THE UNIVERSITY OF WESTERN AUSTRALIA

Micropolarizing Devices for CMOS Polarization Image Sensors

by

Xiaojin ZHAO

(B. Sc. Peking University)

This thesis is presented for
the degree of Doctor of Philosophy of
The University of Western Australia
in the School of Electrical, Electronic and Computer Engineering

September 2010

Micropolarizing Devices for CMOS Polarization Image Sensors

by
Xiaojin ZHAO

School of Electrical, Electronic and Computer Engineering
The University of Western Australia

Abstract

Rapid advances in semiconductor industry complementary metal oxide semiconductor (CMOS) fabrication process have enabled the integration of a camera onto a single silicon chip. Referred to as CMOS image sensor, a camera-on-a-chip offers significant advantages in terms of system miniaturization and manufacturing cost. Like the vast majority of commercially available camera systems, CMOS image sensors are essentially designed to image the world in terms of intensity and color. However, they are “blind” to the third characteristic of light that is polarization. Capturing the polarization state of light reflected or emitted by objects in a scene can not only reveal valuable information about their geometrical, physical, chemical, physiological, and/or metabolic properties but also greatly simplify a number of important machine vision tasks such as autonomous navigation or automatic target detection.

Commercially available CMOS cameras can be made polarization-sensitive by coating individual pixels with micrometer-scale polarizer elements. A micropolarizer array (MPA) is thus formed on top of the photosensitive pixel array. Previously reported micropolarizer implementations suffer from two

main limitations: (i) use of selective etching to pattern polarizer elements at the pixel pitch, which is a difficult process to control at the micrometer scale, and (ii) incomplete polarization signature since the circular polarization component cannot be extracted. This circularly polarized component is crucial to fully determine the polarization state of light since, in general, a ray will be elliptically polarized, that is, it can be decomposed into a linear and circular polarization vector. This thesis addresses the above limitations to enable the development of miniature CMOS single-chip polarization cameras capable of capturing simultaneously all possible polarization states of light reflected or emitted by objects in a scene.

This thesis investigates and demonstrates a number of novel MPA design and fabrication technologies, which completely remove the need for selective etching and enable the extraction of all possible polarization states of incident light. The well-controlled-process of ultraviolet (UV) photolithography is used, for the first time, for the patterning of high resolution pixel-level MPAs with submicron thicknesses. Another unique feature of the developed MPAs is that they can be fabricated using standard and well-established CMOS manufacturing flows, enabling low-cost mass production. Both absorptive-type and reflective-type linear polarizers are explored for applications with both natural passive light source (e.g. polarization difference imaging and partial-linear polarization imaging) and artificial collimated active light source for full Stokes imaging. The proposed implementations significantly scale the MPA pitch size down to $2\mu m$. Reported experimental results validate the concept of high performance photo-aligned MPAs with major principal transmittance and extinction ratio as high as $\sim 80\%$ and ~ 3200 (35dB), respectively.

TABLE OF CONTENTS

Title Page	i
Abstract	i
Table of Contents	iii
List of Figures	vi
List of Tables	x
List of Abbreviations	xii
List of Publications	xii
Acknowledgements	xiv
1 Introduction	1
1.1 Thesis Background and Motivation	1
1.2 Thesis Objective and Contribution	5
1.3 Thesis Organization	7
2 Stokes Polarization Imaging and Polarization Image Sensors	10
2.1 Introduction	10
2.2 Intensity and Color Imaging Techniques Overview	11
2.2.1 Intensity Imaging	11
2.2.2 Color Imaging	12
2.3 Stokes Parameters and Stokes Polarization Imaging	16
2.3.1 Stokes Parameters	16
2.3.2 Mueller Matrix	21

2.3.3	Stokes Parameters Measurement	24
2.3.4	Stokes Polarization Imaging	25
2.4	Solid-State Polarization Image Sensors	27
2.4.1	Multiple-frame Polarization Image Sensing with Unpat- terned Polarizing Devices	28
2.4.2	Simultaneous Polarization Image Sensing with Beam Split- ting Prism	30
2.4.3	Simultaneous Polarization Image Sensing with Patterned Micropolarizing Devices	31
2.5	Conclusion	31
3	Micropolarizer Array for Partial Linear Polarization Imaging	33
3.1	Introduction	33
3.2	Overview of Previous Implementations	34
3.2.1	Classification	34
3.2.2	Limitations	38
3.3	Liquid-crystal Micropolarizer Array for Polarization Difference Imaging	40
3.3.1	Metal-Wire-Grid Linear Polarizer	41
3.3.2	Optical Modeling and Simulation Results	42
3.3.3	Liquid-crystal Photoalignment	48
3.3.4	Fabrication Process and Experimental Results	50
3.4	Azo-dye Micropolarizer Array for Partial-linear Polarization Imag- ing	57
3.4.1	Absorptive Linear Polarizer and Beer-Lambert Law	57
3.4.2	Photo-induced Dichroism of AD1	59
3.4.3	“Guest-host” Micropolarizer Array	64
3.4.4	Fabrication Process and Experimental Results	67
3.5	Conclusion	72
4	Micropolarimeter Array for Circular Polarization Imaging	73
4.1	Introduction	73
4.2	Review of Circular Polarization Vision	74
4.2.1	Circular Polarization Vision of Ocean Creatures	74
4.2.2	Active Circular Polarization Imaging Systems	75

4.3	Liquid-crystal Micropolarimeter Array for Circular Polarization Imaging	77
4.3.1	Array Pattern Design	77
4.3.2	Structure and Optical Modeling	78
4.3.3	Fabrication Process Flow	81
4.3.4	Experimental Results	83
4.4	Conclusion	86
5	Micropolarimeter Array for Full Stokes Polarization Imaging	87
5.1	Introduction	87
5.2	Liquid-crystal Micropolarimeter Array for Full Stokes Polarization Imaging	88
5.2.1	System Design and Implementation	88
5.2.2	Liquid-crystal Micropolarimeter Array Fabrication	95
5.2.3	Experimental Results	98
5.3	Conclusion	103
6	Conclusion and Future Work	105
6.1	Conclusion	105
6.2	Future Work	107
	Bibliography	109

List of Figures

1.1	Light is a transverse electromagnetic wave with its electric and magnetic fields orthogonal to the direction of propagation. These two fields change with time and space in a sinusoidal fashion. . .	2
1.2	Intensity image of a freckle (A.1) and its corresponding polarization image (B.1) [13].	3
2.1	Color image sensing technique with three image sensors.	13
2.2	Commonly-used color filter array patterns for the RGB representation.	14
2.3	Spectral curves of the absorption coefficient and the penetration depth for silicon [31].	14
2.4	Cross-section of the triple-well structure for color imaging. . . .	15
2.5	Spectral response of a triple-well structure with UMC 0.18 μ m process.	15
2.6	Propagation of the transverse optical field.	16
2.7	Interaction between the incident light and arbitrary polarizing element.	21
2.8	Classical Stokes parameters measurement configuration.	24
2.9	First generation polarization image sensor with mechanically-controlled unpatterned polarizing devices.	28
2.10	Unpatterned TNLC based polarization image sensor.	29
2.11	Simultaneous polarization image sensing technique with beam splitting prism and multiple image sensors.	30
2.12	CMOS polarization image sensor with fully integrated micropolarizing devices.	31
3.1	Composition of partial-linearly polarized light.	34
3.2	Refractive-type MPA based on birefringent YVO_4 crystal. . . .	34

3.3	Reflective-type MPA composed of a dual layer visible-regime patterned metal wire grid polarizer.	35
3.4	Absorptive-type micropolarizer array based on selectively doped/undoped PVA film.	36
3.5	Absorptive-type MPA based on RIE of PVA film or polarization dichroic dye film.	37
3.6	Comparison between MPAs with different thicknesses when applied to oblique incident light.	38
3.7	Reflective-type metal wire grid polarizer.	41
3.8	Interaction between the incident light and the GTNLC/linear polarizer combination.	42
3.9	Relationship between the element A of GTNLC Mueller matrix and the LC twist angle ϕ for different retardations.	45
3.10	Relationship between the element B of GTNLC Mueller matrix and the LC twist angle ϕ for different retardations.	45
3.11	Relationship between the element C of GTNLC Mueller matrix and the LC twist angle ϕ for different retardations.	46
3.12	Color dispersion of the GTNLC Mueller matrix elements A , B and C for 90° twisted GTNLC ($\Delta n = 0.225$, $d = 5\mu m$).	47
3.13	Color dispersion of the GTNLC Mueller matrix elements A , B and C for 90° twisted GTNLC ($\Delta n = 0.225$, $d = 10\mu m$).	47
3.14	Two GTNLCs with different LC molecules arrangement: (A) 90° twisted; (B) untwisted.	48
3.15	Chemical formula of the UV-sensitive SD1.	50
3.16	Absorption spectrum of the UV-sensitive SD1.	50
3.17	Micropolarizer array pattern for PDI.	51
3.18	Photo-aligned liquid-crystal MPA fabrication process flow.	52
3.19	Microphotographs of the fabricated LC MPA.	54
3.20	Transmittances of 0° and 90° micropolarizers following Malus' law at different wavelengths.	55
3.21	Spectral measurements of the major principal transmittance for 0° and 90° micropolarizer elements.	55
3.22	Absorption of an incident light as it travels through an absorptive media.	57
3.23	Chemical formula of AD1.	59
3.24	Polarization dichroism of AD1: (A) with 0° linear analyzer on top; (B) with 90° linear analyzer on top.	59

3.25	Array pattern for partial linear polarization imaging.	60
3.26	Photo-patterned AD1 MPA fabrication process flow.	61
3.27	Microphotographs of the fabricated AD1 MPA: (A) with 0° linear analyzer on top; (B) with 90° linear analyzer on top; (C) with 45° linear analyzer on top; (D) with −45° linear analyzer on top.	62
3.28	Spectral measurement results of the major principal transmittance with AD1 concentration varied from 1% to 5%.	62
3.29	Spectral measurement results of the ER.	63
3.30	Rod-like AD1 molecules and their long molecular axes.	64
3.31	Molecules ordering comparison between (A) photo-induced AD1 ordering and (B) predetermined PLC molecules induced ordering in “guest-host” system.	65
3.32	PLC pre-alignment process.	66
3.33	Fabrication process flow of “guest-host” MPA.	68
3.34	Measured major principal transmittances of UV-oriented AD1 micropolarizer and “guest-host” micropolarizer, with AD1 concentration varied from 1% to 5%.	69
3.35	Measured extinction ratios of UV-oriented AD1 micropolarizer and “guest-host” micropolarizer.	70
3.36	Microphotographs of the fabricated “guest-host” MPA, inspected by a linear polarization analyzer along the following orientations: (A) 0 degree; (B) 90 degree; (C) 45 degree; (D) −45 degree.	71
4.1	(A) Photograph of the stomatopod crustacean <i>Odontodactylus cultrifer</i> ; (B) the stomatopod crustacean <i>Odontodactylus cultrifer</i> ’s telson keel photographed with a left-handed circular polarization analyzer; (C) the stomatopod crustacean <i>Odontodactylus cultrifer</i> ’s telson keel photographed with a right-handed circular polarization analyzer; (D) the eye of <i>Odontodactylus scyllarus</i> , which is a close relative of <i>Odontodactylus cultrifer</i> [73, 74].	74
4.2	Illustration of active circular polarization imaging.	76
4.3	Array pattern for circular polarization imaging.	77
4.4	Cross-section of proposed MCPA array.	78
4.5	Constructions of circular polarization analyzers: (A) for right-handed circularly polarized component; (B) for left-handed circularly polarized component.	79
4.6	Proposed MCPA array fabrication process flow.	82

4.7	Microphotographs of the fabricated MCPA array: (A) illuminated by 90° linearly polarized light; (B) illuminated by 0° linearly polarized light; (C) illuminated by 45° linearly polarized light; (D) illuminated by right-handed circularly polarized light; (E) illuminated by left-handed circularly polarized light.	84
4.8	Spectral measurement results of the transmittances with right/left-handed circularly polarized input light.	85
4.9	Spectral measurement result of the MCPA extinction ratio.	85
5.1	CMOS polarization image sensor architecture with integrated LCMP array for full Stokes polarization imaging.	88
5.2	Relationship between the LC Mueller matrix elements and the LC twist angle ϕ : (A) D versus ϕ ; (B) E versus ϕ ; (C) F versus ϕ	93
5.3	Top view and cross-sections of the proposed CMOS polarization image sensor's "superpixel" consisting of four LCMPs: $LCMP_{45^\circ twisted}$, $LCMP_{-45^\circ twisted}$, $LCMP_{E-field}$ and $LCMP_{Untwisted}$	94
5.4	(A) Cross-section of proposed CMOS polarization image sensor with integrated LCMP array; (B) fabricated LCMP array with the second substrate as "dummy" CMOS imager substrate to enable LCMPs' optical characterization (CMOS imager substrate is opaque).	96
5.5	Microphotographs of fabricated LCMP array illuminated by linearly or circularly polarized input: (A) 0° linearly polarized; (B) 90° linearly polarized; (C) -45° linearly polarized; (D) right-handed circularly polarized; (E) left-handed circularly polarized.	98
5.6	Malus measurement results of $LCMP_{45^\circ twisted}$	100
5.7	Malus measurement results of $LCMP_{-45^\circ twisted}$	101
5.8	Malus measurement results of $LCMP_{E-field}$	101
5.9	Spectral measurement results of $LCMP_{Untwisted}$	102

List of Tables

3.1	Extinction ratios at different wavelengths	56
3.2	Optical performance comparison with previously reported implementations, where the photo-aligned LC, UV-oriented AD1 and “guest-host” MPAs proposed in this thesis are represented by [59]*, [60]* and [64]*, respectively.	71
5.1	Extinction ratios of different LCMPs	100
5.2	Comparison between experimentally extracted Stokes parameters and ideal values for different polarized inputs	103

List of Abbreviations

AD1	Azo-Dye-1
CCD	Charge Coupled Device
CFA	Color Filter Array
CMOS	Complementary Metal Oxide Semiconductor
CMY	Cyan Magenta Yellow
CPU	Central Processing Unit
DMF	Dimethylformamide
DOCP	Degree of Circular Polarization
DSP	Digital Signal Processor
ECB	Electrically Controlled Birefringence
ER	Extinction Ratio
GTNLC	General Twisted Nematic Liquid Crystal
ITO	Indium Tin Oxide
LC	Liquid Crystal
LCD	Liquid Crystal Display
LCMP	Liquid Crystal Micropolarimeter
LCVR	Liquid Crystal Variable Retarder
MCPA	Micro-Circular-Polarization-Array
MOS	Metal Oxide Semiconductor
MP	Micropolarizer
MPA	Micropolarizer Array
MWGP	Metal Wire Grid Polarizer
PDI	Polarization Difference Imaging
PLPI	Partial-Linear Polarization Imaging
PLC	Polymerizable Liquid Crystal
PR	Photoresist
PSG	Polarization State Generator
PVA	Polyvinyl Alcohol
RGB	Red Green Blue
RIE	Reactive Ion Etching
SD1	Sulfonic-Dye-1
TN	Twisted Nematic
TNLC	Twisted Nematic Liquid Crystal
UV	Ultraviolet
UVO	Ultraviolet-Ozone

List of Publications

- **Journal Papers**

1. X. Zhao, A. Bermak, F. Boussaid and V. G. Chigrinov, “A ‘Guest-Host’ Micropolarizer Array Based on Photo-aligned Polymerizable Nematic Liquid Crystal,” submitted to *IEEE Photonics Technology Letters*, 2010.
2. X. Zhao, A. Bermak, F. Boussaid and V. G. Chigrinov, “Liquid-crystal micropolarimeter array for full Stokes polarization imaging in visible spectrum,” *Optics Express*, vol. 18, no. 17, pp. 17776-17787, 2010.
3. X. Zhao, A. Bermak, F. Boussaid, T. Du and V. G. Chigrinov, “High-resolution photo-aligned liquid-crystal micropolarizer array for polarization imaging in visible spectrum,” *Optics Letters*, vol. 34, no. 23, pp. 3619-3621, 2009.
4. X. Zhao, F. Boussaid, A. Bermak and V. G. Chigrinov, “Thin Photo-Patterned Micropolarizer Array for CMOS Image Sensors,” *IEEE Photonics Technology Letters*, vol. 21, no. 12, pp. 805-807, 2009.
5. X. Zhao, F. Boussaid and A. Bermak, “Characterization of a 0.18 μ m CMOS Color Processing Scheme for Skin Detection,” *IEEE Sensors Journal*, vol. 7, no. 11, pp. 1471-1474, 2007.

• **Refereed International Conference Papers**

1. X. Zhao, A. Bermak, F. Boussaid and V. G. Chigrinov, “Liquid-crystal micropolarimeter array for visible linear and circular polarization imaging,” *IEEE International Symposium on Circuits and Systems (IS-CAS)*, pp. 637-640, Paris, 2010.
2. X. Zhao, A. Bermak, F. Boussaid, L. Yao and V. G. Chigrinov, “A High-Resolution Micro-Circular-Polarization-Analyzer Array for Real-Time Active Circular Polarization Imaging,” *IEEE Biomedical Circuits and Systems Conference (BioCAS)*, pp. 49-52, Beijing, 2009.
3. X. Wu, X. Zhao, A. Bermak and F. Boussaid, “An AER based CMOS polarization image sensor with photo-aligned micropolarizer array,” *Asia Symposium on Quality Electronic Design (ASQED)*, pp. 126-130, Kuala Lumpur, 2009.
4. X. Zhao, A. Bermak and F. Boussaid, “A CMOS Digital Pixel Sensor with Photo-Patterned Micropolarizer Array for Real-Time Focal-Plane Polarization Imaging,” *IEEE Biomedical Circuits and Systems Conference (BioCAS)*, pp. 145-148, Baltimore, 2008.
5. X. Zhao, S. Chen, F. Boussaid and A. Bermak, “A 0.18 μ m CMOS On-Chip Skin Detection Scheme Based on NPNP-Triple-Junction Structure,” *IEEE International Symposium on Integrated Circuits (ISIC)*, pp. 333-336, Singapore, 2007.

Acknowledgements

I would like to take this chance to express my sincerest thanks to my thesis supervisor Prof. Farid Boussaid for his guidance, encouragement and support throughout my study at the University of Western Australia (UWA). Since this project is under a double-badged PhD program between the UWA and the Hong Kong University of Science and Technology (HKUST), I am also deeply grateful to my thesis co-supervisor Prof. Amine Bermak from the HKUST, whose thoughtfulness and sincere concern, encourage me throughout the study. Also, I would like to thank Prof. Vladimir G. Chigrinov from HKUST for his continuous support on my project and serving as my thesis examination committee member.

I would like to give special thanks to the other members of my thesis examination committee: Prof. Christian Fayomi, Prof. Son Lam Phung and Prof. Abbes Amira nominated by the UWA side; Prof. Christopher Y. H. Chao, Prof. George Jie Yuan, Prof. Qing-Ping Sun and Prof. Kong Pang Pun nominated by the HKUST side. Many thanks for their valuable time on reading my thesis and attending my thesis presentation.

The completion of this dissertation would not be possible without the help from my colleagues in Center for Display Research (CDR) of HKUST, especially, Dr. Lishuang Yao, Mr. Tao Du, Dr. Anatoli Murauski and Mr. Jacob Y. L. Ho for sharing their valuable experience and assisting me on the liquid crystal (LC) cell fabrication and test setup. I also would like to thank my research group members in Integrated Circuit Design Lab (ICLAB) of UWA

Microelectronics Research Group (MRG) for their friendships and kindly help in both my research and daily life.

Finally, I would like to dedicate this dissertation to my family for their continuous support and endless love.

Chapter 1

Introduction

1.1 Thesis Background and Motivation

Commercially available camera systems are essentially designed to image the world in terms of intensity and color; this because the human retina is only sensitive to this type of visual information [1]. Other creatures on earth, like bees, octopus, waterstriders, backswimmers, dragonflies or cuttlefish, have eyes, sensitive to another fundamental characteristic of light that is polarization [2]. Polarization is defined as the path traced (Figure 1.1) by the tip of the electric field as the light's electromagnetic wave propagates [2].

Light whose electric field oscillates in a particular way is said to be polarized. If the oscillation is constrained to a single plane, light is said to be linearly polarized. If light is composed of two plane waves of equal amplitude but with a phase difference of 90° , then the light is said to be circularly polarized. A light wave which is vibrating in more than one plane is referred to as unpolarized light. Examples of unpolarized light include light emitted by the sun, by a lamp or by a candle flame. Unpolarized light can become partially polarized after scattering, transmission or reflection.

All possible states of polarization can be represented by one vector known

Figure 1.1: Light is a transverse electromagnetic wave with its electric and magnetic fields orthogonal to the direction of propagation. These two fields change with time and space in a sinusoidal fashion.

as the Stokes vector S [3]. This vector describes the polarization of light through four components $[S_0, S_1, S_2, S_3]$, providing information about reflecting objects that traditional intensity/color-based cameras ignore. Concretely, geometrical, chemical, physical, physiological and metabolic properties of the target such as surface smoothness, shape, size, color, orientation, molecular structure can be readily extracted if the Stokes vector components are available [4]. Polarization provides information that is largely uncorrelated with intensity and color images. As a result, it provides insightful and complementary data on the physical nature of a feature, object or target. In fact, the exploitation of polarization data has been found to be a powerful and reliable technique to determine the optical signature of a target [5]. Demonstrated applications include remote satellite image sensing [6], aerial reconnaissance, autonomous navigation, marine biology, mineral exploration, automatic target recognition, industrial process control (e.g. quality inspection), machine vision tasks targets in scattering media [7] and non-contact fingerprint detection [8].

In addition, biomedical researchers have observed that when polarized light impinges on a biological tissue, its polarization state changes as it propagates through the tissue [9–11]. Light that reflects from the surface retains its polarization while light that backscatters from somewhere below the surface

of the tissue is depolarized [11]. The degree of depolarization of the incident polarized light depends on the type of tissue (tumor, fat, glandular, fibrous) it encounters during its propagation [12,13]. It can be used as a means to image cancerous tumors because cancerous cells are known to change their morphology (e.g. increased nucleus size or number of mitochondria), which changes the amount of scattering and hence the degree of depolarization [12,13]. The latter has been shown to be a powerful discrimination criterion for the imaging of cancerous tissues [12,13]. Deeper structures in the tissue could also be imaged by using multi-wavelength illumination, as photons reach different penetration depths inside the tissue [9]. This imaging technology can be used for *in vivo*

Figure 1.2: Intensity image of a freckle (A.1) and its corresponding polarization image (B.1) [13].

imaging of the skin, mucosa, vascular system and gastrointestinal tracts with relatively simple apparatus at high speed [9,12,13]. Figure 1.2 illustrates the use of this technology for the screening of melanoma, a skin cancer that occurs in the epithelial layers of the skin [13]. Figure 1.2 shows the intensity image of a freckle that is compared with its corresponding polarization image. In the case of freckle A.1, the freckle's pigmentation disappears in the polarized image B.1, signaling that there is nothing abnormal under the freckle [13].

Despite its considerable potential, the widespread use of polarization imaging has been limited because of factors such as size, weight, cost, user interface, and/or alignment/calibration requirements for such apparatus, which consists typically of a combination of image sensors, electro/mechanically controlled linear polarizers, retarders and digital signal processors (DSP)/central processing units (CPU) [6]. To sense the polarization state of light, these systems

would typically require the capture of multiple images of the same scene, each of which is acquired by means of looking through different polarization elements. The obvious drawback of this approach is that both the scene and the camera must be stationary across multiple frames, to avoid introducing interframe motion. To eliminate these errors, some systems acquire multiple images at the same time but then the problem becomes spatial registration since each camera will image the scene from a slightly different perspective [6].

The first generation of polarization imaging systems was implemented by simply mounting an unpatterned linear polarizer in front of a digital camera. Different polarization images were generated in successive frames by rotating the linear polarizer with hand or motor [7]. Wolff *et al.* improved the latter design by replacing the mechanically rotated linear polarizer with an electrically configured polarizing element [14]. However, polarization information could still not be simultaneously captured in a single frame. To enable real-time polarization imaging and the extraction of all the four Stokes parameters, Barter *et al.* proposed to separate the different polarization components by sophisticated polarization beaming splitting prisms and sense them simultaneously by at least four image sensors [15, 16]. However, spatial registration of multiples images is required and complicated by the need to compensate for both mechanical misalignment and aberrations due to separate optical paths [6].

To alleviate the above obstacles, a promising approach is to directly pattern micropolarizing devices on top of each pixel of the image sensor array. In this way, each pixel will look through a micropolarizer of a given orientation with a single polarization component sensed by each pixel. The three other missing components of the Stokes vector are recovered by examining the intensity values of neighboring pixels. A 2×2 (or larger) convolution kernel is applied to estimate the Stokes vector at each point. In essence, this process is similar to color filter array (CFA) interpolation or demosaicing. The adopted approach tolerates a 1-pixel registration error to allow for all polarization measurements to be made simultaneously at each pixel. Because it

uses the semiconductor industry standard complementary metal oxide semiconductor (CMOS) fabrication process, this approach offers other significant advantages in terms of manufacturing cost, system volume, weight, power dissipation and system integration on a single silicon chip [17].

A number of micropolarizing devices have been reported in the literature [2, 18–22]. In [18–21], reactive-ion-etching (RIE) was used to pattern dichroic polymer films and form a micropolarizer array (MPA) capable of extracting (S_0, S_1, S_2) for partial-linear polarization imaging (PLPI). In [2], Momeni *et al.* demonstrated an MPA made of refractive YVO_4 crystal for polarization difference imaging (PDI). An aluminum film was evaporated on top of the YVO_4 crystal then patterned by liftoff to form the birefringent MPA. In [22], Harnett *et al.* presented a liquid-crystal MPA for PDI with evaporated gold films used as orientation layers. Liftoff was subsequently used to pattern the gold film.

1.2 Thesis Objective and Contribution

All previously reported micropolarizer implementations suffer from two main limitations:

- use of selective etching to pattern polarizer elements at the pixel pitch, which is a difficult process to control at the micrometer scale, and
- incomplete polarization signature since the circular polarization component cannot be extracted. This circularly polarized component is crucial to fully determine the polarization state of light since, in general, a ray will be elliptically polarized, that is, it can be decomposed into a linear and circular polarization vector [6].

The objective of this research is to alleviate the above limitations and enable the development of the first miniature CMOS single-chip polarization

camera capable of capturing simultaneously all possible polarization states of incident light. To this end, this thesis investigates and demonstrates a number of novel MPA designs and fabrication technologies. All of the developed micropolarizer fabrication technologies completely remove the need for selective etching. Instead, the well-controlled-process of ultraviolet (UV) photolithography is used to enable the patterning of a high resolution pixel-level MPA layer with submicron thickness. Another unique feature of the targeted MPA is that it could be fabricated using standard and well-established CMOS manufacturing flows, enabling low-cost mass production. The developed MPA designs and fabrication technologies can be summarized as follows:

- For PDI, we propose a superior high resolution photo-patterned liquid-crystal (LC) MPA fabrication technology that enables one to control the values of the extinction ratio and transmittance by simply selecting a suitable commercially available linear polarizer for the targeted application. A $2\mu\text{m}$ -pitch is achieved by using UV light to define the orientation of the micropolarizer elements. Reported experimental results validate the high performance photo-aligned LC MPA.
- For PLPI, the well-controlled-process of UV photoalignment is proposed to define micropolarizer orientation patterns on a spin-coated azo-dye-1 (AD1) film. This non-contact photoalignment technique dramatically scales-down the micropolarizing elements' pitch size and thickness. The latter one directly impacts on the the signal cross-talk for scenes captured with large angle oblique incidence. To further improve its optical performance, a “guest-host” MPA based on nematic polymerizable liquid crystal (PLC) is proposed. With dichroic AD1 molecules as the “guest” and PLC molecules as the “host”, the limited orientation degree of the UV-oriented AD1 molecules is significantly enhanced. As a result, the micropolarizer's two most important figures of merit, which are the major principal transmittance and the extinction ratio (ER), are dramatically improved. Reported experimental results validate this improvement by a

~25% increase of the major principal transmittance and a 139% increase of the peak ER. Moreover, the fabricated “guest-host” MPA features a compact micropolarizer pitch of $5\mu m \times 5\mu m$ and a submicron overall MPA thickness of $0.95\mu m$.

- The first micropolarimeter array enabling circular polarization imaging, which has been so far discarded in prior implementations. The micropolarimeter array was implemented by fabricating PLC micro-retarders with perpendicular fast axes on top of a 45° oriented visible-regime metal-wire-grid polarizer (MWGP).
- The first micropolarimeter array for full Stokes polarization imaging. Its pattern consists of four different micropolarimeters for simultaneously analyzing 0° , 90° , 45° linearly polarized and right-handed circularly polarized components of visible incident light. The micropolarimeter array is implemented by micropatterning a thin LC layer and an indium tin oxide (ITO) layer on top of a 45° oriented visible-regime MWGP. In contrast to previously reported MPAs, the proposed implementation enables, for the first time, the extraction of circularly polarized components of light for real-time full Stokes polarimetry. To accommodate applications with large oblique incidence angle, a 150nm ultra-thin visible-regime MWGP is used to reduce the overall thickness of the micropolarimeter array layer to $5\mu m$. This provides a relatively good aspect ratio for pixel size larger than $10\mu m$. Experimental results indicate that the LC-MWGP structure retains MWGP’s superior optical characteristics with a pass transmittance of 75% and ERs of around 1100.

1.3 Thesis Organization

This thesis is organized as follows. Chapter 2 reviews traditional intensity and color image sensing techniques before discussing existing polarization image

sensing techniques. The definitions of Stokes parameters, Stokes vector and Mueller matrix are also briefly reviewed. The last part of the chapter presents the architecture of CMOS polarization image sensor with fully integrated micropolarizing devices. Featuring compactness, low power consumption and low fabrication cost, the proposed sensor enables not only real-time polarization image sensing but also focal plane processing.

Chapter 3 reviews, analyzes and discusses previously reported MPA implementations. The design, fabrication and optical characterization of reflective-type MWGP based LC MPA for PDI are described. Subsequently, the photo-aligned AD1 MPA for PLPI is presented. To further improve its optical performance, a “guest-host” micropolarizing system based on polymerizable nematic liquid crystal is proposed and presented in the following section. Reported experimental results show a significant improvements in terms of major principal transmittance and ER.

Chapter 4 introduces the optical design, modeling, fabrication and characterization of the first micropolarimeter array for circular polarization imaging. The recently discovered circular polarization vision ability of some ocean creatures is also described to illustrate practical uses of circular polarization imaging.

Chapter 5 presents the first micropolarimeter array enabling full Stokes polarization imaging in visible spectrum. The proposed micropolarimeter is fabricated by patterning an LC layer on top of a visible-regime MWGP using UV sensitive sulfonic-dye-1 (SD1) as the LC photoalignment material. This arrangement enables the formation of either micrometer-scale LC polarization rotators, neutral density filters or quarter wavelength retarders. These elements are in turn exploited to acquire all components of the Stokes vector, which describes all possible polarization states of light. The proposed liquid-crystal micropolarimeter array can be integrated on top of a CMOS image sensor for real-time full Stokes polarization imaging. Optical design and fabri-

cation of the liquid-crystal based micropolarimeter array for full Stokes imaging is detailed. Its optical properties are evaluated to validate the proposed approach.

Chapter 6 concludes this thesis and proposes future research work.

Chapter 2

Stokes Polarization Imaging and Polarization Image Sensors

2.1 Introduction

Light possesses three detectable properties that are intensity, color (wavelength) and polarization. The latter can be fully described by four measurable quantities known as Stokes parameters and their column matrix expression is called Stokes vector. When an incident light beam interacts with matter, its polarization state, represented by the Stokes vector, can change. Traditional imaging systems are sensitive to intensity and color but are “blind” to light polarization. In this chapter, we review traditional intensity and color image sensing techniques before discussing existing polarization image sensing techniques. We also briefly review the definitions of Stokes parameters, Stokes vector and Mueller matrix. The last part of the chapter presents the architecture of CMOS polarization image sensor with fully integrated micropolarizing devices. Featuring compactness, low power consumption and low fabrication cost, the proposed sensor enables not only real-time polarization image sensing but also focal plane processing.

2.2 Intensity and Color Imaging Techniques

Overview

2.2.1 Intensity Imaging

Light intensity is defined as the time average of light vector's instantaneous amplitudes. It is probably the only measurable quantity of the optical field [3]. In order to measure intensity, a semiconductor based solid-state photodetector (abbreviated to “photodetector” hereafter) is used. The photodetector is capable of converting optical energy into electrical energy by absorbing photons of different wavelengths, provided that the photons' energy ($E = h\nu = hc/\lambda$) is greater than the bandgap of the semiconductor material (1.12eV for silicon). As a result, electron-hole pairs can be generated during the photon absorption process, where the number of generated electron-hole pairs is proportional to the number of absorbed photons. With the fast generation of the electron-hole pairs, there is another opposite mechanism—recombination. In other words, the photo-generated electron-hole pairs will recombine if there is no effective way to collect them. By applying an electric field to the photon absorption region, the photodetectors can separate and capture the electron-hole pairs. There are two mainstream solid-state photodetectors using different ways to provide the electric field, which are charge coupled device (CCD) with externally added electric field on its metal-oxide-semiconductor (MOS) capacitor and CMOS image sensor with build-in field in its photodiode's pn-junction. In the following, we review the operation principle of a pn-junction photodiode. Its forward current I_F is expressed as

$$I_F = I_{diff}[\exp(\frac{qV}{nkT}) - 1] \quad (2.1)$$

where n is an ideal factor, V is the added voltage, k is the Boltzmann constant, T is the temperature, q is the electric charge and I_{diff} is the diffusion current,

which is given by

$$I_{diff} = qA\left(\frac{D_n}{L_n}n_{po} + \frac{D_p}{L_p}p_{no}\right) \quad (2.2)$$

where $D_{n,p}$, $L_{n,p}$, n_{po} and p_{no} are the diffusion coefficient, diffusion length, minority carrier concentration in the p-type region and the minority carrier concentration in n-type region, respectively. A is the cross-section area of the pn-junction. The photocurrent of the pn-junction photodiode is expressed as follows:

$$I_L = I_{ph} - I_F = I_{ph} - I_{diff}\left[\exp\left(\frac{qV}{nkT}\right) - 1\right] \quad (2.3)$$

where I_{ph} is the photocurrent. When a photodiode is reverse biased, the exponential term in Eq.(2.3) can be neglected and thus I_L becomes

$$I_L \approx I_{ph} + I_{diff} \quad (2.4)$$

It is indicated that the output current of the photodiode is equal to the sum of the photocurrent and diffusion current. Therefore, the photocurrent is proportional to the input light intensity.

2.2.2 Color Imaging

Color imaging is a process that separates the different spectral components of incident light. Since intensity is the only measurable quantity, a photodetector is needed for measuring each separated spectral component. There are three existing ways to separate/filter the different spectral components of light:

- Dichroic mirrors with three image sensors. As shown in Figure 2.1, the photodetector arrays of three image sensors are used for sensing red, green and blue components, respectively. To separate the incident light into three beams with different colors, two dichroic mirrors are exploited.

Figure 2.1: Color image sensing technique with three image sensors.

Although high color-fidelity can be achieved with this configuration, it requires complex and expensive optics. It is mainly used in broadcasting systems, where high-quality images are required.

- CFA, which is essentially a mosaic of tiny color filters placed over the pixel sensors of an image sensor to capture color information. The full visible spectrum can be covered by the combinations of red, green and blue components (also known as RGB color representation) or cyan, magenta and yellow components (also known as CMY color representation). The relationship between the CMY and the RGB color representations can be expressed as follows:

$$Ye = R + G \quad (2.5)$$

$$Mg = R + B \quad (2.6)$$

$$Cy = G + B \quad (2.7)$$

With photodetectors covered by these micrometer-scale RGB or CMY color filters, light components with different wavelengths can be simultaneously captured to construct the color image. Figure 2.2 presents two

commonly-used CFA patterns for the RGB representation [30].

Figure 2.2: Commonly-used color filter array patterns for the RGB representation.

Figure 2.3: Spectral curves of the absorption coefficient and the penetration depth for silicon [31].

- Triple-well structure — For an incident monochromatic light beam penetrating the silicon substrate, the generation rate of electron-hole pair is a function of its wavelength and the distance to the surface. The depth at which the intensity of the incident light penetrating the material falls to $1/e$ (about 37%) of the original value at the surface is defined as the penetration depth. According to Beer-Lambert law, the intensity of an electromagnetic wave inside a material falls exponentially from the surface as:

$$I(z) = I_0 e^{-\alpha z} \quad (2.8)$$

where z is the distance to the surface and α is the absorption coefficient. The penetration depth denoted as δ is equal to $1/\alpha$.

Figure 2.4: Cross-section of the triple-well structure for color imaging.

Figure 2.5: Spectral response of a triple-well structure with UMC $0.18\mu\text{m}$ process.

Figure 2.3 shows the spectral curves of the absorption coefficient and the penetration depth for silicon. In order to effectively capture the light components with different wavelengths, a triple-well structure in Figure 2.4 was proposed [31]. With blue photons captured at a depth of $\sim 0.2\mu\text{m}$, green photons captured at a depth of $\sim 0.6\mu\text{m}$ and red photons captured at a depth of $\sim 2\mu\text{m}$, the need of fabricating expensive CFA is

completely removed. Figure 2.5 presents the spectral response of a NPNP triple-well structure using UMC $0.18\mu m$ CMOS standard process [32,33].

2.3 Stokes Parameters and Stokes Polarization Imaging

2.3.1 Stokes Parameters

Light phenomena can be accurately explained by using the notion of electromagnetic field propagating as wave through different media, with the wave vibrating in a direction perpendicular to the propagation direction. As shown in Figure 2.6, the transverse components are represented by:

$$E_x(z, t) = E_{0x} \cos(\omega t - kz + \delta_x) \quad (2.9)$$

$$E_y(z, t) = E_{0y} \cos(\omega t - kz + \delta_y) \quad (2.10)$$

where E_{0x} and E_{0y} are the instantaneous amplitudes at time t along the x and y coordinates, δ_x and δ_y are the instantaneous phase factors, and ω is the instantaneous angular frequency.

Figure 2.6: Propagation of the transverse optical field.

Here, we consider a pair of plane waves that are orthogonal to each other

at a point in space, $z = 0$ is taken for convenience, so Eq.(2.9) and Eq.(2.10) can be rewritten as:

$$E_x(t) = E_{0x}(t)\cos[\omega t + \delta_x(t)] \quad (2.11)$$

$$E_y(t) = E_{0y}(t)\cos[\omega t + \delta_y(t)] \quad (2.12)$$

The polarization state of light is defined as the path traced by the tip of the electric field as the wave propagates. However, the amplitude of the optical field cannot be observed. It is *Sir George Gabriel Stokes* (1819-1903) who defined four measurable quantities known as Stokes parameters to represent the polarization state in terms of observables [3]. These quantities are intensities and can be derived by taking a time average of the polarization ellipse:

$$\frac{E_x^2(t)}{E_{0x}^2(t)} + \frac{E_y^2(t)}{E_{0y}^2(t)} - 2\frac{E_x(t)}{E_{0x}(t)}\frac{E_y(t)}{E_{0y}(t)}\cos\delta(t) = \sin^2\delta(t) \quad (2.13)$$

where $\delta(t) = \delta_y(t) - \delta_x(t)$. Here the time average is represented by the symbol $\langle \dots \rangle$, so we write Eq.(2.13) as:

$$\frac{\langle E_x^2(t) \rangle}{E_{0x}^2} + \frac{\langle E_y^2(t) \rangle}{E_{0y}^2} - 2\frac{\langle E_x(t)E_y(t) \rangle}{E_{0x}E_{0y}}\cos\delta = \sin^2\delta \quad (2.14)$$

where

$$\langle E_x(t)E_y(t) \rangle = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T E_x(t)E_y(t)dt \quad (2.15)$$

Multiplying Eq.(2.14) by $4E_{0x}^2E_{0y}^2$, we can have:

$$\begin{aligned} 4E_{0y}^2\langle E_x^2(t) \rangle + 4E_{0x}^2\langle E_y^2(t) \rangle - 8E_{0x}E_{0y}\langle E_x(t)E_y(t) \rangle\cos\delta \\ = (2E_{0x}E_{0y}\sin\delta)^2 \end{aligned} \quad (2.16)$$

From Eq.(2.11) and Eq.(2.12), we can find the average values of Eq.(2.16):

$$\langle E_x^2(t) \rangle = \frac{1}{2}E_{0x}^2 \quad (2.17)$$

$$\langle E_y^2(t) \rangle = \frac{1}{2} E_{0y}^2 \quad (2.18)$$

$$\langle E_x(t) E_y(t) \rangle = \frac{1}{2} E_{0x} E_{0y} \cos \delta \quad (2.19)$$

Substituting Eq.(2.17), Eq.(2.18) and Eq.(2.19) into Eq.(2.16) yields:

$$2E_{0x}^2 E_{0y}^2 + 2E_{0x}^2 E_{0y}^2 - (2E_{0x} E_{0y} \cos \delta)^2 = (2E_{0x} E_{0y} \sin \delta)^2 \quad (2.20)$$

In order to express the final result in terms of intensity, we add and subtract the quantity $E_{0x}^4 + E_{0y}^4$ to the left-hand side of Eq.(2.20). Upon doing this and grouping terms, we are led to the following equation:

$$(E_{0x}^2 + E_{0y}^2)^2 - (E_{0x}^2 - E_{0y}^2)^2 - (2E_{0x} E_{0y} \cos \delta)^2 = (2E_{0x} E_{0y} \sin \delta)^2 \quad (2.21)$$

Now the quantities inside the parentheses can be written as [3]:

$$S_0 = E_{0x}^2 + E_{0y}^2 \quad (2.22)$$

$$S_1 = E_{0x}^2 - E_{0y}^2 \quad (2.23)$$

$$S_2 = 2E_{0x} E_{0y} \cos \delta \quad (2.24)$$

$$S_3 = 2E_{0x} E_{0y} \sin \delta \quad (2.25)$$

The four equations in Eq.(2.22), Eq.(2.23), Eq.(2.24) and Eq.(2.25) are the Stokes parameters for a plane wave. The first Stokes parameter S_0 represents the total intensity of the light. The second parameter S_1 describes the amount of linear horizontal or vertical polarization, the third parameter S_2 describes the amount of linear $+45^\circ$ or -45° polarization and the fourth parameter S_3 describes the amount of right-handed or left-handed circular polarization. All the four Stokes parameters are real quantities and expressed in terms of intensities. In order to bypass the time-averaging process for obtaining the Stokes parameters of an optical beam, the real optical amplitudes can be represented

in terms of complex amplitudes:

$$E_x(t) = E_{0x} \exp[i(\omega t + \delta_x)] = E_x \exp(i\omega t) \quad (2.26)$$

$$E_y(t) = E_{0y} \exp[i(\omega t + \delta_y)] = E_y \exp(i\omega t) \quad (2.27)$$

where

$$E_x = E_{0x} \exp(i\delta_x) \quad (2.28)$$

$$E_y = E_{0y} \exp(i\delta_y) \quad (2.29)$$

Now we can obtain the Stokes parameters from the formulas:

$$S_0 = E_x E_x^* + E_y E_y^* \quad (2.30)$$

$$S_1 = E_x E_x^* - E_y E_y^* \quad (2.31)$$

$$S_2 = E_x E_y^* + E_y E_x^* \quad (2.32)$$

$$S_3 = i(E_x E_y^* - E_y E_x^*) \quad (2.33)$$

The four Stokes parameters can be arranged in a column matrix and written as

$$S = \begin{bmatrix} S_0 & S_1 & S_2 & S_3 \end{bmatrix}^T \quad (2.34)$$

The Stokes parameters in column matrix is denoted as Stokes vector. The following cases are considered as examples of the representation of polarized light in terms of the Stokes parameters [3]:

- Linear horizontal polarized light: For this case, $E_{0y} = 0$, then we have:

$$\begin{bmatrix} S_0 & S_1 & S_2 & S_3 \end{bmatrix}^T = \begin{bmatrix} I_0 & I_0 & 0 & 0 \end{bmatrix}^T = I_0 \cdot \begin{bmatrix} 1 & 1 & 0 & 0 \end{bmatrix}^T \quad (2.35)$$

where $I_0 = E_{0x}^2$ is the total intensity.

- Linear vertical polarized light: For this case, $E_{0x} = 0$, then we have:

$$\begin{bmatrix} S_0 & S_1 & S_2 & S_3 \end{bmatrix}^T = \begin{bmatrix} I_0 & -I_0 & 0 & 0 \end{bmatrix}^T = I_0 \cdot \begin{bmatrix} 1 & -1 & 0 & 0 \end{bmatrix}^T \quad (2.36)$$

where $I_0 = E_{0y}^2$ is the total intensity.

- Linear $+45^\circ$ polarized light: For this case, $E_{0x} = E_{0y} = E_0$ and $\delta = 0$, then we have:

$$\begin{bmatrix} S_0 & S_1 & S_2 & S_3 \end{bmatrix}^T = \begin{bmatrix} I_0 & 0 & I_0 & 0 \end{bmatrix}^T = I_0 \cdot \begin{bmatrix} 1 & 0 & 1 & 0 \end{bmatrix}^T \quad (2.37)$$

where $I_0 = 2E_0^2$ is the total intensity.

- Linear -45° polarized light: For this case, $E_{0x} = E_{0y} = E_0$ and $\delta = \pi$, then we have:

$$\begin{bmatrix} S_0 & S_1 & S_2 & S_3 \end{bmatrix}^T = \begin{bmatrix} I_0 & 0 & -I_0 & 0 \end{bmatrix}^T = I_0 \cdot \begin{bmatrix} 1 & 0 & -1 & 0 \end{bmatrix}^T \quad (2.38)$$

where $I_0 = 2E_0^2$ is the total intensity.

- Right-handed circularly polarized light: For this case, $E_{0x} = E_{0y} = E_0$ and $\delta = \pi/2$, then we have:

$$\begin{bmatrix} S_0 & S_1 & S_2 & S_3 \end{bmatrix}^T = \begin{bmatrix} I_0 & 0 & 0 & I_0 \end{bmatrix}^T = I_0 \cdot \begin{bmatrix} 1 & 0 & 0 & 1 \end{bmatrix}^T \quad (2.39)$$

where $I_0 = 2E_0^2$ is the total intensity.

- Left-handed circularly polarized light: For this case, $E_{0x} = E_{0y} = E_0$ and $\delta = -\pi/2$, then we have:

$$\begin{bmatrix} S_0 & S_1 & S_2 & S_3 \end{bmatrix}^T = \begin{bmatrix} I_0 & 0 & 0 & -I_0 \end{bmatrix}^T = I_0 \cdot \begin{bmatrix} 1 & 0 & 0 & -1 \end{bmatrix}^T \quad (2.40)$$

where $I_0 = 2E_0^2$ is the total intensity.

2.3.2 Mueller Matrix

In classical optics, Mueller matrix, as the matrix representation of the Stokes parameters, is a powerful mathematical tool for describing the interaction between the incident light and any arbitrary optical polarizing element. Figure 2.7 shows an incident beam interacting with a polarizing element. Suppose the incident beam's Stokes parameters are represented by S_i and the emerging beam's Stokes parameters are represented by S'_i , where $i = 0, 1, 2, 3$.

Figure 2.7: Interaction between the incident light and arbitrary polarizing element.

By assuming that S'_i can be expressed as a linear combination of the four Stokes parameters of the incident beam, we can have:

$$S'_0 = m_{00}S_0 + m_{01}S_1 + m_{02}S_2 + m_{03}S_3 \quad (2.41)$$

$$S'_1 = m_{10}S_0 + m_{11}S_1 + m_{12}S_2 + m_{13}S_3 \quad (2.42)$$

$$S'_2 = m_{20}S_0 + m_{21}S_1 + m_{22}S_2 + m_{23}S_3 \quad (2.43)$$

$$S'_3 = m_{30}S_0 + m_{31}S_1 + m_{32}S_2 + m_{33}S_3 \quad (2.44)$$

In matrix form it is written as:

$$\begin{bmatrix} S'_0 \\ S'_1 \\ S'_2 \\ S'_3 \end{bmatrix} = \begin{bmatrix} m_{00} & m_{01} & m_{02} & m_{03} \\ m_{10} & m_{11} & m_{12} & m_{13} \\ m_{20} & m_{21} & m_{22} & m_{23} \\ m_{30} & m_{31} & m_{32} & m_{33} \end{bmatrix} \cdot \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} \quad (2.45)$$

or

$$S' = M \cdot S \quad (2.46)$$

where S and S' are the Stokes vectors of the incident light and the emerging light, respectively; the 4×4 matrix M is known as the Mueller matrix, which was introduced by Hans Mueller during the early 1940s [3].

When an incident beam interacts with an optical polarizing element, its polarization state is always changed. The polarization state can be changed through the following ways:

- changing the amplitudes.
- changing the phase.
- changing the direction of the orthogonal field components.
- transferring energy from the polarized states to the unpolarized state.

An optical element that changes the orthogonal amplitudes unequally is called a polarizer or diattenuator; an optical element that introduces a phase shift between the orthogonal components is called a phase retarder or phase shifter. If the optical device rotates the orthogonal components of the incident beam through an angle θ as it passes through the element, it is called a polarization rotator. Finally, if energy in polarized states goes to the unpolarized state, the element is a depolarizer. These effects can be easily understood from Eq.(2.9) and Eq.(2.10), where the incident light's polarization state can be changed by varying the amplitudes, E_{0x} or E_{0y} , or the phase δ_x/δ_y and finally, the direction of $E_x(z, t)$ and $E_y(z, t)$. In this thesis, linear polarizer, phase retarder and polarization rotator are introduced for the optical design of micropolarizing devices, therefore, the Mueller matrices of a linear polarizer, a phase retarder and a polarization rotator are presented as follows [3]:

- $M_{linearpolarizer}$: Mueller matrix of a linear polarizer with its pass transmission axis at an angle θ with respect to x-axis:

$$\begin{bmatrix} A & B\cos 2\theta & B\sin 2\theta & 0 \\ B\cos 2\theta & A\cos^2 2\theta + C\sin^2 2\theta & (A-C)\sin 2\theta \cos 2\theta & 0 \\ B\sin 2\theta & (A-C)\sin 2\theta \cos 2\theta & A\sin^2 2\theta + C\cos^2 2\theta & 0 \\ 0 & 0 & 0 & C \end{bmatrix} \quad (2.47)$$

with

$$A = \frac{p_x^2 + p_y^2}{2} \quad (2.48)$$

$$B = \frac{p_x^2 - p_y^2}{2} \quad (2.49)$$

$$C = p_x p_y \quad (2.50)$$

and where the quantities p_x and p_y are the absorption coefficients of the orthogonal optical axes ($0 \leq p_x, p_y \leq 1$). An ideal linear polarizer is one which has transmission along only one axis and no transmission along the orthogonal axis (i.e. $p_x = 1, p_y = 0$ or $p_x = 0, p_y = 1$).

- $M_{retarder}$: Mueller matrix of a phase retarder with a phase shift of ϕ :

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos \phi & \sin \phi \\ 0 & 0 & -\sin \phi & \cos \phi \end{bmatrix} \quad (2.51)$$

- $M_{rotator}$: Mueller matrix of a polarization rotator with a polarization rotation angle α :

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\alpha & \sin 2\alpha & 0 \\ 0 & -\sin 2\alpha & \cos 2\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2.52)$$

2.3.3 Stokes Parameters Measurement

There are many methods for measuring Stokes parameters, the most straightforward and probably best known one was proposed by Stokes, that is the quarter-wave retarder polarizer method [3]. Figure 2.8 presents the configuration of the measurement. The Mueller matrix of an ideal linear polarizer with its pass transmission axis set at an angle of θ is:

$$M_{ILP}(\phi) = \frac{1}{2} \begin{bmatrix} 1 & \cos 2\theta & \sin 2\theta & 0 \\ \cos 2\theta & \cos^2 2\theta & \sin 2\theta \cos 2\theta & 0 \\ \sin 2\theta & \sin 2\theta \cos 2\theta & \sin^2 2\theta & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (2.53)$$

Figure 2.8: Classical Stokes parameters measurement configuration.

From Eq.(2.51) and Eq.(2.53), the Stokes vector S'' of the emerging light in Figure 2.8 is:

$$S'' = M_{ILP} \cdot M_{retarder} \cdot S \quad (2.54)$$

where S is the Stokes vector of the incident light, M_{ILP} is the Mueller matrix of an ideal linear polarizer and $M_{retarder}$ is the Mueller matrix of a retarder. Since only the first Stokes parameter (i.e. total intensity) is measurable, the

intensity of the emerging light from the retarder-polarizer combination S_0'' is:

$$S_0'' = I(\theta, \phi) = \frac{1}{2}[S_0 + S_1 \cos 2\theta + S_2 \sin 2\theta \cos \phi + S_3 \sin 2\theta \sin \phi] \quad (2.55)$$

Eq.(2.55) was first introduced by Stokes and known as Stokes' intensity relation for the Stokes parameters. The Stokes parameters are then found by setting different values for θ and ϕ . In fact, one set of (θ, ϕ) corresponds to one optical polarizing device. Mathematically, at least four intensity measurements with four different optical polarizing devices having four different values of (θ, ϕ) are needed to extract all the Stokes parameters in Eq.(2.55). The four Stokes parameters can then be expressed by the linear combinations of the emerging light intensities after transmitting through the four different optical polarizing devices:

$$S_0 = C_{00} \cdot I_0(\theta_0, \phi_0) + C_{01} \cdot I_1(\theta_1, \phi_1) + C_{02} \cdot I_2(\theta_2, \phi_2) + C_{03} \cdot I_3(\theta_3, \phi_3) \quad (2.56)$$

$$S_1 = C_{10} \cdot I_0(\theta_0, \phi_0) + C_{11} \cdot I_1(\theta_1, \phi_1) + C_{12} \cdot I_2(\theta_2, \phi_2) + C_{13} \cdot I_3(\theta_3, \phi_3) \quad (2.57)$$

$$S_2 = C_{20} \cdot I_0(\theta_0, \phi_0) + C_{21} \cdot I_1(\theta_1, \phi_1) + C_{22} \cdot I_2(\theta_2, \phi_2) + C_{23} \cdot I_3(\theta_3, \phi_3) \quad (2.58)$$

$$S_3 = C_{30} \cdot I_0(\theta_0, \phi_0) + C_{31} \cdot I_1(\theta_1, \phi_1) + C_{32} \cdot I_2(\theta_2, \phi_2) + C_{33} \cdot I_3(\theta_3, \phi_3) \quad (2.59)$$

where $I_i(\theta_i, \phi_i)$ ($i = 0, 1, 2, 3$) is the emerging light intensities after passing four different optical polarizing devices, C_{ij} ($i, j = 0, 1, 2, 3$) is the coefficient matrix.

2.3.4 Stokes Polarization Imaging

In the above analysis, there is always an assumption that the incident light's polarization state, which is fully described by Stokes vector, is spatially uniform. Actually, the incident beams' polarization states in real world are far more complex, as it could be directly emitted from a light source or reflected by some object(s) in an imaged scene. Therefore, there is always a non-uniform spatial distribution of the incident beams' Stokes vectors. Traditional intensity

imaging is a well-known technique to capture the incident beams' spatial intensity distribution. In order to extract the Stokes vector of every spatial location in the image scene, a novel technique known as Stokes polarization imaging was proposed to visualize the world in terms of polarization. A typical Stokes polarization imaging system consists of three fundamental building blocks: an optical lens, a polarizing layer and a two-dimensional photodetector array. A complete set of Stokes polarization images includes four images corresponding to the four Stokes parameters S_0 , S_1 , S_2 and S_3 , which are also named S_0 image, S_1 image, S_2 image and S_3 image. The generation of S_0 image, S_1 image, S_2 image and S_3 image are named S_0 imaging, S_1 imaging, S_2 imaging and S_3 imaging. In fact, the intensity imaging is included by the Stokes polarization imaging because intensity of light is just the first parameter of the Stokes vector (S_0). In other words, Stokes polarization images are more general than intensity image and provide a much richer description of an imaged scene [3]. As previously mentioned, four times intensity measurements are needed for every pixel of Stokes images. As a result, every pixel is associated with a 4×4 coefficient matrix. For mega-pixels photodetector arrays, the total amount of calculations required to estimate the Stokes parameters is prohibitively high. Mathematically, the most effective way to reduce the amount of calculations, is to simplify the coefficient matrix by exploiting different optical polarizing system designs.

In this thesis, to enable different polarization imaging applications, we propose different combinations of optical polarizing devices.

For PDI [7], which requires the extraction of S_0 and S_1 , we use:

$$S_0 = I(0^\circ, 0^\circ) + I(90^\circ, 0^\circ) \quad (2.60)$$

$$S_1 = I(0^\circ, 0^\circ) - I(90^\circ, 0^\circ) \quad (2.61)$$

where $I(0^\circ, 0^\circ)$ represents 0° linear polarizer and $I(90^\circ, 0^\circ)$ represents 90° linear polarizer.

For PLPI, which requires the extraction of S_0 , S_1 and S_2 , we use:

$$S_0 = I(0^\circ, 0^\circ) + I(90^\circ, 0^\circ) \quad (2.62)$$

$$S_1 = I(0^\circ, 0^\circ) - I(90^\circ, 0^\circ) \quad (2.63)$$

$$S_2 = I(45^\circ, 0^\circ) - I(-45^\circ, 0^\circ) \quad (2.64)$$

where $I(0^\circ, 0^\circ)$ represents 0° linear polarizer, $I(90^\circ, 0^\circ)$ represents 90° linear polarizer, $I(45^\circ, 0^\circ)$ represents 45° linear polarizer and $I(-45^\circ, 0^\circ)$ represents -45° linear polarizer.

For circular polarization imaging, which requires the extraction of S_0 and S_3 , we use:

$$S_0 = I(45^\circ, 90^\circ) + I(45^\circ, -90^\circ) \quad (2.65)$$

$$S_3 = I(45^\circ, 90^\circ) - I(45^\circ, -90^\circ) \quad (2.66)$$

where $I(45^\circ, 90^\circ)$ represents 90° phase retarder/ 45° linear polarizer combination and $I(45^\circ, -90^\circ)$ represents -90° phase retarder/ 45° linear polarizer combination.

2.4 Solid-State Polarization Image Sensors

Solid-state image sensors are key components of digital cameras and multimedia devices. There are two mainstream solid-state imaging technologies: CCD and CMOS image sensors. Invented by W. Boyle and G. Smith at Bell Laboratory in 1970, CCDs dominated the market for several decades because they offer smaller pixel size and lower noise compared with its CMOS counterpart. From the 1990s, CMOS image sensors started to become competitive through their inherent advantages of lower power, lower cost, and capability of integrating both the image sensing and processing functions together on a single silicon chip. Like the vast majority of commercially available camera systems,

CMOS image sensors are essentially designed to image the world in terms of intensity and color. However, they are “blind” to the third characteristic of light that is polarization. There are three main approaches to make commercially available CMOS cameras polarization-sensitive: (i) multiple-frame polarization image sensing with unpatterned polarizing device, which requires several successive frames to capture complete polarization information; (ii) simultaneous polarization image sensing combining a beam splitting prism and multiple image sensors and (iii) simultaneous polarization image sensing by patterning micropolarizing devices on top of the image sensor. The above three technologies are described and compared in the following subsections.

2.4.1 Multiple-frame Polarization Image Sensing with Unpatterned Polarizing Devices

Figure 2.9: First generation polarization image sensor with mechanically-controlled unpatterned polarizing devices.

Traditional image sensing systems are geared towards capturing intensity images rather than polarization images. The first generation polarization image sensor was implemented by mounting a linear polarizing filter in front of an intensity image sensor and mechanically rotating the filter by hand or motor

into different orientations (Figure 2.9). Polarization images can then be generated in several successive frames. The obvious drawback of this approach is that both the scene and the camera must be stationary across multiple frames, to avoid introducing interframe motion. In addition, it is necessary to compensate for mechanical misalignment of the rotated linear polarizer. Complex image processing algorithms are thus required to address the aforementioned issues. Wolff *et al.* [14] proposed to replace the mechanically controlled linear

Figure 2.10: Unpatterned TNLC based polarization image sensor.

polarizer with an unpatterned twisted nematic liquid crystal (TNLC) based polarizing device, which can be electrically-configured to extract different polarized components of the incident light (Figure 2.10) [29, 34, 35]. This implementation indeed obviates the need for mechanical rotating, however, it suffers from several inherent disadvantages of unpatterned polarizing devices:

- Since they are based on an electrically-controlled polarizing device, a complex control unit is necessary to synchronize the polarizing device with the image sensing circuitry. This makes the system bulkier, more expensive and power hungry.
- Unpatterned polarizing devices exclude the possibility of real-time polarization image sensing and processing.

- Large storage silicon area is necessary to record the first generated polarization images until all the others are ready for further processing.

2.4.2 Simultaneous Polarization Image Sensing with Beam Splitting Prism

As mentioned in Section 2.4.1, there is a fundamental performance limit in the multiple-frame polarization image sensing technique because several frames are used to achieve acquisition of all polarization images, making data inherently uncorrelated in time. To eliminate the errors caused by the interframe motion, Barter *et al.* proposed a simultaneous polarization image sensing technique [15, 16]. As shown in Figure 2.11, the different polarization components of incident light are separated by sophisticated beam splitting prism and sensed by multiple image sensors. Although all the polarization images are captured at the same time, the problem becomes spatial registration since each image sensor will image the scene from a slightly different perspective. Spatial registration is complicated by the need to compensate for both mechanical misalignment and aberrations due to separate optical paths.

Figure 2.11: Simultaneous polarization image sensing technique with beam splitting prism and multiple image sensors.

2.4.3 Simultaneous Polarization Image Sensing with Patterned Micropolarizing Devices

Patterned micropolarizing devices are trading-off spatial resolution to generate the complete set of polarization images in a single frame. Real-time polarization image sensing and processing are thus enabled. Furthermore, recent advances in CMOS image sensor technology provide today a unique opportunity to integrate both image sensing and processing together on a single chip, to enable the concept of a high speed, low power, low cost CMOS polarimetric sensor. Commercially available CMOS cameras can be made polarization-sensitive by coating individual pixels with micrometer-scale polarizing elements. Figure 2.12 illustrates the architecture of CMOS polarization image sensor with fully integrated micropolarizing devices.

Figure 2.12: CMOS polarization image sensor with fully integrated micropolarizing devices.

2.5 Conclusion

In this chapter, traditional intensity/color based imaging techniques are first reviewed. In addition, the concepts of Stokes parameters and Stokes polarization imaging are introduced. It is shown that all possible polarization states

can be fully described by the four components of the Stokes vector. Furthermore, existing polarization image sensing techniques are presented and discussed. Finally, the architecture of a fully integrated CMOS polarization image sensor coated with micropolarizing devices is described.

Chapter 3

Micropolarizer Array for Partial Linear Polarization Imaging

3.1 Introduction

In most natural scenes, the light reflected/emitted from objects is partial-linearly polarized [36]. As shown in Figure 3.1, partial-linearly polarized light consists of unpolarized and linearly polarized light. It can be fully described by the first three Stokes parameters S_0 , S_1 and S_2 . Partial linear polarization images, which includes S_0 , S_1 and S_2 images, are more general than intensity image (i.e. S_0 image) and can significantly simplify a wide range of machine vision tasks with natural light source such as sunlight. The partial-linearly polarized incident light can be simultaneously extracted by using four different micropolarizing devices, which are 0° micropolarizer (MP), 90° micropolarizer, 45° micropolarizer and -45° micropolarizer.

In this chapter, previously reported MPA implementations are classified and their limitations are presented in Section 3.2. Section 3.3 presents the optical design and fabrication of the proposed reflective-type liquid-crystal MPA for PDI. Section 3.4 describes the fabricated photo-patterned azo-dye based

Figure 3.1: Composition of partial-linearly polarized light.

MPA for PLPI. In order to further improve the azo-dye molecules' orientation degree and the micropolarizer's optical properties in terms of major principal transmittance and ER, a "guest-host" MPA with PLC as the "host" material and AD1 as the "guest" material is also proposed.

3.2 Overview of Previous Implementations

3.2.1 Classification

In order to extract the different Stokes parameters of the incident light, the incident light's intensity (i.e. S_0) has to be measured through different micropolarizing elements. Since linear polarizer is the only optical device capable of varying the light intensity [3], it is indispensable in micropolarizing device design. Depending on the linear polarizer type, previously proposed MPA implementations can be classified into refractive-type, reflective-type or absorptive-type.

Figure 3.2: Refractive-type MPA based on birefringent YVO_4 crystal.

- Refractive-type

Momeni *et al.* demonstrated a MPA made of birefringent YVO_4 crystal (Figure 3.2). An aluminum film is deposited by evaporation on top of the YVO_4 crystal then patterned by liftoff to form the birefringent MPA [2].

- Reflective-type

1. Gruev *et al.* presented a MPA composed of a dual layer visible-regime patterned MWGP [37–39], which is fabricated by advanced interference lithography. By depositing and reactive-ion-etching an aluminum layer, 80nm wide aluminum wires with 160nm wire pitch can be achieved. The two layers are offset by 45 degree and merged together to form the final MPA (Figure 3.3).
2. Metal interconnection (usually metal 1) of standard CMOS process is used as the reflective-type MPA [40–43].

Figure 3.3: Reflective-type MPA composed of a dual layer visible-regime patterned metal wire grid polarizer.

- Absorptive-type

1. Absorptive-type MPA based on selectively doped/undoped polyvinyl alcohol (PVA) film.
 - a) Kalayjian *et al.* demonstrated a micropolarizer fabrication method by patterning iodine-doped PVA film. Concretely, masking and etching steps are used to undope iodine selectively in regions of PVA. The dichroic effect of said undoped regions is destroyed by removing the iodine from the polymer sheet (Figure 3.4) [44–47].

Figure 3.4: Absorptive-type micropolarizer array based on selectively doped/undoped PVA film.

- b) Guo *et al.* presented a high-resolution micropolarizer array for extracting the first three Stokes parameters by selectively undoping the iodine-doped PVA film (Figure 3.4) [48]. Two state polarization filter arrays with $25\mu m$ spatial resolution and three state polarization filter arrays with $48\mu m$ spatial resolution were demonstrated.
- c) Wang *et al.* disclosed several methods for creating twisted nematic (TN) polymerizable liquid crystal micropolarizers including: (a) two-step UV exposure; (b) e-field alignment; (c) multi-rubbing and (d) photo-induced alignment. Two LC microdomains are formed, one is in TN state and the other one is in isotropic state. In the TN state, LC molecules are twisted by 90° and it is optically equal to a polarization rotator; while in the isotropic state, the arrangement of LC molecules is random [49].
- d) Harnett *et al.* presented a liquid-crystal micropolarizer array with evaporated gold film as the orientation layers. Gold is evaporated to LC substrate with predetermined direction and liftoff is used to pattern the gold film. One more LC microdomain means one more gold evaporation and liftoff. Two

LC microdomains are formed with their gold evaporation directions perpendicular to each other [22].

Figure 3.5: Absorptive-type MPA based on RIE of PVA film or polarization dichroic dye film.

2. Absorptive-type MPA based on RIE of PVA film or polarization dichroic dye film.
 - a) S. M. Faris disclosed several methods of manufacturing micropolarizers: selective bleaching/treating PVA film with patterned photoresist on top, selective PVA film etching (including chemical etching, photochemical etching, excimer laser etching and reactive ion etching) with patterned photoresist on top, mechanical cutting/milling and electrically controlled liquid-crystal cell with patterned ITO electrodes [18].
 - b) Gruev *et al.* demonstrated a dual-tier MPA for extracting partial polarization information. This dual-tier micropolarizer array is formed by multiple laminating and selective reactive ion etching of PVA film. PVA layers are laminated with a predetermined angle between the polarizing axis orientations of different PVA layers (Figure 3.5) [19, 20, 50, 51].
 - c) Guo *et al.* demonstrated a fabrication method of thin-film MPAs.

A dichroic dye material is firstly spin-coated then rubbed to form a thin polarizing film. Reactive ion etching is applied successively to pattern the thin polarizing film (Figure 3.5) [21].

3.2.2 Limitations

Several limitations exist in previous implementations.

- Refractive-type
 1. Refractive crystal has high optical quality but is not amenable to high-resolution fabrication.
 2. Refractive crystal is difficult to handle during fabrication.
 - a) Too soft and susceptible to moisture, such as calcite ($CaCO_3$).
 - b) Mohs hardness too high, such as rutile (TiO_2).
 3. There is a stringent requirement for normal light incidence, which makes the applications with oblique incidence infeasible.
 4. Low spatial resolution due to the large pixel size, which makes the MPA not compatible with advanced high-resolution CMOS imagers. As shown in Figure 3.2, the reported pixel size d in Figure 3.2 is $151.4\mu m$ [2].

Figure 3.6: Comparison between MPAs with different thicknesses when applied to oblique incident light.

5. Thick MPA can induce big cross-talk between neighboring pixels. As illustrated in Figure 3.6, when considering the actual integration of the micropolarizer on top of the image sensor, the thickness of the MPA is indeed an important issue because the level of optical crosstalk between adjacent pixels increases with the thickness of the micropolarizer. The reported YVO_4 crystal thickness c in Figure 3.2 is $887.59\mu m$ [2].

- Reflective-type

1. To be an effective reflective-type polarizer such as MWGP, the metal line width and space should be a small fraction (usually 1/10) of the incident light wavelength, which is $40nm \sim 70nm$ for visible spectrum. Expensive and complex advanced lithography techniques are necessary to pattern the thin metal layer. Those techniques include interference lithography [37–39], electron-beam lithography and nanoimprint lithography [52–54].
2. The use of interconnection metal of standard CMOS process is promising due to its full compatibility with the fabrication of CMOS image sensors. However, the metal of standard CMOS process is used for interconnections between different electronic devices. As a result, process optimization is focused on its electrical properties not optical properties. For instance, most metal interconnections, used in advanced CMOS process, are in copper. The MWGPs based on copper possess poorer optical properties (such as extinction ratio) compared with the ones based on aluminum. Reported ER in [40] is only ~ 10 .

- Absorptive-type

1. Absorptive-type MPA based on selectively doped/undoped PVA film.

- a) Reported micropolarizer pixel size of $25\mu m$ [44, 48] is relatively large.
 - b) Thickness related signal cross-talk with large angle oblique incidence. Technically, it is difficult to manufacture uniformly stretched PVA film with a thickness of less than $10\mu m$. In addition, the need of multiple layers for extracting S_0 , S_1 and S_2 greatly aggravates the situation.
 - c) Complex selective doping/undoping or RIE etching process. There are many sensitive doping/undoping and RIE processing conditions such as gas species and selection ratios of both etching and photoresist (PR) stripping [44, 48]. Moreover, it is difficult to maintain the optical properties of PVA film during the whole process.
2. Absorptive-type MPA based on RIE of PVA film or polarization dichroic dye film.
- a) Rubbing processed dye-based polarizing film can generate dust, electrostatic charges and scratches leading to poor yield.
 - b) To fabricate multiple layers, a protection layer is needed for all the interlayers, making the process more complex.
 - c) Well-treated substrate is needed for the rubbing process.
 - d) Complex and sensitive RIE is needed, which is difficult to control at the micrometer scale.

3.3 Liquid-crystal Micropolarizer Array for Polarization Difference Imaging

A liquid crystal based polarizing device composed of a general twisted nematic liquid crystal (GTNLC) cell and a linear polarizer is inherently a superior candidate for fabricating micropolarizer array. The first GTNLC-based mi-

cropolarizing device was proposed by Harnett *et al.* for polarization-difference imaging [22]. It uses evaporated gold films to align LC molecules and selective etching for patterning, with a minimum pitch of only $100\mu m \times 100\mu m$. In this section, we propose a superior high resolution MPA fabrication technology, which combines an MWGP with a micro-patterned GTNLC. It exhibits a significantly higher spatial resolution and enables one to control the values of the ER and transmittance by simply selecting a suitable commercially available linear polarizer for the targeted applications.

3.3.1 Metal-Wire-Grid Linear Polarizer

An MWGP is a planar array of parallel metal wires. Light emerging from the MWGP, is linearly polarized with its polarization direction perpendicular to the wires. In contrast to an absorptive-type linear polarizer, the linearly polarized component of incident light parallel to the wires is reflected rather than absorbed. To be an effective polarizer, the spacing between the wires should be a small fraction of the wavelength of the incident light. This requirement makes it quite challenging to fabricate a visible-regime MWGP with nanometer-scale metal wire width and spacing (i.e. $40\text{nm} \sim 70\text{nm}$, $1/10$ of the wavelength of visible light). Several publications have paved the way to the

Figure 3.7: Reflective-type metal wire grid polarizer.

patterning nano-scale MWGP for linear polarizer application in visible spec-

trum [52–54]. All of these implementations are compatible with CMOS image sensor fabrication process. A metal layer (usually aluminum) is first deposited on top of the CMOS image sensor substrate. By coating and exposing the photoresist with advanced lithography techniques, such as interference lithography [37–39], electron-beam lithography and nanoimprint lithography [52–54], nanometer-scale patterned PR can be formed on top of the aluminum layer. RIE is then used to complete the metal wire grid patterning. In this thesis, a visible-regime MWGP from Moxtek Inc. was used.

3.3.2 Optical Modeling and Simulation Results

Figure 3.8: Interaction between the incident light and the GTNLC/linear polarizer combination.

GTNLC is an intensity-lossless optical device and can be represented by the combination of a waveplate and a polarization rotator [55]. By orienting the GTNLC alignment layers to arrange the LC molecules, the GTNLC can behave optically as a polarization rotator or a polarization phase retarder, for example. Figure 3.8 shows a polarizing device consisting of a GTNLC and an ideal linear polarizer. LC molecules are oriented by aligning the top alignment layer along one reference direction and the bottom alignment layer along another direction. The twist angle with respect to the above-mentioned reference direction is ϕ . The Mueller matrix of an GTNLC with twist angle ϕ

is given as follows [55]:

$$\begin{aligned}
M_{GTNLC} &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & A & B & C \\ 0 & D & E & F \\ 0 & G & H & K \end{bmatrix} \\
&= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 - 2(c^2 + d^2) & 2(bd - ac) & -2(ad + bc) \\ 0 & 2(ac + bd) & 1 - 2(b^2 + c^2) & 2(ab - cd) \\ 0 & 2(ad - bc) & -2(ab + cd) & 1 - 2(b^2 + d^2) \end{bmatrix}
\end{aligned} \tag{3.1}$$

with

$$a = \cos(\phi)\cos(\chi) + \frac{\phi}{\chi}\sin(\phi)\sin(\chi) \tag{3.2}$$

$$b = \frac{\delta}{\chi}\cos(\phi)\sin(\chi) \tag{3.3}$$

$$c = \sin(\phi)\cos(\chi) - \frac{\phi}{\chi}\cos(\phi)\sin(\chi) \tag{3.4}$$

$$d = \frac{\delta}{\chi}\sin(\phi)\sin(\chi) \tag{3.5}$$

$$\chi^2 = \phi^2 + \delta^2 \tag{3.6}$$

$$\delta = \frac{\pi}{\lambda} \cdot \Delta n \cdot d \tag{3.7}$$

where ϕ is the LC twist angle, d is the LC layer thickness, Δn is the LC birefringence and λ is the wavelength of the incident light. In the design and

fabrication of GTNLC cell, the twist angle ϕ and the cell retardation $\Delta n \cdot d$ are the two main design parameters. The Mueller matrix of a linear polarizer with its pass transmission axis set at an angle of θ is:

$$M_{ILP} = \frac{1}{2} \begin{bmatrix} 1 & \cos 2\theta & \sin 2\theta & 0 \\ \cos 2\theta & \cos^2 2\theta & \sin 2\theta \cos 2\theta & 0 \\ \sin 2\theta & \sin 2\theta \cos 2\theta & \sin^2 2\theta & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (3.8)$$

According to Figure 3.8, Stokes parameters of the emerging light can be expressed as:

$$\begin{bmatrix} S_0'' \\ S_1'' \\ S_2'' \\ S_3'' \end{bmatrix} = M_{ILP} \cdot \begin{bmatrix} S_0' \\ S_1' \\ S_2' \\ S_3' \end{bmatrix} = M_{ILP} \cdot M_{GTNLC} \cdot \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} \quad (3.9)$$

Since the first Stokes parameter S_0 represents the total intensity of the light, the total intensity of the emerging light in Figure 3.8 is:

$$I(\phi, \Delta n \cdot d) = 0.5[S_0 + (A \cos 2\theta + D \sin 2\theta)S_1 + (B \cos 2\theta + E \sin 2\theta)S_2 + (C \cos 2\theta + F \sin 2\theta)S_3] \quad (3.10)$$

If we configure the linear polarize horizontally (i.e. $\theta = 0^\circ$), we can have:

$$I(\phi, \Delta n \cdot d) = 0.5(S_0 + A \cdot S_1 + B \cdot S_2 + C \cdot S_3) \quad (3.11)$$

It is indicated that the total intensity we are interested in is only dependent on the elements A , B and C of the GTNLC Mueller matrix. Using Eq.(3.1), the relationships between the three elements and the twist angle ϕ can be plotted for different retardations ($2\pi\Delta n \cdot d/\lambda$) in Figure 3.9, Figure 3.10 and Figure 3.11, respectively.

Figure 3.9: Relationship between the element A of GTNLC Mueller matrix and the LC twist angle ϕ for different retardations.

Figure 3.10: Relationship between the element B of GTNLC Mueller matrix and the LC twist angle ϕ for different retardations.

Figure 3.11: Relationship between the element C of GTNLC Mueller matrix and the LC twist angle ϕ for different retardations.

From the simulation results in Figure 3.9, Figure 3.10 and Figure 3.11, we can observe the following two points:

- For untwisted ($\phi = 0^\circ$) GTNLC/horizontal linear polarizer combination, the Mueller matrix elements (A, B, C) are always equal to $(1, 0, 0)$, which makes the combination a perfect 0° horizontal linear polarizer: $I(0^\circ, \Delta n \cdot d) = 0.5(S_0 + S_1)$.
- For 90° twisted GTNLC/horizontal linear polarizer combination, if the following Mauguin condition is satisfied:

$$2\pi\Delta n \cdot d \gg \lambda \quad (3.12)$$

or

$$\Delta n \cdot d \gg \lambda \quad (3.13)$$

the Mueller matrix elements (A, B, C) are approximately equal to $(-1, 0, 0)$, which makes the combination an approximate vertical linear polarizer: $I(90^\circ, \Delta n \cdot d) \approx 0.5(S_0 - S_1)$.

Figure 3.12: Color dispersion of the GTNLC Mueller matrix elements A , B and C for 90° twisted GTNLC ($\Delta n = 0.225$, $d = 5 \mu m$).

Figure 3.13: Color dispersion of the GTNLC Mueller matrix elements A , B and C for 90° twisted GTNLC ($\Delta n = 0.225$, $d = 10 \mu m$).

In addition, if we plot the curves of the Mueller matrix elements A , B and C versus wavelength for 90° twisted GTNLC (Figure 3.12 and Figure 3.13), we can find color dispersion is alleviated by designing GTNLC cells with large $\Delta n \cdot d$.

Figure 3.14 presents the molecules arrangements of the 90° twisted and untwisted GTNLC cells. In Figure 3.14 (A), 90° twisted ($\phi = 90^\circ$) GTNLC cell is optically equal to 90° polarization rotator if the Mauguin condition in Eq.(3.13) is satisfied. As mentioned in Chapter 2, the polarization difference

Figure 3.14: Two GTNLCs with different LC molecules arrangement: (A) 90° twisted; (B) untwisted.

imaging (i.e. extraction of S_0 and S_1) can be enabled with 0° and 90° linear polarizer. In the next section, we will present how to photo-pattern the LC alignment layers with high spatial resolution so that the LC molecules can be arranged accordingly. Thus, compact 0° and 90° linear micropolarizers can be fabricated for extracting S_0 and S_1 .

3.3.3 Liquid-crystal Photoalignment

Photoalignment is a non-contact LC alignment or orientation method [56–58]. Basically, it uses photosensitive materials to align the LC molecules. These materials could be sensitive to different light spectrum. The LC alignment

materials are usually “photo-aligned” with linearly polarized light. It was first proposed to address the issues brought by the mechanical rubbing process widely used in the liquid crystal display (LCD) applications. Mechanical rubbing is a traditional process for aligning LC molecules on a glass substrate. It generates grooves in the rubbing direction on the LC alignment layers. The LC molecules are then aligned into these grooves during a later LC filling process. However, the grooves generated by this method are much larger than the dimension of LC molecules. Alignment of LC molecules in these grooves may be perturbed, and a portion of LC molecules may not be aligned exactly in the rubbing direction. This inefficient alignment of LC molecules reduces contrast in the display. The misaligned area may occupy a large portion of small pixels and result in speckles on the display. In addition, mechanical rubbing on a glass substrate may generate dust, electrostatic charges and scratches, and further reduce the yield.

In the proposed micropolarizing devices fabrication technology, photoalignment is used as it provides following advantages:

- As a non-contact LC alignment process, it is fully compatible with photolithography process widely used in the CMOS fabrication process.
- Spatial resolution is limited by the used photolithography masks. This means that the micropolarizing element size can greatly benefit from the rapid scaling of pixel size in CMOS imagers.
- Photoalignment completely removes the need of complex selective etching process regardless of the pattern used for the LC alignment layers [22] and micropolarizer [19–21, 44–47, 50, 51].

In this thesis, a UV-sensitive LC photoalignment material is synthesized, whose chemical formula and absorption spectrum are presented in Figure 3.15 and Figure 3.16, respectively.

Figure 3.15: Chemical formula of the UV-sensitive SD1.

Figure 3.16: Absorption spectrum of the UV-sensitive SD1.

3.3.4 Fabrication Process and Experimental Results

Figure 3.17 illustrates the design of the array pattern for polarization difference imaging (S_0 and S_1 imaging). Its basic element “superpixel” consists of two micropolarizers for simultaneously analyzing 0° and 90° linearly polarized components of incident light. With in-pixel processing circuitry on the CMOS image sensor, the first two Stokes parameters S_0 and S_1 can be calculated for each superpixel in real time. The polarization difference images can be generated in one single frame and real-time processing such as image segmentation/classification can be enabled with on-chip digital image processing unit.

In this section, an optimized high resolution ($2\mu\text{m}$) LC micropolarizer array fabrication process is presented. It enables one to control the values of the ER and transmittance by simply selecting a suitable commercially available linear polarizer for the targeted application. Our approach involves combining this linear polarizer and a micro-patterned liquid crystal cell, which is

Figure 3.17: Micropolarizer array pattern for PDI.

essentially an LC layer placed between two treated glass substrates (Figure 3.18). The inner-surfaces of the LC cell consist of two layers of spin-coated SD1 film. After sufficient exposure to linearly polarized UV light, this SD1 material exhibits a molecular photo-orientation mechanism characterized by the SD1 having an absorption oscillator perpendicular to the projected polarized UV light. This UV induced molecule reorientation remains stable against subsequent UV, moisture and thermal exposure.

Note that the photo-patterned SD1 film does not form by itself a micropolarizer array because SD1 does not exhibit polarization dichroism. Instead, SD1 is used here to define the molecular orientation of individual patterns on the inner surfaces of the LC cell. By selectively photo-patterning these inner surfaces, we can make the LC cell act as a retarder or rotator (Figure 3.14). The latter occurs wherever the orientation pattern of the bottom inner layer is not identical to the top inner layer, in which case, the helical structure formed by the LC molecules across the liquid crystal twists/rotates the orientation of

incoming linearly polarized light. In other words, incoming linearly polarized light follows the rotation of the molecules. In the other case, the LC cell acts as a retarder whose phase can be controlled by simply modulating the thickness of the liquid crystal layer. We demonstrate this technology through the fabrication of a $2\mu\text{m}$ -pitch micropolarizer array comprising 0° and 90° linear micropolarizer elements.

Figure 3.18: Photo-aligned liquid-crystal MPA fabrication process flow.

The fabrication steps required to form the micropolarizer array are presented in Figure 3.18. Two transparent thin glass slides are used as the liquid crystal first substrate and second substrate. In the following, we will refer to the inner surface and the outer surface of each of these substrates, which will encapsulate the LC layer. The fabrication process of the MPA can be summarized as follows:

- The inner surfaces of the two glass substrates are first placed in an ultraviolet-ozone (UVO) cleaner for 20min to remove organic contaminants.
- A solution of SD1 in dimethylformamide (DMF) with a concentration of 1% by weight is then spin-coated (800rpm for 10s then 3000rpm for

40s) on the inner surfaces of both substrates. Both substrates are subsequently baked at 140°C for 20min to remove remaining solvents and strengthen the adhesion of SD1 onto the substrates.

- The SD1 coated inner surfaces of both substrates are exposed to 90° linearly polarized UV light for 15min without photolithography mask applied. This results in a 0° photo-orientation of the SD1 molecules, since the latter adopt a stable molecular orientation perpendicular to the projected linearly polarized UV light.
- The inner surface of the second substrate coated with SD1 is then exposed to 0° linearly polarized UV light for 15min, with a photolithography mask exposing the regions of 90° twisted LC cells, resulting in a 90° photo-reorientation of the SD1 molecules in the exposed regions.
- Spacers with 5 μ m diameter are sprayed on the inner surface of the first substrate.
- The two substrates are then assembled together with their inner surfaces facing each other, leaving a 5 μ m cell gap between the inner surfaces. Thermal epoxy is used for this assembly. The attached substrates are then baked at 120°C for one hour to cure the epoxy.
- Liquid crystal E7 (from Merck) is then inserted between the two treated glass substrates. The resulting LC cell is immediately end-sealed with thermal epoxy and baked at 120°C for one hour.
- A thin linear polarizing film is laminated on the outer surface of the second substrate with its polarizing axis along 0°. It is this linear polarizer that mainly determines the ER and transmittance of the fabricated photo-patterned MPA, since the LC merely acts as a rotator provided that the Mauguin condition in Eq.(3.13) is fulfilled. To satisfy the latter condition, we have chosen LC E7 ($\Delta n=0.225$) and $d=5\mu$ m for the cell gap.

- In the final fabrication step, a UV blocking filter is laminated on the outer surface of the first substrate to protect the device from lifetime environmental UV exposure.

Using the above fabrication process, we have been able to attain a $2\mu\text{m} \times 2\mu\text{m}$ pitch (Figure 3.19), which is, to the best of our knowledge, the most compact pixel pitch ever reported for any micropolarizer array. The only other reported

Figure 3.19: Microphotographs of the fabricated LC MPA.

LC-based micropolarizer technology was proposed by Harnett *et al.* [22]. It

uses evaporated gold films to align LC molecules and selective etching for patterning with a minimum pitch of only $100\mu\text{m}\times 100\mu\text{m}$. Using linearly polarized light at different wavelengths, we have evaluated the performance of the fabricated MPA.

Figure 3.20: Transmittances of 0° and 90° micropolarizers following Malus' law at different wavelengths.

Figure 3.21: Spectral measurements of the major principal transmittance for 0° and 90° micropolarizer elements.

Figure 3.20 indicates that Malus law is well satisfied. Figure 3.21 shows a transmittance as high as $\sim 80\%$. The maximum ER for twisted and untwisted LC modes is ~ 3200 (35dB) (Table 3.1). The twisted arrangement of

LC molecules (Figure 3.14) is seen to result in relatively lower major principal transmittance and ER. Since the performance of the photo-aligned LC-MPA is mainly determined by the linear polarizer, one could choose from any commercially available thin polarizer films so as to achieve the desired values for the ER and transmittance. When considering the actual integration of the MPA on top of the image sensor, the thickness of the micropolarizer array needs to be minimized so as to reduce optical crosstalk between adjacent pixels. This can be achieved by: a) replacing the laminated linear polarizing film (Figure 3.18) with a commercially available ultra-thin ($\sim 150\text{nm}$) MWGP, b) placing the MWGP on top of the image sensor before spin-coating it with SD1 and c) further reducing the thickness of the LC cell. The fabrication process is thus identical to that outlined in Figure 3.18, except for the fact that the 0° polarizer is now placed internally that is on top of the image sensor. In these conditions, the minimum achievable micropolarizer thickness will correspond to the thickness of the LC cell ($< \sim 5\mu\text{m}$). Besides minimizing the thickness, the effect of optical crosstalk could also be mitigated through the use of microlenses above each pixel to redirect and focus oblique incident light [59].

Table 3.1: Extinction ratios at different wavelengths

Wavelength (nm)	0° MP	90° MP
450	33.2dB	28.6dB
500	29.7dB	25.9dB
550	30.4dB	26.1dB
600	35.3dB	34.9dB
650	32.3dB	27.9dB

3.4 Azo-dye Micropolarizer Array for Partial-linear Polarization Imaging

3.4.1 Absorptive Linear Polarizer and Beer-Lambert Law

A linear polarizer is an optical device designed to produce a given linearly polarized state independently of the polarization state of incident light. Absorptive linear polarizers operate on the principle of differential absorption along orthogonal axes. They are also known as dichroic polarizers because of unequal spectrally dependent absorptions. The first absorptive linear polarizer—Polaroid, was invented by Edwin Land in 1928 by using aligned microcrystals of herapathite in a transparent medium of index similar to that of the crystalline material [3].

Figure 3.22: Absorption of an incident light as it travels through an absorptive media.

Beer-Lambert Law, also known as Beer's Law, quantitatively describes the interactions between incident light and an absorptive media through which the light is traveling. It relates the absorption of light to the properties of the material and states that there is a logarithmic dependence between the transmittance T of light through the material and the product of the absorption

coefficient of the material α and the distance l the light travels through the material (Figure 3.22). The absorption coefficient can, in turn, be written as a product of the molar absorptivity of the absorber ε and the concentration c of absorbing species in the material. These relations are usually written as:

$$T = \frac{I_1}{I_0} = e^{-\alpha l} = e^{-\varepsilon l c} \quad (3.14)$$

where I_0 and I_1 are the intensities of the incident light and the transmitted light, respectively. The transmittance can then be expressed in terms of absorbance:

$$A = -\ln\left(\frac{I_1}{I_0}\right) = -\ln(T) = \varepsilon l c \quad (3.15)$$

This implies that the absorbance becomes linear with the concentration. There are at least five conditions that need to be fulfilled in order for Beers law to be valid. These conditions are:

- The absorbers must act independently of each other.
- The absorbing medium must be homogeneously distributed in the interaction volume and must not scatter the radiation.
- The incident radiation must consist of parallel rays, each traversing the same length in the absorbing medium.
- The incident radiation should preferably be monochromatic, or have at least a width that is more narrow than the absorbing transition.
- The incident flux must not influence the atoms or molecules; it should only act as a non-invasive probe of the species under study. In particular, this implies that the light should not cause optical saturation or optical pumping, since such effects will deplete the lower level and possibly give rise to stimulated emission.

If any of these conditions is not fulfilled, there will be deviations from Beer-Lambert law.

3.4.2 Photo-induced Dichroism of AD1

A photosensitive azo-dye material AD1 (Figure 3.23) was first synthesized for the photo-patterning of the micropolarizer array. This material exhibits a strong polarization dichroism after sufficient exposure to linearly polarized UV light (Figure 3.24). The local polarization axis is formed in the illuminated

Figure 3.23: Chemical formula of AD1.

regions of the azo-dye film. The degree of molecular order depends on the exposure energy. The polarizing axis of the photo-induced AD1 linear polarizer is perpendicular to the polarizing orientation of the projected UV light, which corresponds to a stable configuration. With the well-controlled process of photolithography, different MPA patterns can be transferred onto a single azo-dye film layer using appropriate masks and UV polarizers.

Figure 3.24: Polarization dichroism of AD1: (A) with 0° linear analyzer on top; (B) with 90° linear analyzer on top.

Figure 3.25 illustrates the array pattern design for partial-linear polarization imaging (S_0 , S_1 and S_2 imaging). Its basic element “supperpixel” consists of four micropolarizers for simultaneously analyzing 0°, 90°, 45° and −45° linearly polarized components of incident light. With in-pixel processing circuitry

Figure 3.25: Array pattern for partial linear polarization imaging.

on the CMOS image sensor, the first three Stokes parameters S_0 , S_1 and S_2 can be calculated for each superpixel in real time. The partial-linear polarization images can be generated in one single frame.

The fabrication steps required to photo-pattern AD1 film (shown in Figure 3.26) can be outlined as follows:

- Transparent glass substrates are placed in UVO cleaner (Model NO. 144AX from Jelight) for 20 minutes to remove organic contaminants and achieve improved spin coat uniformity.
- A solution of AD1 in 1,2-dichloroethane is filtered and spin-coated on top of a glass substrate at room temperature for 40s with a spin speed of 3000rpm.
- Immediately after the spin coat, samples are baked at 100°C for 30min in order to remove the solvent and strengthen the adhesion of the AD1 film to the glass substrate.

Figure 3.26: Photo-patterned AD1 MPA fabrication process flow.

- Samples are then exposed to linearly polarized UV light with 0° , 90° , 45° and -45° orientations. Four different photolithography masks are applied successively to form the MPA pattern of Figure 3.25. The exposure time is 30min. A 1000-W Xenon arc lamp and a UV sheet polarizer from Oriel Instruments were used. The intensity of the polarized UV light at 365nm was about $6\text{mW}/\text{cm}^2$.

Figure 3.27 presents the microphotographs of the fabricated MPA. Linear analyzers with 0° , 90° , 45° and -45° orientations were placed on top of the sample to visualize the orientations of the pixel-level micropolarizers. The reported micropolarizer pitch of $10\mu\text{m} \times 10\mu\text{m}$ here is not an indication of the resolution limit of the proposed implementation. The resolution limit (i.e. minimum micropolarizer pitch) of the proposed micropolarizer fabrication technology is set by the alignment technology. In order to evaluate the optical performance of the MPA, two important figures of merit that are the major principal transmittance and the ER have been extracted. Figure 3.28 reports the major principal transmittance measured with the wavelength varied from 400nm to 700nm. A peak ER of ~ 131 was measured for a 4wt% solution of AD1 in

Figure 3.27: Microphotographs of the fabricated AD1 MPA: (A) with 0° linear analyzer on top; (B) with 90° linear analyzer on top; (C) with 45° linear analyzer on top; (D) with -45° linear analyzer on top.

Figure 3.28: Spectral measurement results of the major principal transmittance with AD1 concentration varied from 1% to 5%.

Figure 3.29: Spectral measurement results of the ER.

1,2-dichloroethane (Figure 3.29) [60–62].

The proposed photo-patterned AD1 micropolarizer fabrication technology has the following characteristics:

- The AD1 (Figure 3.23) is photo-chemically stable against subsequent UV, moisture and thermal exposure [57]. The inter-molecular interaction in the reoriented azo-dye molecular domain cannot be easily destroyed. The packaging together with a UV filter will further improve the micropolarizer stability and durability.
- An ER of ~ 131 compared to a maximum value of 1000 for commercially available PVA film based linear polarizer. We are currently working at further increasing the value of the ER by optimizing process parameters.
- Reduced cross-talk between adjacent photodetectors as illustrated in Figure 3.6 with submicron ($\sim 0.3\mu\text{m}$) MPA thickness.
- High spatial resolution only limited by the alignment technology. The adopted UV photoalignment provides far better control compared to previously reported etching-based patterning [19–21, 44–47, 50, 51].

- Simplified CMOS compatible fabrication process, which completely removes the need for complex selective etching and has the potential to further benefit from the rapid scaling of the minimum feature size of standard CMOS process. Transparent glass substrate is chosen here for better visualization and characterization of the fabricated MPA in terms of transmittance and ER (CMOS image sensor substrate is opaque), which will be replaced by real CMOS image sensor substrate without changing any other steps in the future integration.

3.4.3 “Guest-host” Micropolarizer Array

In the previous section, photosensitive dichroic AD1 has been proven a superior candidate for fabricating high-resolution micropolarizing device of CMOS polarization image sensor. After sufficient exposure to linearly polarized UV light, rod-like AD1 molecules (Figure 3.30) can be oriented with their long molecular axes towards the direction perpendicular to the polarizing orientation of projected linearly polarized UV light. Experimental results indicate that the rod-like AD1 molecules can efficiently absorb the polarized light (400nm~550nm) with polarizing orientation in parallel with their long molecular axes while transmitting the polarized light with polarizing orientation perpendicular to their long molecular axes. When sufficiently exposed to linearly polarized UV light, an AD1 film can exhibit strong polarization dichroism. However, the

Figure 3.30: Rod-like AD1 molecules and their long molecular axes.

orientation degree of AD1 molecules is a function of the exposure energy and saturates after prolonged UV exposure. This limits the AD1 film’s major principal transmittance and ER. As shown in Figure 3.31, a “guest-host” MPA,

with photo-aligned PLC as the “host” material and AD1 molecules as the “guest”, is proposed to improve the orientation degree of AD1 molecules and thus the optical performance.

Figure 3.31: Molecules ordering comparison between (A) photo-induced AD1 ordering and (B) predetermined PLC molecules induced ordering in “guest-host” system.

Nematic PLC consists of rod-like organic molecules, whose regional ordering is characterized by the parallel alignment of molecules, along their long molecular axes. A well-known property of nematic liquid crystals is that the orientation of the molecules can be controlled with an external electric field. Furthermore, Heilmeyer discovered that by controlling the molecular orientation of a nematic “host” material, the properties of the “guest” materials mixed with the nematic “host” can be controlled [63]. In this thesis, we propose to exploit this property of “host” nematic liquid crystals to better control the molecular orientation of AD1 (the “guest”) and improve its optical properties. Instead of applying an external electric field to orient the PLC “host” molecules [63], we propose a non-contact high resolution photoalignment technique based on a UV-sensitive SD1 film, used in LCDs [56–58]. As depicted in Figure 3.32 (A), the image sensor is first spin-coated with this SD1 film. After subsequent irradiation by linearly polarized UV light, photoalignment of SD1 molecules occurs [Figure 3.32 (B)] with the SD1’s long molecular axes perpendicular to the polarization direction of projected linearly polarized UV

light. The AD1-PLC “guest-host” mixture is then spin-coated on top of the SD1 film, which will act as an alignment layer for the PLC “host” molecules and the AD1 “guest” molecules. Figure 3.32 (C) depicts this reorientation process with “host” and “guest” molecules aligned with SD1 molecules. Polymerization of the “host” provides thermal and UV stability [Figure 3.32 (D)]. With different masks exposing different microdomains of SD1 layer to linearly polarized UV light, the SD1 layer can be photo-patterned with predetermined pattern and different PLC alignment directions can be formed for different microdomains.

Figure 3.32: PLC pre-alignment process.

In contrast to photo-induced ordering of AD1 molecules [Figure 3.31 (A)], in the “guest-host” micropolarizer system, the ordering of the “guest” AD1 molecules follows that of “host” PLC molecules. By using PLC alignment layers, the “host” PLC molecules can better control the orientation of the “guest” AD1 molecules [Figure 3.31 (B)].

3.4.4 Fabrication Process and Experimental Results

To demonstrate the proposed “guest-host” MPA technology, we fabricated an array for the extraction of full linear polarization information (Figure 3.25). The “guest-host” MPA exhibits a 2×2 pattern comprising of 0° , 90° , 45° and -45° micropolarizers. To enable the optical characterization of the fabricated MPA, a transparent glass substrate was used instead of the silicon-based opaque CMOS image sensor substrate. The fabrication steps of the “guest-host” MPA shown in Figure 3.33 can be summarized as follows:

- Place a transparent glass substrate in an UVO cleaner (Model NO. 144AX from Jelight) for 20min to remove organic contaminants and improve the spin coat uniformity of PLC photoalignment material (SD1).
- Spin coat a solution of SD1 in DMF with a concentration of 1% by weight on top of the substrate at a spin speed of 800rpm for 10s then 3000rpm for 40s.
- Bake the substrate with SD1 immediately after the spin coat at 110°C for 20min in order to remove the solvent and strengthen the adhesion between the SD1 film and the substrate.
- Expose the substrate with SD1 to 90° linearly polarized UV light for 15min with the first mask applied, resulting in 0° photo-aligned SD1 molecules in the exposed microdomains.
- Expose the substrate with SD1 to 0° linearly polarized UV light for 15min with the second mask applied, resulting in 90° photo-aligned SD1 molecules in the exposed microdomains.
- Expose the substrate with SD1 to -45° linearly polarized UV light for 15min with the third mask applied, resulting in 45° photo-aligned SD1 molecules in the exposed microdomains.

Figure 3.33: Fabrication process flow of “guest-host” MPA.

- Expose the substrate with SD1 to 45° linearly polarized UV light for 15min with the fourth mask applied, resulting in -45° photo-aligned SD1 molecules in the exposed microdomains.
- Spin coat a mixture of AD1 solution and PLC solution (from DIC corp.) with a mass ratio of 1:1 on top of the substrate at a spin speed of 800rpm for 5s then 3000rpm for 30s.
- Bake the substrate at 50°C for 3min to remove the solvent.
- Irradiate UV light (265nm) to polymerize the spin-coated PLC for 3min.

The fabricated “guest-host” MPA was characterized by measuring the two important figures of merit that are major principal transmittance and ER. Measurements were performed using a broadband linear polarizer (from Moxtek Inc.) inserted between a mini deuterium halogen light source (Mikropack DT-Mini-2-GS) and the fabricated sample, to provide linearly polarized input light with wavelength varied from 400nm to 550nm.

Figure 3.34: Measured major principal transmittances of UV-oriented AD1 micropolarizer and “guest-host” micropolarizer, with AD1 concentration varied from 1% to 5%.

Figure 3.35: Measured extinction ratios of UV-oriented AD1 micropolarizer and “guest-host” micropolarizer.

Figure 3.34 compares the measured major principal transmittances of both the UV-oriented AD1 micropolarizer [60] and the proposed “guest-host” micropolarizer. A $\sim 25\%$ improvement of the major principal transmittance is achieved. In addition, Figure 3.35 shows that the peak ER is increased from 131 to 313 for an AD1 concentration of 4%. These results demonstrate that mixing AD1 with a “host” nematic liquid crystal provides superior MPA performance. The fabricated “guest-host” MPA was inspected using a microscope’s white light source and a linear polarization analyzer. Figure 3.36 presents the recorded microphotographs with the analyzer’s polarizing axis oriented along 0° , 90° , 45° and -45° . The micropolarizer pitch is $5\mu m \times 5\mu m$. The overall “guest-host” MPA thickness was measured by a surface profiler (Tencor P-10) and found to be $0.95\mu m$ [64].

The optical performance comparison with previously reported implementations are tabulated in Table 3.2, where the photo-aligned LC, UV-oriented AD1 and “guest-host” MPAs proposed in this thesis are represented by [59]*, [60]* and [64]*, respectively.

Figure 3.36: Microphotographs of the fabricated “guest-host” MPA, inspected by a linear polarization analyzer along the following orientations: (A) 0 degree; (B) 90 degree; (C) 45 degree; (D) -45 degree.

Table 3.2: Optical performance comparison with previously reported implementations, where the photo-aligned LC, UV-oriented AD1 and “guest-host” MPAs proposed in this thesis are represented by [59]*, [60]* and [64]*, respectively.

	[2]	[22]	[44]	[48]	[21]	[19]	[59]*	[60]*	[64]*
Parameters Extracted	$S_{0,1}$	$S_{0,1}$	$S_{0,1}$	$S_{0,1,2}$	$S_{0,1,2}$	$S_{0,1,2}$	$S_{0,1}$	$S_{0,1,2}$	$S_{0,1,2}$
ER	-	-	-	-	330	1000	3200	131	313
MP Directions	2	2	2	3	3	3	2	4	4
Minimum MP Size (μm)	151	100-200	25	25	14.1	8	2	10	5
MPA Thickness (μm)	887	-	10	20	4	20	5	0.3	0.95

3.5 Conclusion

In this chapter, a reflective-type liquid-crystal micropolarizer array with high ER (32dB) is proposed. Compared with previously reported liquid-crystal based MPA implementations [22], the spatial resolution is dramatically scaled from $100\mu m$ to $2\mu m$. In addition, an ultra-thin ($\sim 0.3\mu m$) photo-aligned azo-dye based absorptive-type MPA is presented. In order to further improve the azo-dye molecular ordering, a novel “guest-host” micropolarizer system with PLC as the “host” material and AD1 as the “guest” material is demonstrated. Experimental results validate that micropolarizers exploiting “guest-host” interactions offer superior optical performance compared to a photo-aligned AD1 polarizing film. We report a $\sim 25\%$ increase of the major principal transmittance and a 139% increase of the peak ER. This is achieved by controlling the “guest” molecular orientation through the photoalignment of “host” molecules. The proposed non-contact MPA fabrication technology prevents mechanical damage, electronic charge or contamination to the substrate. High spatial resolution with a pixel pitch of $5\mu m \times 5\mu m$ is achieved. Moreover, it is also compatible with standard CMOS process, enabling the integration of a “guest-host” micropolarizer array over a CMOS image sensor to realize the concept of a low cost single-chip polarization camera.

Chapter 4

Micropolarimeter Array for Circular Polarization Imaging

4.1 Introduction

Reported MPA implementations have focused so far on the extraction of linearly or partial-linearly polarized components. Prior works have discarded circularly polarized components. This is generally adequate for applications, in which objects are illuminated by sun or some other natural light sources. However, for applications, in which objects illuminated by collimated active light source, circular polarization components can provide valuable information on the imaged scene. Gilbert *et al.* proposed to improve underwater visibility by using circular polarization imaging [65–69]. Additionally, in the biomedical field, circular polarization imaging also shows great promise in the applications of superficial tissue characterization, optical coherence tomography and optical biopsy [70–72]. Many biological tissues such as collagen, sickled red blood cells, myelin and elastic fibers can change uniquely the polarization state of projected circularly polarized light. By measuring the depolarization degree of the projected circularly polarized light backscattered from these tissues, dramatically increased contrast and specificity can be achieved for identifying

the tissue structure. In this chapter, a high-resolution ($5\mu\text{m}$) micro-circular-polarization-analyzer (MCPA) array is proposed for real-time active circular polarization imaging. MCPAs for extracting right-handed and left-handed circularly polarized components of incident light are implemented by fabricating PLC micro-retarders with perpendicular fast axes on top of a 45° laminated linear polarizing film.

4.2 Review of Circular Polarization Vision

4.2.1 Circular Polarization Vision of Ocean Creatures

Figure 4.1: (A) Photograph of the stomatopod crustacean *Odontodactylus cultrifer*; (B) the stomatopod crustacean *Odontodactylus cultrifer*'s telson keel photographed with a left-handed circular polarization analyzer; (C) the stomatopod crustacean *Odontodactylus cultrifer*'s telson keel photographed with a right-handed circular polarization analyzer; (D) the eye of *Odontodactylus scyllarus*, which is a close relative of *Odontodactylus cultrifer* [73, 74].

It was revealed recently that circular polarization vision is another impor-

tant behavior in the animal kingdom in addition to linear polarization vision capability [73, 74]. Stomatopod crustaceans have a visual system capable of sensing and processing circularly polarized light [Figure 4.1 (A)]. This was observed through four lines of evidence: behavior, electrophysiology, optical anatomy and details of signal design. In addition, as demonstrated in [73], some species in the animal kingdom are capable of differentiating the handedness of circularly polarized light. Figure 4.1 (B) and (C) illustrates the stomatopod crustacean *Odontodactylus cultrifer*'s telson keel photographed with a left-handed circular polarization analyzer and a right-handed circular polarization analyzer in front of the camera, respectively. Striking contrast difference can be observed between Figure 4.1 (B) and Figure 4.1 (C). Figure 4.1 (D) shows the eye of *Odontodactylus scyllarus*, which is a close relative of *Odontodactylus cultrifer*.

4.2.2 Active Circular Polarization Imaging Systems

Circular polarization can be fully described by the first and the fourth Stokes parameters with the following expression:

$$S_0 = I(45^\circ, 90^\circ) + I(45^\circ, -90^\circ) \quad (4.1)$$

$$S_3 = I(45^\circ, 90^\circ) - I(45^\circ, -90^\circ) \quad (4.2)$$

where $I(45^\circ, 90^\circ)$ is the light intensity filtered with a fast-axis-horizontal quarter wavelength retarder (90° retardation) then a 45 degree linear polarizer and $I(45^\circ, -90^\circ)$ is the light intensity filtered with a fast-axis-vertical quarter wavelength retarder (-90° retardation) then a 45 degree linear polarizer. In addition, the degree of circular polarization (DOCP), which is the intensity fraction attributable to circularly polarized components [6], can be used to quantitatively characterize the incident circularly polarized light in terms of

Stokes parameters:

$$DOCP = \frac{S_3}{S_0} = \frac{I(45^\circ, 90^\circ) - I(45^\circ, -90^\circ)}{I(45^\circ, 90^\circ) + I(45^\circ, -90^\circ)} \quad (4.3)$$

Figure 4.2 illustrates an active circular polarization imaging system. Collimated circularly polarized light ($DOCP = 1$ or -1) is generated by mounting a wide-band circular polarizer in front of a white light source. Image scene with object in turbid/scattering media is illuminated by this active light source; while the reflected light is captured and analyzed by a circular polarization image sensor. The depolarization degree of the circularly polarized incident light (described by $DOCP$) can be calculated for different pixels of the circular polarization image sensor, which correspond to different spatial locations of image scene. Image segmentation/classification algorithms are subsequently applied on the circular polarization images to provide enhanced contrast between objects and background [65–69].

Figure 4.2: Illustration of active circular polarization imaging.

4.3 Liquid-crystal Micropolarimeter Array for Circular Polarization Imaging

In contrast to previously reported implementations with unpatterned mechanically/electrically circular-polarization-analyzers mounted in front of a digital camera, we propose here a micro-patterned MCPA array, whose design and fabrication are presented in the following subsections.

4.3.1 Array Pattern Design

Figure 4.3: Array pattern for circular polarization imaging.

Figure 4.3 presents the array pattern design for circular polarization imaging (S_0 and S_3 imaging). Its basic element “superpixel” consists of two MCPAs for simultaneously analyzing right-handed and left-handed circularly polarized components of incident light. With in-pixel processing circuitry on the CMOS image sensor, the Stokes parameters S_0 and S_3 can be calculated for

Figure 4.4: Cross-section of proposed MCPA array.

each superpixel in real time. According to the Stokes parameters expression in Eq.(4.1) and Eq.(4.2), $I(45^\circ, 90^\circ)$ and $I(45^\circ, -90^\circ)$ can be sensed simultaneously with two photodetectors covered by two circular polarization analyzers (Figure 4.3). Figure 4.4 shows the cross-section of proposed MCPA array. Quarter wavelength micro-retarders with perpendicular fast axes are patterned on top of a 45° laminated linear polarizing film to implement the MCPA array. Photodetector columns are alternatively covered by different micro-patterned MCPA strips. With simultaneously sensed photocurrents proportional to $I(45^\circ, 90^\circ)$ and $I(45^\circ, -90^\circ)$, processing circuitry can be integrated into the two adjacent photodetectors to extract S_0 , S_3 and DOCP in real time.

4.3.2 Structure and Optical Modeling

Figure 4.5 illustrates the constructions of circular polarization analyzers for analyzing right-handed circularly polarized component and left-handed circularly polarized component, respectively. The Mueller matrix of a quarter-wavelength retarder with 90° retardation is:

$$M_{QWR_{90}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{bmatrix} \quad (4.4)$$

Figure 4.5: Constructions of circular polarization analyzers: (A) for right-handed circularly polarized component; (B) for left-handed circularly polarized component.

The Mueller matrix of a 45° linear polarizer is:

$$M_{L_{45}} = \frac{1}{2} \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (4.5)$$

According to Figure 4.5 (A), Stokes parameters of the emerging light can be expressed as:

$$\begin{bmatrix} S''_0 \\ S''_1 \\ S''_2 \\ S''_3 \end{bmatrix} = M_{L_{45}} \cdot \begin{bmatrix} S'_0 \\ S'_1 \\ S'_2 \\ S'_3 \end{bmatrix} = M_{L_{45}} \cdot M_{QWR_{90}} \cdot \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} \quad (4.6)$$

Since the first Stokes parameter S_0 represents the total intensity of the light, the total intensity of the emerging light in Figure 4.5 (A) is:

$$I_{R-Circular-Analyzer} = S_0 + S_3 \quad (4.7)$$

On the other hand, the Mueller matrix of a quarter-wavelength retarder with -90° retardation is:

$$M_{QWR_{-90}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad (4.8)$$

The Mueller matrix of a 45° linear polarizer is:

$$M_{L45} = \frac{1}{2} \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (4.9)$$

According to Figure 4.5 (B), Stokes parameters of the emerging light can be expressed as:

$$\begin{bmatrix} S_0'' \\ S_1'' \\ S_2'' \\ S_3'' \end{bmatrix} = M_{L45} \cdot \begin{bmatrix} S_0' \\ S_1' \\ S_2' \\ S_3' \end{bmatrix} = M_{L45} \cdot M_{QWR-90} \cdot \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} \quad (4.10)$$

Since the first Stokes parameter S_0 represents the total intensity of incident light, the total intensity of the emerging light in Figure 4.5 (A) is:

$$I_{L-Circular-Analyzer} = S_0 - S_3 \quad (4.11)$$

Therefore, we have:

$$S_0 = I_{R-Circular-Analyzer} + I_{L-Circular-Analyzer} \quad (4.12)$$

$$S_3 = I_{R-Circular-Analyzer} - I_{L-Circular-Analyzer} \quad (4.13)$$

4.3.3 Fabrication Process Flow

PLC has been demonstrated a superior candidate for quarter wavelength retarder fabrication [75]. With SD1 as PLC photoalignment material, high-resolution micro-retarder array can be formed on top of a 45° laminated linear polarizing film. Figure 4.6 illustrates the proposed MCPA array fabrication process flow. A transparent glass substrate with 45° oriented nano-scale

MWGP on top (from Moxtek Inc.), instead of the CMOS imager substrate (Figure 4.4), is chosen here to enable the characterization of both transmittance and ER of the fabricated MCPA array, because the CMOS imager substrate is opaque.

Figure 4.6: Proposed MCPA array fabrication process flow.

Detailed fabrication steps are outlined as follows:

- Place the aforesaid glass substrate with the polarizing film on top in an UVO cleaner (Model NO. 144AX from Jelight) for 20min to improve the spin coat uniformity of PLC photoalignment material SD1.

- Spin coat a solution of SD1 (1% by weight) on top of the polarizing film at a spin speed of 800rpm for 10s then 3000rpm for 40s.
- Bake the substrate with SD1 immediately after the spin coat at 70°C for 20min in order to remove the solvent and strengthen the adhesion between the SD1 film and the polarizing film.
- Expose the substrate with SD1 to 90° linearly polarized UV light for 15min without mask applied, resulting in 0° photo-aligned SD1 molecules.
- Expose the substrate with SD1 to 0° linearly polarized UV light for 15min with a mask applied, resulting in 90° photo-aligned SD1 molecules in the exposed microdomains.
- Spin coat a PLC solution (from DIC) with a concentration of 25% by weight on top of the photo-patterned SD1 layer at a spin speed of 800rpm for 5s then 3000rpm for 30s.
- Bake the sample at 50°C for 3min to remove the solvent.
- Irradiate UV light for 3min to polymerize the spin-coated PLC.

4.3.4 Experimental Results

To visualize the micro-patterned MCPAs, samples are illuminated by 0°, 90°, 45° linearly polarized and circularly polarized light, respectively. Transmitted light is captured and recorded by microscope. Figure 4.7 presents the recorded microphotographs. It is revealed that the fabricated MCPA array is only sensitive to circularly polarized light and there is almost no contrast between different microdomains for linearly polarized input light. In addition, high-resolution MCPA with a feature size as small as 5 μ m is achieved. Spectral measurements of transmittance and MCPA ER are implemented to characterize the optical performance of the MCPA array. A collimated circularly

polarized light source ($\text{DOCP} = 1$ or -1) with the wavelength varied from 400nm to 700nm is used as input.

Figure 4.7: Microphotographs of the fabricated MCPA array: (A) illuminated by 90° linearly polarized light; (B) illuminated by 0° linearly polarized light; (C) illuminated by 45° linearly polarized light; (D) illuminated by right-handed circularly polarized light; (E) illuminated by left-handed circularly polarized light.

Figure 4.8 shows the spectral measurement results of the transmittances with right-handed ($\text{DOCP} = 1$) and left-handed ($\text{DOCP} = -1$) circularly polarized input light sources. Figure 4.9 shows the spectral measurement result of the MCPA extinction ratio, which reaches the maximum at the wavelength of 557nm. The MCPA extinction ratio is defined by the transmittance ratio between right-handed ($\text{DOCP} = 1$) and left-handed ($\text{DOCP} = -1$) circularly polarized input light sources.

Figure 4.8: Spectral measurement results of the transmittances with right/left-handed circularly polarized input light.

Figure 4.9: Spectral measurement result of the MCPA extinction ratio.

4.4 Conclusion

In this chapter, we have demonstrated a high-resolution MCPA array for real-time active circular polarization imaging in visible spectrum. PLC micro-retarders with perpendicular fast axes are formed on top of a 45° laminated linear polarizing film to implement the MCPAs for simultaneously extracting right-handed and left-handed circularly polarized components. With SD1 as the PLC photoalignment material, an MCPA feature size as small as $5\mu\text{m}$ is achieved. Reported experimental results validate the proposed implementation with a pass transmittance of $\sim 75\%$ and a peak MCPA extinction ratio of ~ 120 at the wavelength of 557nm [76].

Chapter 5

Micropolarimeter Array for Full Stokes Polarization Imaging

5.1 Introduction

Traditional polarimetric imaging systems are typically not capable of full Stokes polarization imaging [7, 8, 65, 66], relying instead on only a subset of the Stokes vector components: (S_0, S_1) for PDI, (S_0, S_1, S_2) for PLPI [7, 8] or (S_0, S_3) for circular polarization imaging [65, 66]. None of the reported micropolarimeter implementations can extract the complete polarization information. In this chapter, we report the first micropolarimeter array capable of full Stokes polarization imaging. The proposed liquid crystal micropolarimeter (LCMP) array is fabricated by patterning an LC layer on top of a visible-regime MWGP using ultra-violet sensitive SD1 as the LC photoalignment material. This arrangement enables the formation of either micrometer-scale LC polarization rotators, neutral density filters or quarter wavelength retarders. These elements are in turn exploited to acquire all components of the Stokes vector.

5.2 Liquid-crystal Micropolarimeter Array for Full Stokes Polarization Imaging

5.2.1 System Design and Implementation

Figure 5.1: CMOS polarization image sensor architecture with integrated LCMP array for full Stokes polarization imaging.

An integrated polarization image sensing system consists of three fundamental building blocks: optics, light polarizing elements and underlying photodetectors. By redirecting the light reflected from an illuminated scene through the optical lens to its focal plane, the different polarized components of light can be filtered by the polarizing elements covering individual photodetectors. For example, linearly polarized components with different polarization orientations can be examined by a combination of a polarization rotator and a linear polarizer [3]. On the other hand, circularly polarized components can be examined by a combination of a polarization retarder and a linear polarizer [3]. In this thesis, we propose to combine a visible-regime MWGP, used as a linear polarizer, together with a patterned LC layer, used here as either polarization rotator, polarization retarder or neutral density filter depending on the LC orientation layers. Figure 5.1 illustrates how the proposed LCMP array can be integrated on top of a CMOS image sensor to extract the full Stokes components for every pixel of the captured image.

Suppose the initial Stokes parameters for the incident light are (S_0, S_1, S_2, S_3) , they become (S'_0, S'_1, S'_2, S'_3) after passing through the LC cell and $(S''_0, S''_1, S''_2, S''_3)$ after passing through the MWGP. As a unitary intensity-lossless system, the Mueller matrix of the LC cell can be expressed as [55]:

$$M_{LC} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & A & B & C \\ 0 & D & E & F \\ 0 & G & H & K \end{bmatrix} \quad (5.1)$$

When an electric field is applied and exceeds a given threshold value, the LC cell can be represented by a neutral density filter. When there is no electric field applied, the LC cell can be represented by the combination of a polarization phase retarder and a polarization rotator. Its Mueller matrix is given as [55]:

$$M_{LCnoEfield} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 - 2(c^2 + d^2) & 2(bd - ac) & -2(ad + bc) \\ 0 & 2(ac + bd) & 1 - 2(b^2 + c^2) & 2(ab - cd) \\ 0 & 2(ad - bc) & -2(ab + cd) & 1 - 2(b^2 + d^2) \end{bmatrix} \quad (5.2)$$

with

$$a = \cos(\phi) \cdot \cos(\chi) + \frac{\phi}{\chi} \cdot \sin(\phi) \cdot \sin(\chi) \quad (5.3)$$

$$b = \frac{\delta}{\chi} \cdot \cos(\phi) \cdot \sin(\chi) \quad (5.4)$$

$$c = \sin(\phi) \cdot \cos(\chi) - \frac{\phi}{\chi} \cdot \cos(\phi) \cdot \sin(\chi) \quad (5.5)$$

$$d = \frac{\delta}{\chi} \cdot \sin(\phi) \cdot \sin(\chi) \quad (5.6)$$

$$\chi^2 = \phi^2 + \delta^2 \quad (5.7)$$

$$\delta = \frac{\pi}{\lambda} \cdot \Delta n(\lambda) \cdot d \quad (5.8)$$

where ϕ is the LC twist angle, d is the LC layer thickness, $\Delta n(\lambda)$ is the LC birefringence and λ is the wavelength of the incident light. The twist angle ϕ and the phase retardation 2δ are the two main design parameters in the design and fabrication of the LC cell. The Mueller matrix of the MWGP with its polarization axis oriented at an angle of θ is [3]:

$$M_{linear} = \frac{1}{2} \begin{bmatrix} 1 & \cos 2\theta & \sin 2\theta & 0 \\ \cos 2\theta & \cos^2 2\theta & \sin 2\theta \cdot \cos 2\theta & 0 \\ \sin 2\theta & \sin 2\theta \cdot \cos 2\theta & \sin^2 2\theta & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (5.9)$$

The Stokes parameters of the emerging light, depicted in Figure 5.1, can be thus expressed by multiplying the above-mentioned initial Stokes parameters (in vector form) by the Mueller matrices of the LC cell and the MWGP successively as follows:

$$\begin{bmatrix} S''_0 \\ S''_1 \\ S''_2 \\ S''_3 \end{bmatrix} = M_{linear} \cdot \begin{bmatrix} S'_0 \\ S'_1 \\ S'_2 \\ S'_3 \end{bmatrix} = M_{linear} \cdot M_{LC} \cdot \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} \quad (5.10)$$

The total intensity, S''_0 , of the emerging light (Figure 5.1) is given:

$$S''_0 = I(\theta, \phi, \delta) = 0.5(S_0 + J \cdot S_1 + L \cdot S_2 + N \cdot S_3) \quad (5.11)$$

with

$$\begin{cases} J = A \cdot \cos 2\theta + D \cdot \sin 2\theta \\ L = B \cdot \cos 2\theta + E \cdot \sin 2\theta \\ N = C \cdot \cos 2\theta + F \cdot \sin 2\theta \end{cases} \quad (5.12)$$

Mathematically, at least four intensity measurements taken through four different LCMPs, each with its unique set of parameters (J, L, N) , are needed to determine the four Stokes parameters S_0, S_1, S_2, S_3 . The four intensity measurements can be quantitatively expressed as:

$$\begin{cases} I_1 = 0.5(S_0 + J_1 \cdot S_1 + L_1 \cdot S_2 + N_1 \cdot S_3) \\ I_2 = 0.5(S_0 + J_2 \cdot S_1 + L_2 \cdot S_2 + N_2 \cdot S_3) \\ I_3 = 0.5(S_0 + J_3 \cdot S_1 + L_3 \cdot S_2 + N_3 \cdot S_3) \\ I_4 = 0.5(S_0 + J_4 \cdot S_1 + L_4 \cdot S_2 + N_4 \cdot S_3) \end{cases} \quad (5.13)$$

To determine all four Stokes parameters simultaneously, we propose to adopt an approach similar to that used in a color filter array, with each pixel making only one of the four necessary intensity measurements ($I_1 - I_4$). The three other intensities are recovered by examining the intensity values of neighboring pixels. This approach trades-off spatial resolution to allow for the acquisition of all Stokes components in a single image capture. The basic element of the LCMP array, referred to as superpixel, consists of four micropolarimeters. Eq.(5.11) suggests that one can choose from a number of different possible combinations of four micropolarimeters, with parameters (J_i, L_i, N_i) for $i = [1, 2, 3, 4]$. However, a judicious choice of the design parameters $(\theta, \phi$ and $\delta)$ and coefficients (J, L, N) of each micropolarimeter can significantly reduce the complexity of the silicon implementation of the Stokes parameters computation circuitry. For example, if we orient the MWGP's polarizing axis at $\theta=45^\circ$, (J, L, N) are simplified to (D, E, F) and Eq.(5.11) becomes:

$$S_0'' = I(\phi, \delta) = 0.5(S_0 + D \cdot S_1 + E \cdot S_2 + F \cdot S_3) \quad (5.14)$$

Let's now constrain the phase retardation 2δ of each cell to quarter wavelength:

$$2\delta = \frac{\pi}{2} + 2m\pi \quad \text{or} \quad \delta = \frac{\pi}{4} + m\pi \quad (5.15)$$

for $m = 1, 2, 3, \dots$, where m is referred to as the phase retardation factor. According to Eq.(5.2)-(5.8), when there is no electric field, the coefficients (D, E, F) in Eq.(5.14) become functions of the LC twist angle ϕ and the phase retardation factor m , as shown in Figure 5.2. The following observations can be exploited to simplify the expressions of the elements (D, E, F) of the LC Mueller matrix:

- When the LC twist angle $\phi = 45^\circ$, F and D become 0 and 1 respectively.
- When the LC twist angle $\phi = -45^\circ$, F and D become 0 and -1 respectively.
- When the LC cell is untwisted ($\phi = 0^\circ$), elements (D, E, F) are equal to $(0, 0, 1)$ for all values of m . According to Eq.(5.14), only the right-handed circularly polarized component represented by S_3 can be transmitted for the LCMP with untwisted LC cell. In other words, it is optically equivalent to a right-handed circular polarization analyzer.

The above observations have motivated our choice of 45° twisted, -45° twisted and untwisted LC cells for three out of the four micropolarimeters covering a superpixel (Figure 5.3). For the fourth LCMP, we chose to operate the LC cell in electrically controlled birefringence (ECB) mode. If the electric field exceeds a threshold value, this fourth LC cell is optically equivalent to a neutral density filter, which has no influence on the polarization state of incident light. It follows that the Mueller matrix elements (D, E, F) are equal to $(0, 1, 0)$. Note that in conjunction with the 45° oriented visible-regime MWGP, the LCMP with the neutral density filter LC cell is optically equivalent to a 45° linear polarization analyzer. When the voltage is low, the electric-field controlled

Figure 5.2: Relationship between the LC Mueller matrix elements and the LC twist angle ϕ : (A) D versus ϕ ; (B) E versus ϕ ; (C) F versus ϕ .

Figure 5.3: Top view and cross-sections of the proposed CMOS polarization image sensor's "superpixel" consisting of four LCMPs: $LCMP_{45^\circ \text{twisted}}$, $LCMP_{-45^\circ \text{twisted}}$, $LCMP_{E\text{-field}}$ and $LCMP_{Untwisted}$.

liquid crystal cell $LCMP_{E-field}$ is not equivalent to an ideal neutral density filter and there is some birefringence effect.

Figure 5.3 shows cross-sections for the four micropolarimeters. Note the different LC molecules arrangements are achieved by using LC photoalignment layers. By selectively photo-patterning the inner surfaces of the LC cells, we can make an LC cell act as a retarder, neutral density filter or rotator (Figure 5.3). The latter occurs wherever the orientation of the bottom inner layer is not identical to the top inner layer, in which case incoming light follows the rotation of the molecules. In E-field mode, the orientation of the LC molecules is that of the applied electric field.

5.2.2 Liquid-crystal Micropolarimeter Array Fabrication

To demonstrate the proposed micropolarimeter array technology, we have fabricated LCMP arrays comprising 40000 superpixels (200×200). The size of each superpixel is $20\mu m \times 20\mu m$. Each LCMP was fabricated on a transparent glass substrate, referred to as “second substrate” in Figure 5.4. The use of this dummy CMOS imager substrate enables the optical characterization of each fabricated LCMP, since a CMOS imager substrate is itself opaque. Future work will focus on the actual integration of the proposed LCMP on top of custom made CMOS imager.

Figure 5.4 shows a cross-section of the fabricated LCMP array. The two transparent thin glass slides, used to encapsulate the LC layer, are referred to as “first substrate” and “second substrate”. Note that the visible-regime 150nm-thick MWGP (from Moxtek Inc.) is placed on the inner surface of the second substrate. Azo-dye SD1 was synthesized and used as photoalignment layer to orient the LC molecules. This SD1 material is sensitive to UV light with its peak absorbance at a wavelength of 360nm. This material exhibits a molecular photo-reorientation mechanism characterized by SD1 long molecular axis perpendicular to the polarization direction of projected polarized UV light.

Figure 5.4: (A) Cross-section of proposed CMOS polarization image sensor with integrated LCMP array; (B) fabricated LCMP array with the second substrate as “dummy” CMOS imager substrate to enable LCMPs’ optical characterization (CMOS imager substrate is opaque).

Depending on the orientation of the photo-patterned inner surfaces of the LC cell, the latter can act as a retarder, neutral density filter, or a rotator. The fabrication of the proposed liquid-crystal micropolarimeter array can be summarized as follows:

- An ITO layer with 70nm thickness is deposited on top of the inner surfaces of both the first and the second substrates.
- The deposited ITO layer of the second substrate is selectively etched by a solution composed of hydrochloric acid (HCl), nitric acid (HNO_3) and water (4:1:2 by volume). The remaining ITO regions form the electrodes for $LCMP_{E-field}$ (Figure 5.3).
- The inner surfaces of the two substrates are processed with an UVO cleaner (Model 144AX from Jelight Inc.) for 20min to remove organic contaminants and improve the uniformity of the spin coated LC photoalignment layer.
- An SD1 solution is spin-coated onto the inner surfaces of the two substrates at 800rpm for 10s then 3000rpm for 40s. In order to eliminate

particle impurities, an SD1 solution in DMF, with a concentration of 1% by weight, is filtered before the spin coating.

- The substrates are then baked at 110°C for 20 min to remove the remaining solvent and strengthen the adhesion of SD1 material to the substrates.
- The inner surfaces of the two substrates with the SD1 coating are exposed to 90° linearly polarized UV light for 15min without using any photolithography mask. This results in a 0° photoalignment of the SD1 molecules throughout the entire photoalignment layer.
- Subsequently, the inner surface of the second substrate with the SD1 coating is exposed to -45° linearly polarized UV light for 15min, with a photolithography mask exposing the regions of $LCMP_{45^\circ twisted}$ (Figure 5.3), resulting in a 45° photo-reorientation of the SD1 molecules within the exposed regions.
- The inner surface of the second substrate with the SD1 coating is then exposed to 45° linearly polarized UV light for 15min with a photolithography mask exposing the regions of $LCMP_{-45^\circ twisted}$ (Figure 5.3), resulting in a -45° photo-reorientation of the SD1 molecules within the exposed regions.
- Glass fiber rod spacers with 5μm diameter are sprayed on the inner surface of the first substrate. The two substrates are then assembled together with their inner surfaces facing each other and a 5μm cell gap between the inner surfaces. Thermal epoxy is used for this assembly and the attached substrates are placed into a 120°C oven for one hour to cure the epoxy.
- The resulting empty LC cell is then filled with liquid crystal E7 (from Merck Inc.) before being end-sealed with a thermal epoxy, cured as outlined in the previous step.

5.2.3 Experimental Results

Figure 5.5: Microphotographs of fabricated LCMP array illuminated by linearly or circularly polarized input: (A) 0° linearly polarized; (B) 90° linearly polarized; (C) -45° linearly polarized; (D) right-handed circularly polarized; (E) left-handed circularly polarized.

In order to characterize the optical performance of the fabricated micropolarimeters, a polarization state generator (PSG) composed of a commercial linear polarizer (from Moxtek Inc.) and a commercial broadband quarter wavelength retarder (from Nitto Denko Corp.) was used to generate six different polarized inputs: 0° linearly polarized, 90° linearly polarized, 45° linearly polarized, -45° linearly polarized, right-handed circularly polarized and left-handed circularly polarized. Their corresponding normalized Stokes parameters (S_1/S_0 , S_2/S_0 , S_3/S_0) are (1, 0, 0), (-1, 0, 0), (0, 1, 0), (0, -1, 0), (0, 0, 1) and (0, 0, -1), respectively [3]. The fabri-

cated LCMP array was placed under a microscope with back illumination collimated by a 500nm monochromatic filter and the above-mentioned PSG. Figure 5.5 presents recorded microphotographs. Note that $LCMP_{45^\circ twisted}$, $LCMP_{-45^\circ twisted}$ and $LCMP_{E-field}$ should appear dark when the polarization state of the input light is 90° , 0° and -45° linearly polarized, respectively. $LCMP_{Untwisted}$ should be insensitive to linearly polarized input and should theoretically attenuate half of the input light intensity [3]. This is why it appears grey in Figure 5.5 (A)–(C). In addition, $LCMP_{Untwisted}$ appears bright when the input is right-handed circularly polarized [Figure 5.5 (D)] and dark when the input is left-handed circularly polarized [Figure 5.5 (E)]. It follows that $LCMP_{Untwisted}$ behaves as a right-handed circular polarization analyzer.

Malus measurements were conducted for $LCMP_{45^\circ twisted}$, $LCMP_{-45^\circ twisted}$ and $LCMP_{E-field}$ to extract the two important figures of merit that are major principal transmittance and extinction ratio [3]. They are defined as the maximum transmittance and the ratio between the maximum transmittance and the minimum transmittance in the Malus measurement, respectively [3]. Single LCMP samples with a size of $2.5cm \times 2.0cm$ were fabricated together with the LCMP array to cover the laser beam and enable the LCMP optical characterization. The above-mentioned PSG was inserted between a tunable mini deuterium halogen light source (Model DT-Mini-2-GS from Mikropack GmbH) and the LCMP samples to provide linearly polarized input light with wavelength varied from 400nm to 700nm. A high resolution spectrometer (Model HR2000 from Ocean Optics Inc.) and a computer control were used to calculate and record the light transmitted through the samples. Figure 5.6, Figure 5.7 and Figure 5.8 present the Malus measurement results for three different wavelengths: 450nm (blue light), 550nm (green light) and 650nm (red light). Note that Malus' law is well satisfied for $LCMP_{45^\circ twisted}$, $LCMP_{-45^\circ twisted}$ and $LCMP_{E-field}$ for different wavelengths. Right-handed and left-handed circularly polarized inputs were also provided to illuminate the corresponding LCMP sample and measure its spectral responses. Figure 5.9 shows the

spectral measurement results, with the transmittance maximum for a wavelength of 500nm. This means that the LC cell of $LCMP_{Untwisted}$ behaves as a quarter wavelength retarder for a wavelength of 500nm. Table 5.1 reports the measured extinction ratios for the four LCMPs at a wavelength of 500nm. Note that the values are around 1100, indicating that the MWGP's original extinction ratio is well retained [77–79].

Table 5.1: Extinction ratios of different LCMPs

	Wavelength (500nm)
$LCMP_{45^\circ twisted}$	1132
$LCMP_{-45^\circ twisted}$	1125
$LCMP_{E-field}$	1128
$LCMP_{Untwisted}$	1158

Figure 5.6: Malus measurement results of $LCMP_{45^\circ twisted}$.

The PSG-collimated monochromatic light source (500nm) was used to evaluate the performance of the proposed LCMP optical model [Eq.(5.14)]. The recorded transmittances were compensated by taking into account the transmission loss due to non-polarizing effects, such as surface reflection of glass substrate, non-polarizing absorption/scattering of both LC and MWGP

Figure 5.7: Malus measurement results of $LCMP_{-45^\circ twisted}$.

Figure 5.8: Malus measurement results of $LCMP_{E-field}$.

Figure 5.9: Spectral measurement results of $LCMP_{Untwisted}$.

layers. A collimated unpolarized light beam was projected onto the samples to measure this transmission loss. The compensated transmittances through the single LCMP samples were fed into the proposed LCMP model [Eq.(5.14)], with the model parameters evaluated using Eq.(5.2)-Eq.(5.8):

$$\begin{bmatrix} D_1 & E_1 & F_1 \\ D_2 & E_2 & F_2 \\ D_3 & E_3 & F_3 \\ D_4 & E_4 & F_4 \end{bmatrix} = \begin{bmatrix} 0.9867 & 0.1100 & 0.1193 \\ -0.9867 & 0.1100 & 0.1193 \\ 0.0000 & 0.0000 & 1.0000 \\ 0.0000 & 1.0000 & 0.0000 \end{bmatrix} \quad (5.16)$$

The extracted Stokes parameters, normalized to light intensity (i.e. S_0), are reported in Table 5.2. The fabricated LCMPs are found to behave as expected within 2.3%. Errors can be attributed to measurement noise, round off errors in calculations but also to slight deviations of:

- $\pm 0.5^\circ$ for the LC photoalignment direction, which was manually controlled with a protractor.
- $\pm 1^\circ$ for the LC twist angle ϕ , which was defined by assembling the two

glass substrates.

- $\pm 0.1\mu m$ for the LC layer thickness d , which was controlled by glass fiber rod spacers.
- $\pm 5nm$ for the applied monochromatic filter and $\pm 2 \sim 3^\circ C$ for the room temperature control. These variations can affect the LC birefringence.

Future work will focus on integrating the proposed LCMP array on top of a custom made CMOS imager to evaluate the polarimetric imaging capabilities of a single-chip polarization CMOS imager.

Table 5.2: Comparison between experimentally extracted Stokes parameters and ideal values for different polarized inputs

Polarized inputs	Ideal values			Experimentally extracted			Error (%)		
	S_1/S_0	S_2/S_0	S_3/S_0	S_1/S_0	S_2/S_0	S_3/S_0	S_1/S_0	S_2/S_0	S_3/S_0
0° linearly	1	0	0	1.009	0.013	-0.009	0.9	1.3	0.9
90° linearly	-1	0	0	-1.012	0.017	0.012	1.2	1.7	1.2
45° linearly	0	1	0	-0.011	1.008	0.004	1.1	0.8	0.4
-45° linearly	0	-1	0	0.003	-0.998	-0.012	0.3	0.2	1.2
R-circularly	0	0	1	0.003	-0.013	0.977	0.3	1.3	2.3
L-circularly	0	0	-1	0.004	-0.003	-0.998	0.4	0.3	0.2

5.3 Conclusion

In this chapter, we have demonstrated a liquid-crystal based micropolarimeter array for full Stokes polarization imaging in visible spectrum. In contrast to previously reported micropolarizer arrays, the proposed implementation enables, for the first time, the extraction of circularly polarized components of light for real-time full Stokes polarimetry. To accommodate applications with large oblique incidence angle, a 150nm ultra-thin visible-regime MWGP is used to reduce the overall thickness of the micropolarimeter array layer to $5\mu m$. This provides a relatively good aspect ratio for pixel size larger than

$10\mu m$. Experimental results indicate that the LC-MWGP structure retains MWGP's superior optical characteristics with a pass transmittance of 75% and extinction ratios of around 1100.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

This thesis has investigated, modeled, designed, fabricated and characterized novel micropolarizing devices that could be fully integrated on top of a CMOS image sensor, to enable the concept of a single-chip CMOS polarization image sensor. This unique concept removes the need for registration and offers the opportunity to fabricate low cost compact cameras, with superior polarization acquisition capability. Furthermore, the miniature size of a camera-on-chip enables new applications such as *in-vivo* body exploration. A camera-on-chip will integrate photo-sensing array and signal processing circuitry on a single chip, enabling the development of a new generation of high performance mobile imaging systems. The “selling point” behind the emergence of integrated camera technology lies in the use of semiconductor industry standard CMOS process. This widespread accessible process with well-developed design tools, standard design libraries and fast turn-around time, leads to reduced development and fabrication costs.

In this thesis, the developed micropolarizer designs allow for all possible polarization states of incident light to be captured in a single frame. Fur-

thermore, all the developed micropolarizer fabrication technologies completely remove the need for complex selective etching, which is difficult to control at the micrometer scale. Instead, they all use the well-controlled process of UV photolithography for the high resolution patterning of pixel-level micropolarizing elements.

For PDI, we propose a superior photo-patterned LC based MPA fabrication technology that enables one to control the values of the extinction ratio and transmittance by simply selecting a suitable commercially available linear polarizer for the targeted application. Compared with previously reported LC based MPA implementations, the spatial resolution is dramatically scaled down from $\sim 100\mu m$ to $2\mu m$.

For PLPI, UV photoalignment is used to define micropolarizer orientation patterns on a spin-coated AD1 film. This material exhibits a strong dichroism after sufficient exposure to linearly polarized UV light. The rod-like molecules of a spin-coated AD1 film can be oriented with their long molecular axes perpendicular to the orientation of the projected polarized UV light. However, the orientation degree of AD1 molecules is a function of the exposure energy and saturates after prolonged UV exposure. As a result, a UV-patterned polymer AD1 film exhibits limited major principal transmittance and extinction ratio. To improve the orientation degree of AD1 molecules and thus the optical performance, we propose to exploit “guest-host” interactions in liquid crystals. With dichroic AD1 molecules as the “guest” and PLC molecules as the “host” we demonstrate a better control of the molecular orientation of the “guest” which in turn results in a 25% increase of the major principal transmittance and a 139% increase of the peak extinction ratio. The proposed micropolarizer fabrication technology is simple and cost-effective, requiring only selective photo-patterning of a “guest-host” polymer spin-coated over the image sensor.

For full Stokes polarization imaging, we describe the design, modeling, fabrication, and optical characterization of the first micropolarimeter array

enabling the simultaneous capture of all Stokes vector components whether linear or circular. The proposed micropolarimeter is fabricated by patterning an LC layer on top of a visible-regime MWGP using UV sensitive sulfonic-dye-1 as the LC photoalignment material. This arrangement enables the formation of either micrometer-scale LC polarization rotators, neutral density filters or quarter wavelength retarders. These elements are in turn exploited to acquire all components of the Stokes vector, which describes all possible polarization states of light. Reported major principal transmittance of 75% and extinction ratio of 1100 demonstrate that the MWGPs' superior optical characteristics are retained. The proposed liquid-crystal micropolarimeter array can be integrated on top of a CMOS image sensor for real-time full Stokes polarization imaging.

6.2 Future Work

The contribution of this thesis lies with the design, modeling, fabrication and characterization of high performance micropolarizing devices for CMOS polarization image sensors. To enable the development of a miniature single-chip CMOS polarization camera, future work could include:

- Integrating developed micropolarizing devices on top of CMOS image sensors and evaluating the performance of single-chip CMOS polarization cameras. This actual integration of the micropolarimeter array requires either the fabrication of a custom made image sensor or a close collaboration with a semiconductor fabrication plant, such as TSMC, UMC and AMIS.
- Investigating the benefits of applying different interpolation strategies to estimate the missing parameters at each point, since each pixel can only sense one of the four polarized intensities required to estimate the Stokes vector at each location. The developed interpolation strategies will need to be VLSI-friendly to enable their on-chip integration.

- Exploring new polarization dichroic material and alignment technologies to further improve the micropolarizing elements' optical performance, such as major principal transmittance, extinction ratio.
- Developing a compact and robust circuitry to compute Stokes parameters and compensate for non-idealities such as non-uniform optical performance parameters (e.g. extinction ratio) across the micropolarizing device array.

Bibliography

- [1] L. B. Wolff and A. G. Andreou, "Polarization camera sensors," *Image and Vision Computing*, vol. 13, no. 6, pp. 497-510, 1995.
- [2] M. Momeni and A. H. Titus, "An analog VLSI chip emulating polarization vision of octopus retina," *IEEE Transactions on Neural Networks*, vol. 17, no. 1, pp. 222-232, 2006.
- [3] D. Goldstein, *Polarized Light*, 2nd Edition, New York: Marcel Dekker, 2003.
- [4] A. G. Andreou and Z. K. Kalayjian, "Polarization Imaging: Principles and Integrated Polarimeters," *IEEE Sensors Journal*, vol. 2, no. 6, pp. 566-576, 2002.
- [5] G. C. Giakos, "Multifusion, multispectral, optical polarimetric imaging sensing principles," *IEEE Transactions on Instrumentation and Measurement*, vol. 55, no. 5, pp. 1628-1633, 2006.
- [6] J. S. Tyo, D. L. Goldstein, D. B. Chenault and J. A. Shaw, "Review of passive imaging polarimetry for remote sensing applications," *Applied Optics*, vol. 45, no. 22, pp. 5453-5469, 2006.
- [7] M. P. Rowe, E. N. Pugh, Jr., J. Scott Tyo and N. Engheta, "Polarization-difference imaging: a biologically inspired technique for imaging in scattering media," *Optics Letters*, vol. 20, no. 6, pp. 608-610, 1995.

- [8] S. Lin, K. M. Yemelyanov, E. N. Pugh, Jr. and N. Engheta, "Polarization-based and specular-reflection-based noncontact latent fingerprint imaging and lifting," *Journal of Optical Society of America A*, vol. 23, no. 9, pp. 2137-2152, 2006.
- [9] S. G. Demos, H. B. Radousky and R. R. Alfano, "Deep subsurface imaging in tissues using spectral and polarization filtering," *Optics Express*, vol. 7, no. 1, pp. 23-28, 2000.
- [10] S. G. Demos and R. R. Alfano, "Optical polarization imaging," *Applied Optics*, vol. 36, no. 1, pp. 150-155, 1997.
- [11] G. F. Sudha and T. G. Palanivelu, "Polarimetric imaging of subsurface tissue-numerical results," *Journal of Biomedical Optics*, vol. 10, no. 5, pp. 054014-054018, 2005.
- [12] R. Gurjar, V. Backman, L. T. Perelman, I. Georgakoudi, K. Badizadegan, I. Itzkan, R. R. Dasari and M. S. Feld, "Imaging human epithelial properties with polarized light-scattering spectroscopy," *Nature Medicine*, vol. 7, no. 11, pp. 1245-1248, 2001.
- [13] S. L. Jacques, J. C. Ramella-Roman and K. Lee, "Imaging skin pathology with polarized light," *Journal of Biomedical Optics*, vol. 7, no. 3, pp. 329-340, 2002.
- [14] L. B. Wolff, T. A. Mancini, P. Pouliquen and A. G. Andreou, "Liquid Crystal Polarization Camera," *IEEE Transactions on Robotics and Automation*, vol. 13, no. 2, pp. 195-203, 1997.
- [15] J. D. Barter, H. R. Thompson, Jr., and C. L. Richardson, "Visible-regime polarimetric imager: a fully polarimetric, real-time imaging system," *Applied Optics*, vol. 42, no. 9, pp. 1620-1628, 2003.
- [16] J. D. Barter and P. H. Y. Lee, "Visible Stokes polarimetric imager," *U. S. Patent*, 6,122,404, 2000.

- [17] A. El Gamal and H. Eltoukhy, “CMOS image sensors,” *IEEE Circuits and Devices Magazine*, vol. 21, no. 3, pp. 6-20, 2005.
- [18] S. M. Faris, “Methods for manufacturing micropolarizers,” *U. S. Patent*, 5,327,285, 1994.
- [19] V. Gruev, A. Ortu, N. Lazarus, J. Van de Spiegel and N. Engheta, “Fabrication of a Dual-Tier Thin Film Micro Polarization Array,” *Optics Express*, vol. 15, no. 8, pp. 4994-5007, 2007.
- [20] V. Gruev, J. Van der Spiegel and N. Engheta, “Image Sensor With Focal Plane Polarization Sensitivity,” *Proceedings of International Symposium on Circuits and Systems (ISCAS)*, pp. 1028-1031, 2008.
- [21] J. Guo and D. Brady, “Fabrication of thin-film micropolarizer arrays for visible imaging polarimetry,” *Applied Optics*, vol. 39, no. 10, pp. 1486-1492, 2000.
- [22] C. K. Harnett and H. G. Craighead, “Liquid-crystal micropolarizer array for polarization-difference imaging,” *Applied Optics*, vol. 41, no. 7, pp. 1291-1296, 2002.
- [23] E. R. Fossum, “CMOS image sensors: electronic camera-on-a-chip,” *IEEE Transactions on Electron Devices*, vol. 44, no. 10, pp. 1689-1698, 1997.
- [24] E. Culurciello, R. Etienne-Cummings and K. A. Boahen, “A biomorphic digital image sensor,” *IEEE Journal of Solid-State Circuits*, vol. 38, no. 2, pp. 281-294, 2003.
- [25] W. Yang, “A Wide-Dynamic-Range, Low-Power Photosensor Array,” *Proceedings of IEEE International Solid State Circuits Conference (ISSCC)*, pp. 230-231, 1994.
- [26] X. Qi, X. Guo and J. G. Harris, “A Time-to-first Spike CMOS Imager,” *Proceedings of IEEE International Symposium on Circuits and Systems (ISCAS)*, vol. 4, pp. 23-26, 2004.

- [27] A. Bermak, "A CMOS Imager with PFM/PWM based Analog-to-digital Converter," *Proceedings of IEEE International Symposium on Circuits and Systems (ISCAS)*, vol. 4, pp. 53-56, 2002.
- [28] A. Kitchen, A. Bermak and A. Bouzerdoun, "PWM digital pixel sensor based on asynchronous self-resetting scheme," *IEEE Electron Device Letters*, vol. 25, no. 7, pp. 471-473, 2004.
- [29] N. J. Pust and J. A. Shaw, "Dual-field imaging polarimeter using liquid crystal variable retarders," *Applied Optics*, vol. 45, no. 22, pp. 5470-5478, 2006.
- [30] B. E. Bayer, "Color imaging array," *U. S. Patent*, 3,971,065, 1976.
- [31] R. B. Merrill, "Color separation in an active pixel cell imaging array using a triple-well structure," *U.S. Patent*, 5,965,875, 1999.
- [32] X. Zhao, F. Boussaid and A. Bermak, "Characterization of a $0.18\mu\text{m}$ CMOS Color Processing Scheme for Skin Detection," *IEEE Sensors Journal*, vol. 7, no. 11, pp. 1471-1474, 2007.
- [33] X. Zhao, S. Chen, F. Boussaid and A. Bermak, "A $0.18\mu\text{m}$ CMOS On-Chip Skin Detection Scheme Based on NPNP-Triple-Junction Structure," *Proceedings of IEEE International Symposium on Integrated Circuits (ISIC)*, pp. 333-336, 2007.
- [34] F. Goudail, P. Terrier, Y. Takakura, L. Bigue, F. Galland and V. De-Vlaminck, "Target detection with a liquid-crystal-based passive Stokes polarimeter," *Applied Optics*, vol. 43, no. 2, pp. 274-282, 2004.
- [35] M. Honma, T. Nose and S. Sato, "Liquid crystal polarization-converting devices for edge and corner extractions of images using optical wavelet transforms," *Applied Optics*, vol. 45, no. 13, pp. 3083-3090, 2006.
- [36] T. H. Waterman, "Polarization Sensitivity," *Handbook of Sensory Physiology, Vision of Invertebrates*, New York: Springer, 1981.

- [37] V. Gruev, J. Van der Spiegel and N. Engheta, “Nano-wire Dual Layer Polarization Filter,” *Proceedings of IEEE International Symposium on Circuits and Systems (ISCAS)*, pp. 561-564, 2009.
- [38] V. Gruev and R. Perkins, “A 1M Pixel CCD Image Sensor with Aluminum Nanowire Polarization Filter,” *Proceedings of IEEE International Symposium on Circuits and Systems (ISCAS)*, pp. 629-632, 2010.
- [39] R. Njuguna and V. Gruev, “Linear Current Mode Image Sensor With Focal Plane Spatial Image Processing,” *Proceedings of IEEE International Symposium on Circuits and Systems (ISCAS)*, pp. 4265-4268, 2010.
- [40] T. Tokuda, S. Sato, H. Yamada and J. Ohta, “Polarization analyzing CMOS sensor for microchamber/microfluidic system based on image sensor technology,” *Proceedings of IEEE International Symposium on Circuits and Systems (ISCAS)*, pp. 3162–3165, 2008.
- [41] T. Tokuda, S. Sato, H. Yamada, K. Sasagawa and J. Ohta, “Polarization-analyzing CMOS photosensor with monolithically embedded wire grid polarizer,” *Electronics Letters*, vol. 45, no. 4, pp. 228–230, 2009.
- [42] T. Tokuda, H. Yamada, K. Sasagawa and J. Ohta, “Polarization-Analyzing CMOS Image Sensor with Monolithically Embedded Polarizer for Microchemistry Systems,” *IEEE Transactions on Biomedical Circuits and Systems*, vol. 3, no. 5, pp. 259–266, 2009.
- [43] M. Sarkar, D. S. S. Bello, C. van Hoof and A. Theuwissen, “Integrated polarization-analyzing CMOS image sensor for detecting incoming light ray direction,” *Proceedings of IEEE International Symposium on Circuits and Systems (ISCAS)*, pp. 621-624, 2010.
- [44] Z. K. Kalayjian, A. Andreou, L. Wolff and N. Sheppard, “A polarization contrast retina that uses patterned iodine-doped PVA film,” *Proceedings of 22nd European Solid-State Circuits Conference*, pp. 308-311, 1996.

- [45] Z. K. Kalayjian, A. Andreou and L. Wolff, "1D polarizaiton contrast retina," *Electronics Letters*, vol. 33, no.1, pp. 38-40, 1997.
- [46] Z. K. Kalayjian and A. Andreou, "Integrated high resolution focal-plane polarizaiton imager," *Proceedings of ISA EXPO*, 1998.
- [47] Z. K. Kalayjian and A. Andreou, "Silicon retina for polarization contrast vision," *Proceedings of International Joint Conference on Neural Networks*, pp. 2329-2332, 1999.
- [48] J. Guo and D. Brady, "Fabrication of high-resolution micropolarizer arrays," *Optical Engineering*, vol. 36, no. 8, pp. 2268-2271, 1997.
- [49] Z. Wang, S. F. Han, A. W. Divelbiss and D. C. Swift, "Twisted nematic micropolarizer and its method of manufacturing," *U. S. Patent*, 7,385,669 B2, 2008.
- [50] V. Gruev, J. Van der Spiegel and N. Engheta, "Image Sensor With Focal Plane Extraction of Polarimetric Information," *Proceedings of IEEE International Symposium on Circuits and Systems (ISCAS)*, pp. 213-216, 2006.
- [51] V. Gruev, J. Van der Spiegel and N. Engheta, "Low Power Image Sensor With Polymer Polarization Filters," *Proceedings of IEEE International Symposium on Circuits and Systems (ISCAS)*, pp. 1412-1415, 2008.
- [52] J. Wang, L. Chen, X. Liu, P. Sciortino, F. Liu, F. Walters and X. Deng, "30-nm-wide aluminum nanowire grid for ultrahigh contrast and transmittance polarizers made by UV-nanoimprint lithography," *Applied Physics Letters*, vol. 89, 141105, 2006.
- [53] J. J. Wang, F. Walters, X. Liu, P. Sciortino and X. Deng, "High-performance, large area, deep ultraviolet to infrared polarizers based on 40nm line/78nm space nanowire grids," *Applied Physics Letters*, vol. 90, 061104, 2007.

- [54] S. W. Ahn, K. D. Lee, J. S. Kim, S. H. Kim, J. D. Park, S. H. Lee and P. W. Yoon, "Fabrication of a 50nm half-pitch wire grid polarizer using nanoimprint lithography," *Nanotechnology*, vol. 16, pp. 1874-1877, 2005.
- [55] S. T. Tang and H. S. Kwok, "Characteristic Parameters of Liquid Crystal Cells and Their Measurements," *Journal of Display Technology*, vol. 2, no. 1, pp. 26-31, 2006.
- [56] V. G. Chigrinov, H. S. Kwok, H. Takada and H. Takatsu, "New Developments in Liquid Crystal Photo-Aligning by Azo-Dyes," *Proceedings of Society for Information Display (SID) Digest*, pp. 1253-1256, 2006.
- [57] V. G. Chigrinov, H. S. Kwok, H. Takada and H. Takatsu, "Photo-aligning by azo-dyes: Physics and applications," *Liquid Crystals Today*, vol. 14, no. 4, pp. 1-15, 2005.
- [58] V. Chigrinov, E. Prudnikova, V. Kozenkov, H. Kwok, H. Akiyama, T. Kawara, H. Takada and H. Takatsu, "Synthesis and properties of azo dye aligning layers for liquid crystal cells," *Liquid Crystals*, vol. 29, no. 10, pp. 1321-1327, 2002.
- [59] X. Zhao, A. Bermak, F. Boussaid, T. Du and V. G. Chigrinov, "High-resolution photo-aligned liquid-crystal micropolarizer array for polarization imaging in visible spectrum," *Optics Letters*, vol. 34, no. 23, pp. 3619-3621, 2009.
- [60] X. Zhao, F. Boussaid, A. Bermak and V. G. Chigrinov, "Thin Photo-Patterned Micropolarizer Array for CMOS Image Sensors," *IEEE Photonics Technology Letters*, vol. 21, no. 12, pp. 805-807, 2009.
- [61] X. Wu, X. Zhao, A. Bermak and F. Boussaid, "An AER based CMOS polarization image sensor with photo-aligned micropolarizer array," *Proceedings of Asia Symposium on Quality Electronic Design (ASQED)*, pp. 126-130, 2009.

- [62] X. Zhao, A. Bermak and F. Boussaid, "A CMOS Digital Pixel Sensor with Photo-Patterned Micropolarizer Array for Real-Time Focal-Plane Polarization Imaging," *Proceedings of IEEE Biomedical Circuits and Systems Conference (BioCAS)*, pp. 145-148, 2008.
- [63] G. H. Heilmeyer and L. A. Zanoni, "Guest-Host Interactions in Nematic Liquid Crystals: A New Electro-Optic Effect," *Applied Physics Letters*, vol. 13, no. 3, pp. 91-92, 1968.
- [64] X. Zhao, A. Bermak, F. Boussaid and V. G. Chigrinov, "A 'Guest-Host' Micropolarizer Array Based on Photo-aligned Polymerizable Nematic Liquid Crystal," submitted to *IEEE Photonics Technology Letters*, 2010.
- [65] G. D. Gilbert and J. C. Pernicka, "Improvement of underwater visibility by reduction of backscatter with a circular polarization technique," *Applied Optics*, vol. 6, no. 4, pp. 741-746, 1967.
- [66] G. D. Gilbert, "The effects of particle size on contrast improvement by polarization discrimination for underwater targets," *Applied Optics*, vol. 9, no. 2, pp. 421-428, 1970.
- [67] J. Cariou, B. L. Jeune, J. Lotrian and Y. Guern, "Polarization effects of seawater and underwater targets," *Applied Optics*, vol. 29, no. 11, pp. 1689-1695, 1990.
- [68] P. C. Y. Chang, J. G. Walker, K. I. Hopcraft, B. Ablitt and E. Jakeman, "Polarization discrimination for active imaging in scattering media," *Optics Communications*, vol. 159, no. 1, pp. 1-6, 1999.
- [69] K. Turpin, J. G. Walker, P. C. Y. Chang, K. I. Hopcraft, B. Ablitt and E. Jakeman, "The influence of particle size in active polarization imaging in scattering media," *Optics Communications*, vol. 168, no. 5, pp. 325-335, 1999.

- [70] S. P. Morgan and I. M. Stockford, "Surface-reflection elimination in polarization imaging of superficial tissue," *Optics Letters*, vol. 28, no. 2, pp. 114-116, 2003.
- [71] S. P. Morgan, Q. Zhu, I. M. Stockford and J. A. Crowe, "Rotating orthogonal polarization imaging," *Optics Letters*, vol. 33, no. 13, pp. 1503-1505, 2008.
- [72] G. Moneron, A. C. Boccara and A. Dubois, "Polarization-sensitive full-field optical coherence tomography," *Optics Letters*, vol. 32, no. 14, pp. 2058-2060, 2007.
- [73] T. H. Chiou, S. Kleinlogel, T. Cronin, R. Caldwell, B. Loeffler, A. Siddiqi, A. Goldizen and J. Marshall, "Circular Polarization Vision in a Stomatopod Crustacean," *Current Biology*, vol. 18, no. 6, pp. 429-434, 2008.
- [74] N. W. Roberts, T. H. Chiou, N. J. Marshall and T. W. Cronin, "A biological quarter-wave retarder with excellent achromaticity in the visible wavelength region," *Nature Photonics*, vol. 3, no. 11, pp. 641-644, 2009.
- [75] H. Hasebe, Y. Kuwana, H. Nakata, O. Yamazaki, K. Takeuchi and H. Takatsu, "High Quality Patterned Retarder for Transflective LCDs," *Proceedings of Society for Information Display (SID) Digest*, pp. 1904-1907, 2008.
- [76] X. Zhao, A. Bermak, F. Boussaid, L. Yao and V. G. Chigrinov, "A High-Resolution Micro-Circular-Polarization-Analyzer Array for Real-Time Active Circular Polarization Imaging," *Proceedings of IEEE Biomedical Circuits and Systems Conference (BioCAS)*, pp. 49-52, 2009.
- [77] X. Zhao, A. Bermak, F. Boussaid and V. G. Chigrinov, "Liquid-crystal micropolarimeter array for visible linear and circular polarization imaging," *Proceedings of IEEE International Symposium on Circuits and Systems (ISCAS)*, pp. 637-640, 2010.

- [78] X. Zhao, A. Bermak, F. Boussaid and V. G. Chigrinov, “Liquid-crystal micropolarimeter array for full Stokes polarization imaging in visible spectrum,” *Optics Express*, vol. 18, no. 17, pp. 17776-17787, 2010.
- [79] MOXTEK Inc., “PPL Series”, Available at: <http://www.moxtek.com/products/optics/polarizers/ppl>, [date accessed: 27 Sep. 2010].