

Table of Contents

Abstract (Chinese)	i
Abstract (English)	iii
Table of Contents	v
Figure Captions	ix
List of Tables	xv

Chapter 1 Introduction.....	1
1.1 Information Display Technology.....	1
1.2 Liquid Crystal Displays.....	1
1.3 Backlight Systems in Transmissive and Transflective LCDs.....	5
1.4 Non-absorbing Devices in Transmissive and Transflective LCDs.....	7
1.5 Motivation of this Thesis.....	8
1.6 Organization of this Thesis.....	9
1.7 References.....	10
Chapter 2 Principles of LCD Illumination Systems.....	12
2.1 Working Principle of Lightguide Plate.....	12
2.1.1 Optical Design of Lightguide by the Configuration of Light Sources.....	14
2.1.2 Optical Design of Lightguide by Type of Lightguides.....	15
2.1.3 Optical Design of Lightguide by Shapes of Micro-structures.....	16
2.2 Brightness Enhancement Film (BEF).....	20
2.3 Diffuser Films.....	22
2.4 Polarized Light Propagation in Birefringent Media.....	23
2.5 Reflector Polarizer.....	28
2.6 Concerned Issues for LCD Backlight.....	31
2.7 Simulated Procedures.....	33
2.8 Summary.....	38
2.9 References.....	39

Chapter 3 Fabrication Technologies and Measurement Instruments.....	41
3.1 Introduction.....	41
3.2 Diamond Knife Micro-machining Technology.....	42
3.3 Embossing/Extrusion Technology.....	43
3.4 Injection Molding Technology.....	45
3.5 Measurement Instruments.....	46
3.6 Summary.....	48
3.7 References.....	48
Chapter 4 Polarized Backlights Using Sub-wavelength Grating.....	49
4.1 Principle of Polarized Backlights Using Sub-wavelength Grating.....	49
4.1.1 Theory of the Sub-wavelength Grating.....	50
4.2 Simulation.....	53
4.2.1 Period.....	55
4.2.2 Thickness.....	57
4.3 Double-Layered Sub-Wavelength Grating.....	59
4.3.1 Material of Dielectric Layer.....	60
4.4 Fabrication Technologies.....	64
4.4.1 Electron Beam Lithography (EBL) Technology.....	64
4.4.2 Double-Layered Structure by Using Tri-Level Resist System.....	64
4.4.3 Double-Layered Structure by Using Inductive Coupled Plasma-Reactive Ion Etching (ICP-RIE).....	67
4.5 Measurement System.....	70
4.6 Summary.....	74
4.7 References.....	74
Chapter 5 Polarized Backlights Using Selective Internal Reflection at Micro-grooves.....	76
5.1 Principle of Polarized Backlights Using Selective T.I.R.....	76
5.2 Theory of Selective T.I.R at Micro-grooves.....	77
5.3 Simulation.....	79

5.3.1 Index-mismatching of the Coating Layer.....	80
5.3.2 Influence of Vertex Angles of Micro-grooves.....	82
5.3.3 Influence of Various Substrates.....	86
5.4 Fabrication.....	88
5.5 Measurement.....	89
5.5.1 Uniformity.....	92
5.5.2 Gain of Efficiency.....	93
5.6 Discussion.....	94
5.6.1 Broadening Angular Distribution.....	94
5.6.2 Backward Polarized light Emission.....	96
5.7 Summary.....	98
5.8 References.....	98

Chapter 6 Directional Backlights for Time-multiplexed 3D Displays.....99

6.1 Introduction.....	99
6.1.1 Lenticular Plate.....	100
6.1.2 Integral Imaging.....	102
6.1.3 Parallax Barrier.....	102
6.2 Theory.....	108
6.3 Simulation.....	113
6.4 Fabrication.....	115
6.5 Measurement.....	117
6.6 Concerned Issues.....	119
6.7 Impulse Driving.....	124
6.8 Conclusion.....	126
6.9 References.....	126

Chapter 7 Conclusions and Future Works.....128

7.1.1 Sub-wavelength Grating for Polarization Conversion.....	129
7.1.2 Selective T.I.R at Micro grooves for Polarization Conversion.....	130
7.1.3 Directional Backlights for Time-multiplexed 3D Displays.....	131

7.2 Future Works.....	132
7.2.1 High Efficiency Color Sequential LCD Illumination Systems.....	132
7.2.2 High Efficiency Tandem LCD Illumination Systems for LCD-TVs.....	134
7.3 References.....	135
Appendix – Color Demo Photographs	136
Appendix –Awards.....	138
Publication List	139
Vita	142



Figure Captions

Fig. 1-1. Liquid crystal cell and module layout.....	2
Fig. 1-2. Schematics of a Twisted Nematic (TN) liquid crystal display cell. Incident light is transmissive and absorbed, respectively, by switching off and on the LC cells.....	3
Fig. 1-3. Schematics comparison of LCD types with respective to illuminating light source. (a) reflective (b) transreflective and (c) transmissive LCDs.....	4
Fig. 1-4. Schematics of conventional LCD backlight systems.....	6
Fig. 1-5. Transmissive LCDs with backlight system and the light efficiency after light passes through each component of the LCDs.....	6
Fig. 2-1. Total internal reflection of incident light in the lightguide with PMMA substrate.....	13
Fig. 2-2. Schematics of (a) single edge-lighted and (b) dual edge-lighted lightguides.....	14
Fig. 2-3. Schematics of (a) rectangular type and (b) wedged type lightguides.....	16
Fig. 2-4. Schematics of the micro-reflector array. (a) Incident light on the optical surface of the MR element is reflected. (b) Array of the MR elements on the bottom surface of the lightguide.....	17
Fig. 2-5. Schematics of lightguide with micro-grooves on the bottom surface.....	18
Fig. 2-6. Schematics of lightguide with micro-pyramids on the bottom surface.....	19
Fig. 2-7. The operation of Brightness Enhancement Film (BEF).....	20
Fig. 2-8. Schematics of lightguide with dual patterned surfaces. On the bottom surface, printed dots/ micro structures are covered. On the top surface, micro-grooves are line in Y direction. Only one sheet of BEF, which is line in X direction, is needed.....	22
Fig. 2-9. The structure of diffuser film.....	23
Fig. 2-10. Transformation of a new coordinate axes sets of a polarization ellipse.....	25
Fig. 2-11. The operation of BEF and DBEF.....	29

Fig. 2-12. Schematics of the operation of reflective cholesteric reflective polarizers.....	30
Fig. 2-13. Uniformity of backlights measured by (a) 9-points and (b) 13-points for the mobile size and the notebook size of LCDs, respectively.....	31
Fig. 2-14. (a) Measured angular profiles, (b) measured angular cross section, (c) simulated angular profiles, and (d) simulated angular cross section of Nichia white light LEDs.....	34
Fig. 2-15. Optical devices of backlights built in the simulation model.....	35
Fig. 2-16. Illustration of Monte Carlo ray tracing in the lightguide.....	36
Fig. 2-17. Illustrations of (a) brightness and (b) angular profiles.....	36
Fig. 2-18. (a) Detector array in the backlight model and (b) gradient distributions of lightguide patterns.....	37
Fig. 3-1. (a) Schematics of diamond knife micro-machine and (b) Sharp edge of diamond knife.....	42
Fig. 3-2. Schematics of the fabrication process of embossing optical foils.....	44
Fig. 3-3. Schematics of injection molding machine. The left and right parts of mold are shown. The stamp plate is attached on the left side of mold.....	45
Fig. 3-4. Schematics of measurement setup of ELDIM EZContrast 160R.....	47
Fig. 4-1. Schematics of polarized backlights using sub-wavelength grating. P-polarized light is transmitted while s-polarized light is reflected. S-polarized light is then converted into p-polarized light by passing through the quarter wave plate twice.....	49
Fig. 4-2. Schematic structure of double-layered sub-wavelength grating.....	51
Fig. 4-3. Function of slot structures. The guided rays with oblique incidence were coupled out by the side walls of slot structures. The density of slot structures controlled uniformity on the outcoupling plane.....	52
Fig. 4-4. Illuminance profile of the integrated lightguide. The maximum and minimum values of illuminance are 43000 and 34000 lux, respectively. Consequently, 80% of uniformity was then achieved.....	53
Fig. 4-5. Simulated results of p-polarized light transmission efficiency versus	

wavelength of incident light with various periods of the sub-wavelength grating.....	55
Fig. 4-6. Simulated results of s-polarized light reflection efficiency versus wavelength of incident light with various periods of the sub-wavelength grating.....	56
Fig. 4-7 Simulated results of p-polarized light transmission efficiency versus wavelength of incident light with various thicknesses of metallic layer....	57
Fig. 4-8 Simulated results of s ray reflection efficiency versus wavelength of incident light with various thicknesses of metallic layer.....	58
Fig. 4-9 Simulated results of p-polarized light transmission efficiency versus wavelength of incident light with various materials of dielectric layer....	60
Fig. 4-10 Simulated results of s-polarized light reflection efficiency versus wavelength of incident light with various materials of dielectric layer....	61
Fig. 4-11 Comparison of p-polarized light transmission efficiency between single layer and double layer.....	62
Fig. 4-12 Comparison of s-polarized light reflection efficiency between single layer and double layer.....	62
Fig. 4-13 Flow of fabricating sub-wavelength grating with double-layer structure by using tri-level resist system.....	66
Fig. 4-14 Schematic diagram of high-density-plasma ICP-RIE system.....	67
Fig. 4-15 Flow of fabricating sub-wavelength grating with double layer by using ICP-RIE process.....	69
Fig. 4-16 (a) Top view and (b) cross section of the fabricated sub-wavelength grating.....	70
Fig. 4-17 Schematic diagram of the experimental setup for the characterization of the fabricated sub-wavelength grating.....	70
Fig. 4-18. Comparison of experimental and simulated results of the sub-wavelength grating.....	71
Fig. 5-1. Schematics of polarized backlight. Birefringent layer with micro grooves filled with index-matching layer was aimed to extract the s-polarized light at the interface. Additionally, p-polarized light was trapped in the polymethyl methacrylate (PMMA) lightguide to be recycled.....	76

Fig. 5-2. Illustration of outcoupled s-polarized light due to selective T.I.R at the interface for different half top angles relative to the critical angle $\theta_{c3,4}$ of the anisotropic layer with respect to air:(a) $\varphi < \theta_{c3,4}$ (b) $\varphi = \theta_{c3,4}$ (c) $\varphi > \theta_{c3,4}$	78
Fig. 5-3. Schematics of simulated polarized backlight model built by ASAP.....	79
Fig. 5-4. Illustration of contrast ratio at different refractive index of index-matching layer. Contrast ratio achieves maximum at perfectly matched refractive index $n=1.53$ for PET foil, whereas $n=1.56$ for PEN foil.....	80
Fig. 5-5. Illustration of outcoupled s-polarized light due to selective T.I.R at interface of grooves in anisotropic layer.....	81
Fig. 5-6. Angular distribution of S-polarized light versus vertex angle of grooves in PET foil. The bars represent the amount of angular ranges at FWHM.....	82
Fig. 5-7. Angular distribution of S-polarized light versus vertex angle of grooves in PEN foil.....	83
Fig. 5-8. (a) Angular distributions and (b) Inclined angular cross-sections of extracted s-polarized light at perfectly matched index for PEN and PET foils.....	85
Fig. 5-9. Angular distributions of S-polarized light with (a) PMMA substrate (b) PC substrate while groove angle=50° and perfectly index-matched in PEN foils.....	86
Fig. 5-10. Fabrication process of polarized backlights.....	88
Fig. 5-11 Measurement set up of polarized backlight.....	89
Fig. 5-12. Measured angular profiles of (a) s-polarized light (b) p-polarized light and (c) Contrast ratio of s-polarized to p-polarized light.....	90
Fig. 5-13. Luminance profiles of (a) S-polarized light and (b) P-polarized light. A polarizer was rotated to observe S-polarized and P-polarized light, respectively.....	90
Fig. 5-14. For PEN foil adhered on the substrate of PMMA, luminous intensity versus position from light source for polarized backlight with PEN foil. Curves with square, round, and triangle marks illustrate luminous intensity of s-polarized light with no reflectors, diffuse end reflector only, and both back and end reflectors, respectively.....	91
Fig. 5-15. Measurement set up of flux by (a) clear PMMA (b) polarized backlight with both back and end reflectors.....	92

Fig. 5-16. Schematics of combined grooves with various angles in the birefringent foil.....	94
Fig. 5-17. For $\varphi' = 90^\circ - 270^\circ$ cross section, angular profiles while the vertex angles of grooves are 50° and combined 35° , 50° and 60° , respectively.....	94
Fig. 5-18. (a) Refraction of s-polarized light at the micro grooves (b) Measured angular profiles of s-polarized light from the backside of the lightguide....	95
Fig. 5-19. Dependence of relative intensity on various viewing angles for using a smooth specular reflector and a grooved reflector, respectively.....	96
Fig. 6-1. Principle of lenticular plate to project two images to the respective eyes.....	101
Fig. 6-2. Design of Philips' slanted lenticular plate.....	101
Fig. 6-3. Schematics of 3D integral imaging.....	102
Fig. 6-4. Schematics of the parallax barrier placed between (a) the LC panel and the viewer (b) the LC panel and the backlight.....	103
Fig. 6-5. Parallax barrier combined with PDLC layer to achieve 2D/3D conversion.....	104
Fig. 6-6. Operation of the PDLC layer (a) in the off-state and (b) in the on-state.....	105
Fig. 6-7. Parallax barrier made by an additional LC plate to achieve 2D/3D conversion.....	106
Fig. 6-8. Parallax barrier made by the polarization modifying layer to achieve 2D/3D conversion.....	107
Fig. 6-9. Schematics of time-multiplexed 3D displays.....	108
Fig. 6-10. Operating Principle of the proposed time-multiplexed 3D display.....	109
Fig. 6-11. (a) Schematics of a directional backlight. (b) A large inclined angle of viewing cone was emitted from a micro-grooved lightguide. An asymmetric focusing foil was then utilized to redirect light to the eyes.....	110
Fig. 6-12. Schematics of observer's relative position and viewing angle to the display.....	112
Fig. 6-13. Schematics of a micro-grooved lightguide and an asymmetrical focusing	

foil were built by ASAP.....	113
Fig. 6-14. Angular distributions of micro-grooved lightguide only by tuning the vertex angle of groove.....	114
Fig. 6-15. Angular distributions of the grooved lightguide in combination with the asymmetric focusing foil for (a) region 1, (b) region 2 and (c) region 3...	115
Fig. 6-16. Fabricated procedure of the grooved lightguide in combination with the focusing foil.....	116
Fig. 6-17. Schematics of measurement setup.....	117
Fig. 6-18. Using backlight brightness intensity of $2100\text{cd}/\text{m}^2$, angular distributions of the backlight module with LC panel when (a) left and (b) right side LEDs switched on.....	118
Fig. 6-19. For $\phi = 90^\circ$ cross-section, the simulated and measured brightness intensity dependences on viewing angles.....	118
Fig. 6-20. Optical response waveforms by overdriving/undershooting methods.....	122
Fig. 6-21. Rising and falling times measured as the duration between 10% and 90% transmittance.....	122
Fig. 6-22. Schematics of optical structure of OCB LC.....	123
Fig. 6-23. 3D images for (a) left and (b) right eyes.....	124
Fig. 6-24. Impulse driving implemented by (a) black image data insertion and (b) blinking blacklight.....	124
Fig. 6-25. Demonstrated photographs of a directional backlight with an LCD panel at the positions of (a) left and (b) right eye.....	125
Fig. 7-1. Schematics of color sequential backlight with FLC panel.....	132
Fig. 7-2. Schematics of tandem lightguides for LCD-TVs.....	135

List of Tables

Tab. 4.1	Simulation parameters for determining period of metallic layer.....	54
Tab. 4.2.	Simulation parameters for determining thickness of metallic layer.....	57
Tab. 4.3.	Simulation parameters for determining material of dielectric layer.....	59

