, 90 deg) micropolarizer scan lines. The width of each state is 48 μm. The photograph was taken with linear polarized light in one polarization direction.

4 Conclusion

Two polarization state micropolarizer arrays with 25 μm resolution were fabricated and tested. Three-state micropolarizer scan lines with 48 μm linewidth were also fabricated and tested. While we are pleased with our progress in fabricating these micropolarizer devices, problems with lateral resolution, device thickness, and maintaining layer alignment must be addressed. The lateral distribution of the diffused iodide concentration was observed in the edges of the micropolarizer strips with the higher magnification under the microscope. The typical scale length of the lateral distribution was about 2 μm. We believe this lateral distribution is related to the iodide diffusion condition and the thickness of the PVA film. Further investigation will be conducted on the improvement of the lateral resolution of the device. The thickness of the device is critical in the application since it is related to the maximal incident angle of the light. The thinner the device, the larger can be the incident angle. Further work will focus on three approaches to make thinner devices: using thinner PVA films, metal grid thin film polarizers, and alternatives to stretched film for dichroic dye alignment. Further stretching of the PVA films can make thinner films but stretching the PVA films to less than 10 μm is mechanically unstable. One might try etching stretched films to reduce their thickness, but it is not clear that this approach would yield suitable extinction ratios. The 25 μm resolution we achieved is sufficient for most display applications. But for other high-resolution applications, it still must be improved to achieve good performance. Metal grid polarizers can be made by evaporating and patterning the thin metal films, the thickness can be well controlled and maintained. The metal grid period must be smaller than 1/10 of the wavelength to have a good extinction ratio.[13] Some metal grids have been reported, but the extinction ratios are not good in the visible spectrum.[14,15] Using UV lithography to make such small features less than 100 nm is beyond its technical limit because of the high spatial frequency diffraction involved. Difficulties of fabricating metal grids with less than 50 nm structures still exist even using the e-beam lithography technique. Focused ion beam writing and scanning tunneling microscopy (STM) techniques can make smaller scale structures in principle, but it is less cost effective in the current state of technologies. We expect the further development the ion beam technique and STM can further the advancement of the thin film metal grid micropolarizers. Multilayer approaches to improving the extinction ratio of metal grid polarizers might also be considered.

Acknowledgment

This work was funded in part by the Air Force Office of Scientific Research.

References

1. E. Joubert, P. Miche, and R. Debrie, ''3-D surface reconstruction using a polarization state analysis,'' *J. Opt. (Paris)* **26**(1), 2–8 (1995).
2. A. Ohba, Y. Kimura, S. Sugama, R. Katayama, and Y. Ono, ''Reflection polarizing holographic optical element for compact magneto-optical heads,'' *Appl. Opt.* **29**(34), 5131–5135 (1990).
3. S. M. Faris, ''Multi-mode stereoscopic imaging system,'' U.S. Patent No. 5,264,964 (1993).
4. F. Xu, J. E. Ford, and Y. Fainman, ''Polarization selective computer generated holograms: design, fabrication, and applications,'' *Appl. Opt.* **34**(2), 256–266 (1995).
5. E. H. Land, ''Light polarizer and process of manufacturing the same,'' U.S. Patent No. 2,237,567 (1941).
6. E. H. Land, ''Some aspects of the development of sheet polarizers,'' J. Opt. Soc. Am. **41**(12), 957–963 (1951).
7. E. H. Land and R. P. Blake, ''Light polarizer and process of manufacture,'' U.S. Patent No. 2,380,363 (1945); E. H. Land, ''Light-polarizing sheet of molecularly oriented transparent linear high polymer dyed with dichroic substance and process of manufacture,'' U.S. Patent No. 2,454,515 (1948).
8. M. Hyman, Jr., and C. D. West, ''Sheetlike light-polarizing complex of iodine and a polyvinyl compound with protective surface boric acid-polyvinyl compound complex,'' U.S. Patent No. 2,445,579 (1948).
9. F. J. Binda, ''Heat resistant light-polarizing polyvinyl borate film containing borax,'' U.S. Patent No. 2,554,850 (1951).
10. J. F. Dreyer, ''Method of making light polarizing patterns,'' U.S. Patent No. 3,658,616 (1972).
11. S. M. Faris, ''Methods for manufacturing micropolarizers,'' U.S. Patent No. 5,327,285 (1994).
12. J. Hoβfeld, D. Columbus, H. Sprave, T. Tschudi, and W. Dultz, ''Polarizing computer-generated holograms,'' *Opt. Eng.* **32**(8), 1835–1837 (1993).
13. B. Stenkamp, M. Abraham, W. Ehrfeld, E. Knapek, M. Hintemaier, M. T. Gale, and R. Morf, ''Grid polarizer for the visible spectral region,'' in *Nanofabrication Technologies and Device Integration*, W. Karthe, Ed., *Proc. SPIE* **2213**, 288–296 (1994).
14. R. E. Slocum, ''Evaporative thin metal films as polarizers,'' in *Polarizers and Application*, G. B. Trapani, Ed., *Proc. SPIE* **307**, 25–30 (1981).
15. M. Takakuwa, K. Baba, and M. Miyaqi, ''Ultra-thin polarizing films for the near-infrared region consisting of stacked anisotropic gold island films,'' *Opt. Lett.* **21**(15), 1195–1197 (1996).

Junpeng Guo is a PhD student in the Department of Electrical and Computer Engineering at the University of Illinois at Urbana-Champaign. He received his BS and MS degrees from Peking University and the University of Illinois. His research interests are fabrications of micro-optical device, holographic system, fiber laser and optical communications.

David J. Brady is an associate professor in the Department of Electrical and Computer Engineering and in the Beckman Institute for Advanced Science and Technology at the University of Illinois. Professor Brady received his PhD from the California Institute of Technology in 1990. He was awarded a David and Lucile Packard Foundation Fellowship in 1990. His fields of professional interest are holographic and ultrafast optical systems, optical communications, data storage and imaging, and coherent quantum dynamics.