

# Contents

<b>1. Introduction.</b> By P. Günter and J.-P. Huignard (With 1 Figure) . . . . .	1
References . . . . .	4
<b>2. Photorefractive Effects and Materials</b>	
By P. Günter and J.-P. Huignard (With 31 Figures) . . . . .	7
2.1 Generation of Charge Carriers . . . . .	7
2.2 Transport of Charge Carriers . . . . .	9
2.2.1 Diffusion . . . . .	9
2.2.2 Drift . . . . .	9
2.2.3 Photovoltaic Effect . . . . .	11
2.2.4 Charge Transport Equation . . . . .	13
2.3 Photoinduced Space-Charge Fields . . . . .	16
2.3.1 Short Time Limit . . . . .	18
2.3.2 Saturation Time Limit . . . . .	20
2.3.3 Trap Density Limited Space-Charge Field . . . . .	24
2.4 Photoinduced Refractive Index Changes . . . . .	25
2.4.1 Transmission Gratings Without Rotation of Index Ellipsoids . . . . .	26
2.4.2 Reflection Gratings . . . . .	30
2.4.3 Photoinduced Index Ellipsoid Rotations . . . . .	30
2.5 Isotropic and Anisotropic Bragg Diffraction from Photoinduced Gratings . . . . .	30
2.5.1 Isotropic Bragg Diffraction . . . . .	31
2.5.2 Anisotropic Bragg Diffraction in Uniaxial Crystals . . . . .	32
2.5.3 Light Deflection by Anisotropic Bragg Diffraction in Photorefractive Materials . . . . .	35
2.5.4 Anisotropic Self-diffraction in Photorefractive Materials . . . . .	37
2.5.5 Anisotropic Light Scattering in Photorefractive Materials . . . . .	38
2.6 Multiphoton Photorefractive Effect . . . . .	39
2.7 Fixing of Phase Gratings . . . . .	41
2.7.1 Fixing by Domain Reversal . . . . .	41
2.7.2 Fixing by Ionic Space-Charge Fields . . . . .	42
2.8 Connections with Nonlinear Optics . . . . .	43
2.9 Required Properties of Photorefractive Materials . . . . .	46
2.9.1 Photorefractive Sensitivity . . . . .	47
2.9.2 Dynamic Range (Maximum Refractive Index Change) . . . . .	52

2.9.3	Phase Shift Between Refractive Index and Light Intensity Distribution . . . . .	54
a)	Steady-State $\pi/2$ Phase Shifted Component of Space-Charge Field . . . . .	54
b)	Transient Phase Shift . . . . .	56
2.9.4	Response Time of the Photorefractive Effect . . . . .	56
2.9.5	Angular and Wavelength Selectivity . . . . .	59
2.9.6	Other Requirements . . . . .	60
a)	Resolution . . . . .	60
b)	High Signal-to-Noise Ratio . . . . .	60
c)	Wavelength . . . . .	61
2.10	Materials and Properties . . . . .	61
2.10.1	Oxygen-Octahedra Ferroelectrics . . . . .	61
a)	Transition Metal Dopants as Photorefractive Centers . . . . .	61
b)	Lithium Niobate and Lithium Tantalate . . . . .	63
c)	Potassium Niobate, Potassium Niobate-Tantalate and Barium Titanate . . . . .	64
d)	Barium Sodium Niobate and Barium Strontium Niobate . . . . .	66
2.10.2	Sillenites . . . . .	67
2.10.3	Semiconductors (GaAs, InP, CdFe, ...) . . . . .	69
2.10.4	Electro-optic Ceramics . . . . .	69
2.10.5	Ultraviolet Transparent Materials . . . . .	70
2.10.6	Infrared Transparent Materials . . . . .	70
References	. . . . .	70
<b>3.</b>	<b>Theory of Photorefractive Effects in Electro-optic Crystals</b>	
By G. C. Valley and J. F. Lam (With 8 Figures)	. . . . .	75
3.1	Historical Review . . . . .	75
3.2	Space-Charge Field in the Quasi-Steady Approximation . . . . .	77
3.2.1	Basic Equations . . . . .	78
3.2.2	Zeroth-Order Solutions . . . . .	79
3.2.3	General Solution for First-Order Quantities . . . . .	81
3.2.4	Special Cases . . . . .	82
a)	Steady State with No Holes, No Photovoltaic Field, No Applied Field ( $E_0 = \kappa_e = \kappa_h = p_0 = p_1 = \delta\omega = 0$ ) . . . . .	82
b)	Response Time with No Holes, Photovoltaic or Mean Field . . . . .	83
c)	Applied Field with No Holes or Photovoltaic Effect . . . . .	84
d)	Space-Charge Field and Response Time with Two Charge Carriers and No Applied or Photovoltaic Field . . . . .	84
3.3	Grating Formation and Decay with Short Pulses . . . . .	86
3.3.1	Extension of Quasi-Steady Approximation . . . . .	87
3.3.2	Illumination with Delta-Function Pulses . . . . .	87
3.4	Solutions to the Two- and Four-Wave Mixing Problems . . . . .	89

	Contents	XI
3.4.1 Nearly Degenerate Four-Wave Mixing . . . . .	90	
3.4.2 Self-pumped Phase Conjugation via Nearly Degenerate Backward Stimulated Two-Wave Mixing . . . . .	93	
References . . . . .	97	
<b>4. Dynamic Holographic Gratings and Optical Activity in Photorefractive Crystals.</b> By N. V. Kukhtarev (With 10 Figures) . . . . .	99	
4.1 Dynamic Gratings in Polar Crystals . . . . .	101	
4.1.1 Physical Model of Hologram Writing and Basic Equations	101	
4.1.2 Calculation of the Quasi-Static Electric Field . . . . .	103	
4.1.3 Isotropic Self-diffraction and Running Gratings for Crystals with Symmetry Group $3m$ . . . . .	105	
4.1.4 Anisotropic Self-diffraction, Phase Conjugation, and Phase Doubling for Crystals with Symmetry Group $3m$ . . . . .	107	
4.1.5 Optical Multistability in Four-Wave Phase Conjugation . . . . .	108	
4.1.6 Self-diffraction Gyration . . . . .	110	
4.1.7 Vectorial Self-diffraction and Self-oscillation in Photogalvanic Crystals . . . . .	112	
a) Starting Equations . . . . .	112	
b) Kinetics of the Amplitude Changes . . . . .	114	
c) Steady-State Solutions . . . . .	115	
4.2 Holographic Gratings in Paraelectric Crystals with $23$ Symmetry . . . . .	116	
4.2.1 Basic Equations . . . . .	117	
4.2.2 Calculation of the Light-Wave Amplitudes for a Geometry Without Electrogyration . . . . .	118	
4.2.3 Natural and Photoinduced Electrogyration . . . . .	122	
4.2.4 Anisotropic Phase Conjugation by Four-Wave Mixing . . . . .	124	
4.2.5 Modulation of Beam Coupling by an Electric Field . . . . .	125	
4.2.6 Real-Time Holographic Interferometry . . . . .	126	
4.3 Conclusion . . . . .	127	
4.3.1 Materials Studies from the Kinetics . . . . .	127	
4.3.2 Phase Doubling . . . . .	127	
4.3.3 Optical Hysteresis and Bistability . . . . .	128	
4.3.4 Dynamic Interferometry . . . . .	128	
References . . . . .	128	
<b>5. Photorefractive Centers in Electro-optic Crystals</b>		
By E. Krätzig and O. F. Schirmer (With 22 Figures) . . . . .	131	
5.1 Methods of Investigation . . . . .	132	
5.1.1 Electron Spin Resonance . . . . .	132	
5.1.2 Optical Absorption . . . . .	134	
5.1.3 Mössbauer Effect . . . . .	135	
5.2 Extrinsic Photorefractive Centers in $\text{LiNbO}_3$ and $\text{LiTaO}_3$ and Their Influence on Light-Induced Charge Transport . . . . .	135	

5.2.1 Transition Metals in $\text{LiNbO}_3$ and $\text{LiTaO}_3$ . . . . .	137
5.2.2 Photovoltaic Effects . . . . .	141
5.2.3 Photoconductivity . . . . .	144
5.2.4 Holographic Investigation of Light-Induced Charge Transport . . . . .	148
5.2.5 Protons and Thermal Fixing . . . . .	152
5.3 Intrinsic Centers in $\text{LiNbO}_3$ and $\text{LiTaO}_3$ . . . . .	155
5.3.1 Overview . . . . .	156
5.3.2 $\text{Nb}^{4+}$ in $\text{LiNbO}_3$ . . . . .	157
5.3.3 The Trapped Hole Center in Undoped $\text{LiNbO}_3$ . . . . .	159
5.3.4 Intrinsic Defects in $\text{LiTaO}_3$ . . . . .	160
5.4 Centers in Various Photorefractive Crystals . . . . .	161
References . . . . .	163

## 6. Photorefractive Measurements of Physical Parameters

By R. A. Mullen (With 10 Figures) . . . . .	167
6.1 Background . . . . .	167
6.1.1 Nature of the Charge Transport Mechanism . . . . .	168
6.1.2 Photorefractive Charge Transport via Hopping . . . . .	169
a) Discretization of the Conduction Band Transport Equation . . . . .	169
b) Hopping Theory . . . . .	170
c) Hopping in Barium Titanate (Short Range) . . . . .	171
d) Hopping in the Sillenites (Long Range) . . . . .	172
6.1.3 Relevant Material Parameters . . . . .	174
6.2 Photorefractive Measurement Techniques . . . . .	175
6.3 The Steady State . . . . .	176
6.4 "Quasi-Steady" Transient Experiments . . . . .	178
6.4.1 Without Externally Applied Fields . . . . .	178
6.4.2 Zero-Field Experimental Results . . . . .	180
a) Experimental Description . . . . .	182
b) Nonlinear Intensity Dependence . . . . .	185
c) Nonexponential Decays . . . . .	186
6.4.3 With Externally Applied Fields . . . . .	187
6.5 Intense Short-Pulse Measurements . . . . .	189
6.6 Directions for Future Experiments . . . . .	191
6.6.1 Temperature . . . . .	191
a) Temperature Dependence Intrinsic to Photorefractive Transport Equations . . . . .	191
b) Temperature Dependence of Mobility . . . . .	192
c) Measurement of Activation Energies . . . . .	192
d) Importance to Applications . . . . .	192
6.6.2 Topics Not Yet Investigated . . . . .	193
References . . . . .	193

<b>7. Photorefractive Properties of BaTiO<sub>3</sub></b>	
By M. B. Klein (With 16 Figures) . . . . .	195
7.1 Basic Properties and Technology . . . . .	196
7.1.1 Crystal Growth . . . . .	196
7.1.2 Lattice Structure . . . . .	197
7.1.3 Domains and Poling . . . . .	198
7.1.4 Dielectric and Electro-optic Properties . . . . .	200
7.2 Band Structure and Defects . . . . .	204
7.2.1 Intrinsic Band Structure . . . . .	204
7.2.2 Vacancies and Impurities . . . . .	206
7.2.3 Charge Balance . . . . .	207
7.2.4 Energy Levels of Fe <sup>2+</sup> and Fe <sup>3+</sup> . . . . .	208
7.3 Band Transport Model . . . . .	210
7.3.1 Energy Level Model . . . . .	210
7.3.2 Transport and Rate Coefficients . . . . .	212
7.3.3 Grating Formation . . . . .	214
7.4 Physical Measurements Using the Photorefractive Effect . . . . .	217
7.4.1 Steady-State Measurements . . . . .	218
7.4.2 Transient Measurements . . . . .	222
7.5 Other Measurements in Photorefractive Crystals . . . . .	224
7.5.1 Optical Absorption Coefficient Measurements . . . . .	224
7.5.2 Impurity Identity and Concentrations . . . . .	225
7.5.3 EPR Measurements . . . . .	225
7.5.4 Correlation of Measured Parameters . . . . .	227
7.6 Optimization of Photorefractive Properties . . . . .	229
7.6.1 Influence of Oxidation/Reduction . . . . .	230
7.7 Conclusions . . . . .	234
References . . . . .	234
Additional References . . . . .	236
<b>8. The Photorefractive Effect in Semiconductors</b>	
By A. M. Glass and J. Strait (With 20 Figures) . . . . .	237
8.1 Electro-optic Properties . . . . .	237
8.2 Defects . . . . .	239
8.2.1 Shallow Impurities . . . . .	240
8.2.2 Deep Levels . . . . .	240
a) GaAs:EL2 . . . . .	241
b) GaAs:Cr . . . . .	242
c) InP:Fe . . . . .	243
8.3 Transport Properties . . . . .	244
8.4 Material Response Times . . . . .	247
8.5 Experimental Work . . . . .	249
8.5.1 Continuous-Wave Four-Wave Mixing Experiments . . . . .	250
8.5.2 Pulsed Four-Wave Mixing . . . . .	254

8.5.3 Beam Coupling . . . . .	255
8.5.4 Four-Wave Mixing Using Injection Lasers . . . . .	258
8.5.5 Nonlinear Susceptibility . . . . .	259
8.5.6 Future Directions . . . . .	260
8.6 Conclusion . . . . .	261
References . . . . .	262
 <b>9. Nonstationary Holographic Recording for Efficient Amplification and Phase Conjugation.</b> By S. I. Stepanov and M. P. Petrov	
(With 16 Figures) . . . . .	263
9.1 Theoretical Analysis of Nonstationary Recording Mechanisms . . . . .	265
9.1.1 Basic Equation for a Hologram Complex Amplitude . . . . .	265
9.1.2 Recording a Moving Interference Pattern in a Steady Field . . . . .	268
9.1.3 Recording a Stationary Interference Pattern in an Alternating Electric Field . . . . .	269
9.1.4 Discussion . . . . .	271
9.2 Light Diffraction and Degenerate Four-Wave Mixing in Cubic Photorefractive Crystals . . . . .	272
9.2.1 Introduction to Four-Wave Mixing in Photorefractive Crystals . . . . .	272
9.2.2 Light Diffraction from Volume Phase Holograms in Cubic Photorefractive Crystals . . . . .	274
9.2.3 Four-Wave Mixing with Positive Feedback via Shifted Gratings . . . . .	275
9.2.4 Discussion . . . . .	277
9.3 Nonstationary Holographic Recording Mechanisms in Cubic Photorefractive Crystals . . . . .	278
9.3.1 Recording Moving Interference Patterns in $\text{Bi}_{12}\text{SiO}_{20}$ (BSO) Crystals . . . . .	278
9.3.2 Nonstationary Holographic Recording in an Alternating Field in $\text{Bi}_{12}\text{TiO}_{20}$ (BTO) Crystals . . . . .	280
9.3.3 Discussion . . . . .	282
9.4 Image Amplification and Phase Conjugation in BTO via Nonstationary Recording in an Alternating Electric Field . . . . .	283
9.4.1 Image Amplification in BTO Crystals . . . . .	283
9.4.2 Phase Conjugation in BTO Crystals . . . . .	285
9.4.3 Discussion . . . . .	287
9.5 Conclusion . . . . .	287
References . . . . .	288
Additional References . . . . .	289
 <b>Subject Index</b> . . . . .	291