

Part I Fabrication

1	Micro-Structuring and Ferroelectric Domain Engineering of Single Crystal Lithium Niobate	3
	S. Mailis, C.L. Sones, and R.W. Eason	
1.1	Introduction	3
1.2	Other Methods	4
1.3	Differential Chemical Etching	5
1.3.1	z-Faces	5
1.3.2	y-Faces	9
1.3.3	Microstructures	11
1.4	Summary and Future Work	17
	References	18
2	Fabrication and Characterization of Self-assembled Ferroelectric Linear and Nonlinear Photonic Crystals: GaN and LiNbO₃	21
	L.-H. Peng, H.-M. Wu, and C.-M. Lai	
2.1	Introduction	21
2.2	Micro-Domain Engineering with Conventional Poling Electrode Design	24
2.2.1	Internal Field Effect in the Poling of Congruent-Grown LiNbO ₃ or LiTaO ₃	24
2.2.2	Origin of the Fringe Field	24
2.2.3	Poling Issues with Doped or Stoichiometric LiNbO ₃ and LiTaO ₃	25
2.3	From Micron to Submicron Domain Engineering with Improved Electrode Design	27
2.3.1	Charged Potential Barrier Method	28
2.3.2	Stack of High- <i>k</i> Dielectric Poling Electrode Method	37
2.3.3	Submicron Domain Engineering with Self-assembly Type of Poling Electrodes	39

2.3.4	Submicron Domain Engineering in Ferroelectric Semiconductors	44
2.4	Conclusion	47
	References	49
3	Sub-Micron Structuring of LiNbO₃ Crystals with Multi-Period and Complex Geometries	53
	S. Grilli and P. Ferraro	
3.1	Introduction	53
3.2	Overview of the Etching Techniques Applied to Lithium Niobate	54
3.3	Electric Field Poling and Overpoling	58
3.4	Holographic Lithography	61
3.5	Periodic Sub-micron Structuring	63
3.5.1	Overpoling Applied to One-Dimensional Michelson Resist Gratings	63
3.5.2	Overpoling Applied to Two-Dimensional Michelson Resist Gratings	65
3.5.3	Overpoling Applied to Two-Beams Resist Gratings at Sub-micron Scale	66
3.5.4	Complex Surface Structures by Moiré HL	67
3.6	Double-Face Sub-micron Surface Structures	72
3.7	Possible Applications for Novel Photonic Crystal Devices	73
	References	76
4	Nonlinear Optical Waveguides in Stoichiometric Lithium Tantalate	79
	M. Marangoni and R. Ramponi	
4.1	Material Properties	81
4.1.1	Physical Properties	81
4.1.2	Optical Properties	83
4.2	Waveguide Fabrication Through Reverse-Proton-Exchange	85
4.2.1	Fabrication and Characterization Procedures	87
4.2.2	Modelling	88
4.3	Second-Harmonic Generation in RPE-PPSLT Waveguides	92
4.3.1	Highly Confining Waveguides	93
4.3.2	Weakly-Confining Waveguides	94
	References	97
5	3-D Integrated Optical Microcircuits in Lithium Niobate Written by Spatial Solitons	99
	E. Fazio, M. Chauvet, V.I. Vlad, A. Petris, F. Pettazzi, V. Coda, and M. Alonzo	
5.1	Review of Waveguide Fabrication Techniques	99
5.2	Theory of Photorefractive–Photovoltaic Spatial Solitons in Biased LiNbO ₃	101
5.2.1	Photorefractive Model	101

5.2.2	Time Dependent Electric Field Distribution	101
5.2.3	PR Space Charge Field	103
5.2.4	Soliton Solutions	103
5.2.5	Dark Solitons	105
5.2.6	Bright Solitons	108
5.3	Photorefractive Bright Soliton Observation	111
5.4	Waveguiding in Soliton Channels/Strips	112
5.4.1	Experimental Observation	112
5.4.2	Fixing Soliton Waveguides and Circuits in Lithium Niobate Crystals	114
5.4.3	Waveguide Characteristics	115
5.5	Optical Microcircuits with Soliton Waveguides	116
5.5.1	Passive	116
5.6	Optical Microcircuits with Solitons Waveguides	117
5.6.1	Passive	117
5.6.2	Active	121
5.7	Three-Dimensional Optical Micro-Circuits with SWGs	127
	References	130

Part II Characterization

6	Light Aided Domain Patterning and Rare Earth Emission Based Imaging of Ferroelectric Domains	135
	V. Dierolf and C. Sandmann	
6.1	Introduction and Background	135
6.1.1	Overview	135
6.1.2	Rare Earth Ions in LiNbO ₃	136
6.1.3	Combined Excitation Emission Spectroscopy	138
6.1.4	Confocal Microscopy and Spectroscopy	138
6.2	Application of RE Spectroscopy to the Imaging of Integrated Optical Devices in Lithium Niobate	141
6.2.1	Rare Earth Ions as Probes	142
6.2.2	Imaging of Waveguides	143
6.2.3	Imaging of Ferroelectric Domains and Domain Wall Regions	145
6.2.4	Imaging of Periodically Poled Waveguide Structures	148
6.3	Light Induced Domain Inversion	151
6.3.1	Methods	152
6.3.2	Build-Up of Charge Under Focussed Laser Irradiation	152
6.3.3	Influence of Light on Domain Inversion and Growth	154
6.3.4	Direct Writing of Domain Patterns	156
6.4	Summary and Conclusions	160
	References	161

7	Visual and Quantitative Characterization of Ferroelectric Crystals and Related Domain Engineering Processes by Interferometric Techniques	163
	P. Ferraro, S. Grilli, M. Paturzo, and S. De Nicola	
7.1	Introduction	163
7.2	Measuring the Refractive Indices and Thickness of Lithium Niobate Wafers	164
7.3	Visualization and <i>In-situ</i> Monitoring of Domains Formation	170
7.3.1	Digital Holography and Experimental Configuration for <i>In-situ</i> Investigation of Poling	172
7.3.2	Investigation of the Electro-Optic Effect and Internal Fields	190
7.3.3	Evaluation of Optical Birefringence at Ferroelectric Domain Wall in LiNbO ₃	197
	References	201
8	New Insights into Ferroelectric Domain Imaging with Piezoresponse Force Microscopy	205
	Tobias Jungk, Ákos Hoffmann, and Elisabeth Soergel	
8.1	Introduction	205
8.1.1	Ferroelectrics	206
8.1.2	Lithium Niobate (LiNbO ₃)	206
8.2	Principles of Scanning Force Microscopy (SFM)	207
8.2.1	Tip-Cantilever-Surface Interactions	207
8.2.2	Cantilever Movements	208
8.2.3	Cross-Talk	209
8.2.4	Calibration	210
8.3	Principles of Piezoresponse Force Microscopy (PFM)	210
8.3.1	PFM Setup & Standard Settings	211
8.3.2	System-Inherent Background in PFM Measurements	212
8.3.3	Vectorial Description	213
8.4	Consequences of the System-Inherent Background	214
8.4.1	Background-Induced Misinterpretations	215
8.4.2	Background-Free PFM Imaging	217
8.5	Quantitative Piezoresponse Force Microscopy	217
8.5.1	Amplitude of the PFM Signal	218
8.5.2	Domain Wall Width	219
8.6	Ferroelectric Domain Imaging by Lateral Force Microscopy	220
8.6.1	Lateral PFM-Signal on Domain Faces	221
8.6.2	Lateral PFM-Signal at Domain Boundaries	222
8.7	Conclusions	224
	References	224
9	Structural Characterization of Periodically Poled Lithium Niobate Crystals by High Resolution X-Ray Diffraction	227
	M. Bazzan, N. Argiolas, C. Sada, and P. Mazzoldi	

9.1	Introduction	227
9.2	The Principle of the XRD Technique	230
9.2.1	The Theory of High Resolution X-Ray Diffraction	231
9.2.2	The HRXRD Applied to PPLN Crystals	237
9.3	Experimental Set-Up for Structural Characterization by HRXRD	240
9.4	Applications	243
9.4.1	Investigation of Sub-micrometric PPLN Crystals	243
9.4.2	Investigation of Micrometric PPLN Crystals with Bent Domain Walls	247
9.5	Conclusions	250
	References	252

Part III Applications

10	Nonlinear Interactions in Periodic and Quasi-periodic Nonlinear Photonic Crystals	255
	A. Arie, A. Bahabad, and N. Habshoosh	
10.1	Introduction	255
10.2	Wave Equations in NLPC	257
10.3	Analysis of a Periodic Nonlinear Photonic Crystal	260
10.3.1	The Real Lattice	260
10.3.2	The Reciprocal Lattice	261
10.3.3	Conversion Efficiency for Specific Types of 2D Periodic Structures	262
10.3.4	Radial Symmetric Nonlinear Photonic Crystals	267
10.4	Analysis of a Quasi-periodic Nonlinear Photonic Crystal	268
10.4.1	Statement of the Problem	268
10.4.2	Solution by Quasiperiodic Lattices	269
10.4.3	Establishing an Orthogonality Condition	270
10.4.4	Tiling the Quasi-periodic Lattice by the Dual Grid Construction	271
10.4.5	The Fourier Transform of the Quasi-periodic Lattice	272
10.4.6	From Lattice to a Nonlinear Photonic Crystal	273
10.4.7	A One-Dimensional Example—The Three Wave Doubler	274
10.4.8	Quasi-periodic Nonlinear Optical Devices	277
10.5	Discussion and Summary	281
	References	282
11	Domain-Engineered Ferroelectric Crystals for Nonlinear and Quantum Optics	285
	Marco Bellini, Pablo Cancio, Gianluca Gagliardi, Giovanni Giusfredi, Pasquale Maddaloni, Davide Mazzotti, and Paolo De Natale	
11.1	Introduction	285
11.1.1	Classification of Nonlinear Processes	286
11.1.2	Phase Matching	286

11.2	Nonlinear Optics for Spectroscopic Applications	287
11.2.1	Coherent Sources for Mid-IR Spectroscopy and Metrology	288
11.2.2	OFCS Extension to the Mid-IR	289
11.2.3	Future Perspectives	297
11.3	Structured Nonlinear Crystals for Quantum Optics	298
11.3.1	Quantum Light Sources	298
11.3.2	Single-Photon Detectors	303
	References	306
12	Photonic Bandgap Properties of Lithium Niobate	313
	N. Courjal, F.I. Baida, M.-P. Bernal, J. Dahdah, C. Guyot, H. Lu, B. Sadani, and G. Ulliac	
12.1	Introduction	313
12.2	Electro-Optic LiNbO ₃ Photonic Crystal	314
12.2.1	Electro-Optic Effect in Standard Waveguides	314
12.2.2	A LiNbO ₃ PhC Based Electro-Optic Modulator	315
12.3	Fabrication Process	319
12.3.1	Nanostructuration of LiNbO ₃	320
12.3.2	LiNbO ₃ Optical Waveguides	321
12.3.3	Fabrication of Ridges by Optical Grade Dicing	323
12.4	Examples of Tunable LiNbO ₃ PhCs on Ridges	325
12.4.1	PhC on a Ti-Indiffused APE Ridge Waveguide	325
12.4.2	Free Standing LiNbO ₃ PhC Cavity	328
12.4.3	Tunability of the PhCs in Optimized Ridge Waveguides	329
12.5	Perspectives: 3D PhCS	331
12.6	Conclusion	333
	References	334
13	Lithium Niobate Whispering Gallery Resonators: Applications and Fundamental Studies	337
	L. Maleki and A.B. Matsko	
13.1	Introduction	337
13.2	Modulators	339
13.2.1	Principle of Operation	340
13.2.2	Performance	341
13.3	Tunable Filters	341
13.3.1	First-Order Filter	341
13.3.2	Third-Order Filter	342
13.3.3	Fifth-Order Filter	345
13.3.4	Insertion Loss	345
13.4	WGRs Made of Periodically Poled Lithium Niobate	347
13.4.1	Optical Frequency Doubling	347
13.4.2	Calligraphic Poling	350
13.4.3	Reconfigurable Filters	351

13.5	Photorefractive Damage	352
13.5.1	Congruent LiNbO_3	354
13.5.2	Magnesium Doped Congruent LiNbO_3	356
13.5.3	Crossings and Anticrossings of the Modes	359
13.5.4	Holographic Engineering of the WGM Spectra	359
13.6	Infrared Transparency and Photorefractivity of Lithium Niobate Crystals: Theory	360
13.6.1	Rate Equations	362
13.6.2	Solution of the Rate Equations	365
13.6.3	Absorption of the Light and Initial Concentration of the Filled Traps	368
Appendix A	Basic Properties of WGMs	371
Appendix B	Lithium Niobate Impurities: A Short Review of Existing Results	373
B.1	Small Polarons	373
B.2	Bipolarons	374
B.3	Iron	375
Appendix C	Photorefractivity in Red: A Short Review of the Existing Results	376
C.1	Light Induced Change of Refractive Index	376
C.2	Light Induced Change of Absorption	377
Appendix D	Numerical Values of the Basic Rates Characterizing the Impurities	378
References		381
14	Applications of Domain Engineering in Ferroelectrics for Photonic Applications	385
D.A. Scrymgeour		
14.1	Introduction	385
14.2	Ferroelectrics and Domain Engineering	385
14.3	Applications of Domain Engineered Structures	388
14.3.1	Frequency Conversion	388
14.3.2	Electro-Optic Devices	390
14.4	Challenges of Domain Engineered Ferroelectric Devices	397
14.5	Conclusions	397
References		398
15	Electro-Optics Effect in Periodically Domain-Inverted Ferroelectrics Crystals: Principles and Applications	401
J. Shi and X. Chen		
15.1	Introduction	401
15.2	Basic Principle	402
15.2.1	Electro-Optic Effect in Crystals	402
15.2.2	Electro-Optical Effect for Crystals of $3m$ Symmetry Group	405

15.2.3	Electro-Optical Effect in Periodically Domain-Inverted Crystals with $3m$ Symmetry	408
15.3	Applications	413
15.3.1	Devices Based on Bragg Diffraction Grating Structure	414
15.3.2	Devices Based on Solc-Layered Structure	417
15.3.3	Other Application Devices	419
	References	420
16	The LiNbO₃ Slab Waveguide: A Platform for Terahertz Signal Generation, Detection, and Control	423
	Christopher A. Werley and Keith A. Nelson	
16.1	Introduction to THz Spectroscopy and Polaritonics	423
16.2	LiNbO ₃ Slabs: Dielectric Planar Waveguides	427
16.3	Developments in Polaritonics Methodology	430
16.3.1	Generation of THz Waves	431
16.3.2	Techniques for Imaging THz Waves in LiNbO ₃ Slabs	433
16.3.3	Structuring the Sample and Femtosecond Laser Machining	437
16.4	Direct Visualization of THz Waves in Photonic Structures	438
16.4.1	Reflection and Interference	438
16.4.2	Diffraction off a Grating	439
16.4.3	Waveguiding and Interferometry	440
16.4.4	Filtering and Dispersion Control in Photonic Crystals	441
16.5	THz Field Enhancement and Subwavelength Localization in Metal Antennas	443
16.6	Conclusions	449
	References	449
17	Periodically-Poled Ferroelectric Crystals Based OPO—A Powerful Source for Precision Spectroscopy	453
	M. De Rosa, E. De Tommasi, P. Maddaloni, S. Mosca, I. Ricciardi, A. Rocco, J.-J. Zondy, and P. De Natale	
17.1	Introduction	453
17.2	Principles of Operation	454
17.2.1	Cavity Configurations	455
17.2.2	Frequency Tuning	457
17.2.3	Spectral Features	458
17.3	Atomic and Molecular Spectroscopy with OPOs	460
17.4	Precise, High-Resolution Spectroscopy with OPO	461
17.4.1	The Optical Parametric Oscillator	461
17.4.2	Signal Frequency Stabilization	463
17.4.3	Optical Frequency Comb Referenced OPO	465
17.4.4	CH ₃ I Spectroscopy	467
17.5	Current Developments	469
	References	470

18	Electro-Optical Devices Obtained by LiNbO₃ Crystals	475
	M. Paturzo, V. Pagliarulo, S. Grilli, and P. Ferraro	
18.1	Introduction	475
18.2	Tunable Two-Dimensional Hexagonal Phase Array in Domain-Engineered LN	476
18.2.1	Flexible Phase Array Application for Coherent Diffraction Lithography	481
18.3	Point-Diffraction Interferometer	482
18.4	Conclusions	488
	References	489
	Index	491