

## Contents

Preface XXI

List of Contributors XXVII

1	<b>Lasers: Fundamentals, Types, and Operations</b>	1
	<i>Subhash Chandra Singh, Haibo Zeng, Chunlei Guo, and Weiping Cai</i>	
1.1	Introduction of Lasers	1
1.1.1	Historical Development	1
1.1.2	Basic Construction and Principle of Lasing	2
1.1.3	Einstein Relations and Gain Coefficient	2
1.1.4	Multilevel Systems for Attaining Condition of Population Inversion	3
1.1.5	Threshold Gain Coefficient for Lasing	4
1.1.6	Optical Resonator	5
1.1.7	Laser Modes	7
1.2	Types of Laser and Their Operations	8
1.2.1	Solid Laser	8
1.2.1.1	Doped Insulator Laser	8
1.2.1.2	Semiconductor Laser	13
1.2.2	Gas Laser	15
1.2.2.1	Atomic Gas Laser; He:Ne Laser	16
1.2.2.2	Ion Laser: Argon Ion Laser	17
1.2.2.3	Molecular Laser	18
1.2.3	Liquid Laser	21
1.3	Methods of Producing EUV/VUV, X-Ray Laser Beams	22
1.3.1	Free Electron Lasers (FEL)	22
1.3.2	X-Ray Lasers	24
1.3.3	EUV/VUV Lasers through Higher Harmonic Generation	25

1.4	Properties of Laser Radiation	26
1.4.1	Monochromaticity	26
1.4.2	Directionality	28
1.4.3	Coherence	28
1.4.4	Brightness	29
1.4.5	Focusing of Laser Beam	29
1.5	Modification in Basic Laser Structure	30
1.5.1	Mode Locking	30
1.5.1.1	Basic Principle of Mode Locking	30
1.5.1.2	Mode Locking Techniques	31
1.5.2	Q-Switching	32
1.5.3	Pulse Shaping	33
	References	34
<b>2</b>	<b>Introduction of Materials and Architectures at the Nanoscale</b>	<b>35</b>
	<i>Subhash Chandra Singh, Haibo Zeng, Chunlei Guo, Ram Gopal, and Weiping Cai</i>	
2.1	Origin and Historical Development	35
2.2	Introduction	36
2.3	Band Theory of Solids	37
2.4	Quantum Confinement	41
2.5	Defects and Imperfections	44
2.5.1	Point Defect	45
2.5.2	Line Defects	45
2.5.3	Planar Defects	45
2.5.4	Volume or Bulk Defects	47
2.6	Metal, Semiconductor, and Insulator Nanomaterials	48
2.6.1	Metal Nanoparticles and Their Size-/Shape-Dependent Properties	48
2.6.2	Semiconductor Nanoparticles and Their Size-Dependent Properties	52
2.6.3	Insulator Nanoparticles	53
2.7	Various Synthesis Methods of Nanoscale Materials	53
2.8	Various Techniques of Materials Characterization	54
2.8.1	Light Beam Characterization Techniques (200–1000 nm)	54
2.8.2	Infrared (IR) Characterization (1000–200 000 nm)	55
2.8.3	X-Ray-Beam-Based Characterization Methods	55
2.8.4	Electron-Beam-Based Characterization Methods	56
2.8.5	Nuclear Radiation and Particle-Based Spectroscopy	57
2.9	Self-Assembly and Induced Assembly, Aggregation, and Agglomeration of Nanoparticles	58
2.10	Applications of Lasers in Nanomaterial Synthesis, Modification, and Characterization	59
2.11	Summary and Future Prospects	64
	References	65

**Part I Nanomaterials: Laser Based Processing Techniques 67****3 Laser–Matter Interaction 69****3.1 High-Intensity Femtosecond Laser Interactions with Gases and Clusters 69***Alan M. Heins and Chunlei Guo*

- 3.1.1 Introduction 69
- 3.1.2 Laser–Atom Interactions 69
- 3.1.3 Laser–Molecule Interactions 72
- 3.1.4 High-Pressure Atomic Physics 73
- 3.1.5 Strongly Coupled Plasmas 74
- 3.1.6 Clusters 74
- 3.1.7 Laser–Cluster Production 75
- 3.1.8 Laser–Cluster Interaction 76
- 3.1.9 Aerosol Monitoring 77
- 3.1.10 Atmospheric Effects 78
- 3.1.11 Conclusion and Outlook 79
- References 80

**3.2 Laser-Matter Interaction: Plasma and Nanomaterials Processing 85***Subhash Chandra Singh*

- 3.2.1 Introduction 85
- 3.2.2 Influences of Laser Irradiance on Melting and Vaporization Processes 85
- 3.2.3 Influence of Laser Pulse Width and Pulse Shape 90
- 3.2.4 Influences of Laser Wavelength on Ablation Threshold and Plasma Parameters 94
- 3.2.5 Influences of Background Gas Pressure on the Plasma Characteristic and Morphology of Produced Materials 94
- 3.2.6 Double Pulse Laser Ablation 99
- 3.2.7 Electric- and Magnetic-Field-Assisted Laser Ablation 99
- 3.2.8 Effect of Laser Polarization 101
- 3.2.9 Conclusions 102
- Acknowledgments 103
- References 103

**4 Nanomaterials: Laser-Based Processing in Gas Phase 105****4.1 Synthesis and Analysis of Nanostructured Thin Films Prepared by Laser Ablation of Metals in Vacuum 105***Rashid Ashirovich Ganeev*

- 4.1.1 Introduction 105
- 4.1.2 Experimental Details 106
- 4.1.3 Results and Discussion 106

4.1.4	Conclusions 113
	Acknowledgments 114
	References 114
<b>4.2</b>	<b>Synthesis of Nanostructures with Pulsed Laser Ablation in a Furnace 117</b>
	<i>Rusen Yang and Jung-Il Hong</i>
4.2.1	General Consideration for Pulsed Laser Deposition: an Introduction 117
4.2.1.1	One-Dimensional Nanostructure 117
4.2.2	Thermal-Assisted Pulsed Laser Deposition 120
4.2.2.1	Furnace System 122
4.2.2.2	Laser Ablation Setup 123
4.2.2.3	Experimental Procedure 124
4.2.3	Single-Crystalline Branched Zinc Phosphide Nanostructures with TAPLD 125
4.2.3.1	Properties of $Zn_3P_2$ 125
4.2.3.2	$Zn_3P_2$ Nanostructures 126
4.2.3.3	Properties and Devices Fabrication 130
4.2.3.4	Summary of the $Zn_3P_2$ Nanostructures 135
4.2.4	Aligned Ferrite Nanorods, NWs, and Nanobelts with the TAPLD Process 135
4.2.4.1	Introduction 135
4.2.4.2	Experimental Method 136
4.2.4.3	Results and Discussion 138
4.2.4.4	Summary of the Iron Oxide Nanostructures 140
	References 142
<b>4.3</b>	<b>ZnO Nanowire and Its Heterostructures Grown with Nanoparticle-Assisted Pulsed Laser Deposition 145</b>
	<i>Bingqiang Cao, Ruiqian Guo, and Tatsuo Okada</i>
4.3.1	Introduction 145
4.3.2	From 2D Nanowall to 1D Nanowire with PLD 147
4.3.3	NAPLD Nanowire Growth Mechanism 148
4.3.4	Controlled Nanowire Growth with NAPLD 152
4.3.4.1	Influence of Substrate–Target Distance 152
4.3.4.2	Influence of Laser Energy 153
4.3.4.3	Influence of Substrate Annealing 154
4.3.4.4	Influence of Wetting Layer 156
4.3.5	Growth of Nanowire Heterostructures Based on Low-Density Nanowires 159
4.3.6	Conclusions 162
	Acknowledgments 164
	References 164

<b>4.4</b>	<b>Laser-Vaporization-Controlled Condensation for the Synthesis of Semiconductor, Metallic, and Bimetallic Nanocrystals and Nanoparticle Catalysts</b>	<b>167</b>
	<i>M. Samy El-Shall</i>	
4.4.1	Introduction	167
4.4.2	Brief Overview of Nucleation and Growth from the Vapor Phase	168
4.4.3	The LVCC Method	170
4.4.4	Silicon Nanocrystals	173
4.4.5	Laser Alloying of Nanoparticles in the Vapor Phase	174
4.4.5.1	Gold–Silver Alloy Nanoparticles	177
4.4.5.2	Size Control by Laser Irradiation of Nanoparticles in Solutions	179
4.4.5.3	Gold–Palladium Alloy Nanoparticles	181
4.4.6	Intermetallic Nanoparticles	182
4.4.6.1	FeAl and NiAl Intermetallic Nanoparticles	183
4.4.7	Growth of Filaments and Treelike Assembly by Electric Field	186
4.4.8	Upconverting Doped Nanocrystals by the LVCC Method	190
4.4.9	Supported Nanoparticle Catalysts by the LVCC Method	194
4.4.10	Conclusion	197
	Acknowledgments	197
	References	198
<b>5</b>	<b>Nanomaterials: Laser-Induced Nano/Microfabrocations</b>	<b>203</b>
<b>5.1</b>	<b>Direct Femtosecond Laser Nanostructuring and Nanopatterning on Metals</b>	<b>203</b>
	<i>Anatoliy Vorobyev and Chunlei Guo</i>	
5.1.1	Introduction	203
5.1.2	Basic Principles of Surface Nanostructuring by Direct Femtosecond Laser Ablation	204
5.1.3	Nanostructures	205
5.1.4	Femtosecond Laser-Induced Periodic Structures (Periodic Nanogrooves) on Metals	207
5.1.5	Nanostructure-Textured Microstructures	208
5.1.5.1	Nanostructure-Textured Microgroove Structures	208
5.1.5.2	Nanostructure-Textured Columnar Microstructures	208
5.1.6	Single Nanoholes and Arrays of Nanoholes	209
5.1.7	Applications of Femtosecond Laser-Induced Surface Structures on Metals	210
5.1.7.1	Modification of Optical Properties	210
5.1.7.2	Modification of Wetting Properties	211
5.1.7.3	Biomedical Applications	212
5.1.7.4	Other Applications	213
5.1.8	Summary	214
	References	214

<b>5.2</b>	<b>Laser-Induced Forward Transfer: an Approach to Direct Write of Patterns in Film Form</b>	<b>219</b>
	<i>Hironobu Sakata and Moriaki Wakaki</i>	
5.2.1	Introduction	219
5.2.2	Principle and Method	219
5.2.3	LIFT of Materials	221
5.2.3.1	Metals and Single Element	221
5.2.3.2	Oxides	229
5.2.3.3	Other Compounds Including Biomaterials	234
5.2.4	Applications	235
5.2.5	Summary and Conclusion	238
	References	239
<b>5.3</b>	<b>Laser-Induced Forward Transfer: Transfer of Micro-Nanomaterials on Substrate</b>	<b>241</b>
	<i>Qing Wang, Vahit Sametoglu, and Ying Yin Tsui</i>	
5.3.1	Introduction of Laser-Induced Forward Transfer (LIFT)	241
5.3.2	Spatial Resolution of the LIFT Process	243
5.3.3	Transfer of Thermally and Mechanically Sensitive Materials	248
	References	252
<b>5.4</b>	<b>Laser-Induced Forward Transfer for the Fabrication of Devices</b>	<b>255</b>
	<i>Matthias Nagel and Thomas Lippert</i>	
5.4.1	Introduction	255
5.4.2	LIFT Techniques for Direct-Write Applications	261
5.4.2.1	Traditional LIFT	261
5.4.3	Modified LIFT Methods	277
5.4.3.1	Matrix-Assisted Pulsed Laser Evaporation Direct-Write (MAPLE-DW)	277
5.4.3.2	Laser Molecular Implantation (LMI)	279
5.4.3.3	Layered Donor Systems with Intermediate Absorbing Films	280
5.4.4	Conclusions and Future Aspects	306
	Acknowledgments	306
	References	306
<b>6</b>	<b>Nanomaterials: Laser-Based Processing in Liquid Media</b>	<b>317</b>
<b>6.1</b>	<b>Liquid-Assisted Pulsed Laser Ablation/Irradiation for Generation of Nanoparticles</b>	<b>317</b>
	<i>Subhash Chandra Singh</i>	
6.1.1	Introduction	317
6.1.2	Advantages of Liquid-Phase Laser Ablation over Gas Phase	319
6.1.3	Classification of Liquid-Phase Laser Ablation on the Basis of Target Characteristics	319
6.1.3.1	Liquid-Phase Laser Ablation of Solid Bulk Target Materials	320

6.1.3.2	Laser-Induced Melting and Fragmentation of Liquid-Suspended Particles	387
6.1.3.3	Laser Irradiation of Metal Salts or Liquid Precursors	411
6.1.4	Applications of Nanomaterials Produced by Liquid-Phase Pulsed Laser Ablation/Irradiation	422
6.1.4.1	Applications in PV Solar Cells	422
6.1.4.2	<i>In situ</i> Functionalization for Biological Applications	423
6.1.4.3	Semiconductor NPs as Fluorescent Markers	425
6.1.4.4	Surface-Enhanced Raman Scattering (SERS) Active Substrates	425
6.1.4.5	Nanofertilizer for Seed Germination and Growth Stimulation	426
6.1.4.6	Other Applications	429
6.1.5	Conclusion and Future Prospects	429
	Acknowledgments	429
	References	430
<b>6.2</b>	<b>Synthesis of Metal Compound Nanoparticles by Laser Ablation in Liquid</b>	<b>439</b>
	<i>Haibo Zeng, Shikuan Yang, and Weiping Cai</i>	
6.2.1	Introduction	439
6.2.2	Synthesis of Nanoparticles by LAL	441
6.2.2.1	Oxide Nanoparticles	441
6.2.2.2	Carbide Nanoparticles	447
6.2.2.3	Nitride Nanoparticles	451
6.2.3	Conclusions	454
	Acknowledgments	454
	References	454
<b>6.3</b>	<b>Synthesis of Fourth Group (C, Si, and Ge) Nanoparticles by Laser Ablation in Liquids</b>	<b>457</b>
	<i>Minghui Hong, Guoxin Chen, and Tow Chong Chong</i>	
6.3.1	Laser Ablation in Liquid (LAL)	457
6.3.1.1	Introduction	457
6.3.1.2	Dynamic Process	459
6.3.1.3	Growth Mechanism of Nanoparticles by LAL	462
6.3.1.4	LAL Process	464
6.3.1.5	Nanoparticle Control	466
6.3.1.6	Safety Matters	468
6.3.2	Carbon Nanoparticles	468
6.3.2.1	Diamond Nanoparticles	468
6.3.2.2	Amorphous Carbon Nanoparticles	476
6.3.2.3	Carbon Nanocrystals	479
6.3.2.4	Synthesis of Other Carbon Nanomaterials by LAL	481
6.3.3	Silicon Nanoparticles	486
6.3.4	Germanium Nanoparticles	489
6.3.5	Conclusions	491

	Acknowledgments	491
	References	491
	<b>Part II Nanomaterials: Laser-Based Characterization Techniques</b>	<b>495</b>
<b>7</b>	<b>Raman Spectroscopy: Basics and Applications</b>	<b>497</b>
<b>7.1</b>	<b>Raman Spectroscopy and its Application in the Characterization of Semiconductor Devices</b>	<b>497</b>
	<i>Patrick J. McNally</i>	
7.1.1	Introduction	497
7.1.2	Raman Scattering in Semiconductors	499
7.1.3	Micro-Raman Spectroscopy: Microscale Applications	501
7.1.4	Raman Spectroscopy Approaches the Nanoscale	502
7.1.5	Confocal Raman Spectroscopy – Applications to Future Sub-22 nm Node CMOS Technology	504
7.1.6	Conclusion	508
	Acknowledgments	508
	References	508
<b>7.2</b>	<b>Effect of Particle Size Reduction on Raman Spectra</b>	<b>511</b>
	<i>Vasant G. Sathe</i>	
7.2.1	Introduction	511
7.2.2	Nanoparticles and Phonon Confinement	512
7.2.3	Theoretical Considerations of Optical Phonon Confinement	515
7.2.3.1	Effect of Particle Size Distribution	518
7.2.3.2	Estimation of Dispersion Curve	518
7.2.3.3	Limitations of Phonon Confinement Model	519
7.2.4	Experimental Setup for Confocal Micro-Raman Spectroscopy	520
7.2.5	Case Studies of Raman Spectroscopy of Nanomaterials	520
7.2.5.1	Resonant Raman Spectroscopy of CdS and CdSe Nanoparticles	520
7.2.5.2	CeO <sub>2</sub> Nanostructures	522
7.2.5.3	ZnO Nanostructures	524
7.2.6	Effect of Laser Heating in Nanoparticles	524
7.2.6.1	ZnO Nanostructures	524
7.2.6.2	Effect of Laser Heating and Quantum Confinement in NiFe <sub>2</sub> O <sub>4</sub> Nanostructures	525
7.2.7	Summary and Future Directions	531
	Acknowledgments	532
	References	532
<b>8</b>	<b>Size Determination of Nanoparticles by Dynamic Light Scattering</b>	<b>535</b>
	<i>Haruhisa Kato</i>	
8.1	Introduction	535
8.2	General Principles of DLS (Photon Correlation Spectroscopy)	537

8.3	Particle Size Standards Applied to DLS	542
8.4	Unique DLS Instruments	546
8.4.1	Single-Mode Fiber-Optic Dynamic Light Scattering	546
8.4.2	Photon Cross-Correlation Spectroscopy (PCCS)	547
8.5	Sample Characterization Using DLS Measurements of Nanoparticles	547
8.5.1	DLS Instruments	548
8.5.2	Size Determination of Particles in Suspension	548
8.5.3	Concept of Identifying and Analyzing Uncertainty in the Size of the Secondary Nanoparticles	549
8.5.3.1	Change in Size of the Secondary Nanoparticles during a Time Period	550
8.5.3.2	Difference in Size Determined by Different DLS Instruments	550
8.5.3.3	Difference in Size Determined by Different DLS Instruments	551
8.5.4	Calculation of Combined Uncertainty	551
8.6	Result of DLS Characterization	551
8.7	Conclusion	552
	References	552
<b>9</b>	<b>Photoluminescence/Fluorescence Spectroscopic Technique for Nanomaterials Characterizations</b>	<b>555</b>
<b>9.1</b>	<b>Application of Photoluminescence Spectroscopy in the Characterizations of Nanomaterials</b>	<b>555</b>
	<i>Bingqiang Cao, Haibo Gong, Haibo Zeng, and Weiping Cai</i>	
9.1.1	Introduction	555
9.1.2	Experimental Techniques	557
9.1.3	Applications of General PL Spectroscopy on Nanomaterial Ensembles	559
9.1.3.1	Room-Temperature PL and PLE Spectroscopy	559
9.1.3.2	Temperature-Dependent PL Spectroscopy	561
9.1.3.3	Time-Resolved PL Spectroscopy	564
9.1.3.4	Excitation-Dependent PL Spectroscopy	565
9.1.4	Applications of MicroPL Spectroscopy on Single Nanomaterial	567
9.1.4.1	MicroPL Spectroscopy and Its Applications on Single Nanomaterial	567
9.1.4.2	CL Spectroscopy	567
9.1.4.3	Applications of CL in Single Nanomaterials	568
9.1.5	Conclusions	571
	Acknowledgments	571
	References	572
<b>9.2</b>	<b>Fluorescence Correlation Spectroscopy of Nanomaterials</b>	<b>573</b>
	<i>Kaushal Kumar, Luigi Sanguigno, Filippo Causa, and Paolo Antonio Netti</i>	
9.2.1	Introduction	573
9.2.1.1	What FCS Can Do for Nanoparticles?	576

9.2.1.2	Fluorescence Is a Tool for FCS	576
9.2.1.3	How Does FCS Work?	576
9.2.1.4	Basic Theory of FCS	577
9.2.2	Instrumentation	580
9.2.2.1	Components of the Setup	581
9.2.2.2	Construction of the Instrument	583
9.2.3	Instrument Optimization and Performing FCS Experiments	587
9.2.3.1	Aligning and Optimizing the Setup	587
9.2.3.2	Preparing the Sample for FCS	589
9.2.4	Some FCS Studies on Nanomaterial Characterizations	589
9.2.5	Conclusions and Future Prospects	593
	Acknowledgments	593
	References	594
<b>9.3</b>	<b>Time-Resolved Photoluminescence Spectroscopy of Nanomaterials</b>	<i>Yashashchandra Dwivedi</i> 597
9.3.1	Introduction	597
9.3.1.1	Example	601
9.3.2	Experimental Methods of TRPL	602
9.3.2.1	Pump-Probe Technique	604
9.3.2.2	Single-Photon Counting Technique	604
9.3.2.3	TRPL Imaging Technique	605
9.3.2.4	Nonlinear Optical Techniques	606
9.3.3	Case Study of ZnO	607
9.3.3.1	Origin of ZnO Photoluminescence	608
9.3.3.2	Time-Resolved Spectroscopy of ZnO	612
9.3.4	Concluding Remarks	617
	References	617
<b>10</b>	<b>Photoacoustic Spectroscopy and Its Applications in Characterization of Nanomaterials</b>	<i>Kaushal Kumar, Aditya Kumar Singh, and Avinash Chandra Pandey</i> 621
10.1	Introduction	621
10.1.1	Theory of the Signal Generation	622
10.1.2	Optically Transparent Solids ( $l_\beta > l$ )	625
10.1.3	Optically Opaque Solids ( $l_\beta \ll l$ )	626
10.1.4	Three-Dimensional Heat Flow Model	627
10.1.5	Thermal Diffusivity	627
10.1.6	Saturation Effect in PAS	628
10.1.7	Photoacoustic versus Absorption Spectroscopy	628
10.2	Instrumentation	629
10.2.1	Modulated Continuous Wave Source Spectrometer	630
10.2.1.1	Radiation Sources	630
10.2.1.2	Sample Cell	631

10.2.1.3	Modulation Techniques	633
10.2.1.4	Signal Detectors	634
10.2.1.5	Design of the Low-Cost Continuous Wave PA Spectrophotometer	634
10.2.2	Pulsed Photoacoustic Spectroscopy	639
10.3	Applications of PA Spectroscopy to the Nanomaterials	641
10.3.1	Determination of Optical Band Gap	641
10.3.2	Determination of Absolute Quantum Efficiency	644
10.3.3	Determination of Thermal Diffusivity/Conductivity	645
10.3.4	Photoacoustic Spectroscopy in Biology	646
10.3.5	Determination of Phase Transition with Temperature	648
	References	648
<b>11</b>	<b>Ultrafast Laser Spectroscopy of Nanomaterials</b>	<b>651</b>
	<i>Subhash Chandra Singh and Yashashchandra Dwivedi</i>	
11.1	Introduction	651
11.2	Ultrafast Time-Resolved Spectroscopy	652
11.2.1	Transient Absorption Spectroscopy	653
11.2.2	Time-Resolved Ultrafast Fluorescence Spectroscopy	656
11.2.3	Time-Resolved Ultrafast Infrared Spectroscopy	660
11.2.4	Time-Resolved Ultrafast Raman Spectroscopy	663
11.2.5	Time-Resolved Ultrafast Faraday Rotation (TRFR) Spectroscopy	672
11.3	Other Multiple Wave Ultrafast Spectroscopic Techniques	673
11.3.1	Photon Echoes	673
11.3.2	Four-Wave Mixing	678
11.4	Measurement of Charge Carrier Dynamics	679
11.4.1	Effect of Size and Surface on Charge Carrier Dynamics in Semiconductor NPs	680
11.4.2	Effect of Excitation Power on Charge Carrier Dynamics: Picosecond Dynamics	682
11.4.3	Effects of Size and Surface on the Electron Relaxation Dynamics in Metal NPs	683
11.5	Conclusion and Future Prospects	684
	Acknowledgments	685
	References	685
<b>12</b>	<b>Nonlinear Optical Characterization of Nanomaterials</b>	<b>693</b>
	<i>Rashid Ashirovich Ganeev</i>	
12.1	Influence of Laser Ablation Parameters on the Optical and Nonlinear Optical Characteristics of Colloidal Solution of Semiconductor Nanoparticles	693
12.1.1	Introduction	693
12.1.2	Experimental Setup	694
12.1.3	Results and Discussion	696
12.1.3.1	Measurements of $n_2$ of Semiconductor Solutions	696

12.1.3.2	The Analysis of Self-Interaction Processes in Semiconductor Solutions	699
12.1.3.3	The Sign of Nonlinear Refraction of Semiconductor Nanoparticles	700
12.1.3.4	Nonlinear Absorption Measurements	702
12.2	High-Order Harmonic Generation in Silver-Nanoparticle-Contained Plasma	704
12.2.1	Introduction	704
12.2.2	Experimental Arrangements	705
12.2.3	Results and Discussion	706
12.3	Studies of Low- and High-Order Nonlinear Optical Properties of BaTiO <sub>3</sub> and SrTiO <sub>3</sub> Nanoparticles	714
12.3.1	Introduction	714
12.3.2	Experimental Arrangements	715
12.4	Results and Discussion	717
12.4.1	Structural Characterization of the Samples	717
12.4.2	Nonlinear Refraction and Nonlinear Absorption of BaTiO <sub>3</sub> - and SrTiO <sub>3</sub> -Nanoparticle-Contained Suspensions	719
12.5	High-Order Harmonic Generation from the BaTiO <sub>3</sub> - and SrTiO <sub>3</sub> -Nanoparticle-Contained Laser Plumes	723
12.6	Conclusions	725
	Acknowledgments	727
	References	727
<b>13</b>	<b>Polarization and Space-Charge Profiling with Laser-Based Thermal Techniques</b>	<b>729</b>
	<i>Axel Mellinger and Rajeev Singh</i>	
13.1	Introduction	729
13.1.1	Overview	729
13.1.2	History of Thermal Techniques for Polarization and Space-Charge Depth-Proiling	730
13.2	Theoretical Foundations and Data Analysis	732
13.2.1	One-Dimensional Heat Conduction	733
13.2.2	The One-Dimensional LIMM Equation and its Solutions	736
13.2.2.1	Scale Transformation	737
13.2.2.2	Tikhonov Regularization	739
13.2.2.3	Monte Carlo Technique	740
13.2.2.4	Other Techniques	741
13.2.3	Two- and Three-Dimensional Analysis	741
13.3	Experimental Techniques	743
13.3.1	Basic Principle	744
13.3.2	Laser Intensity Modulation Method (LIMM)	745
13.3.3	Thermal Pulses	746
13.3.4	Three-Dimensional Mapping	747
13.4	Applications	748

- 13.4.1 Films of Polyvinylidene Fluoride and its Copolymers 748
- 13.4.1.1 Comparison of Focused LIMM and TPT 748
- 13.4.1.2 Poling Dynamics 749
- 13.4.2 PVDF-TrFE Coaxial Sensor Cables 749
- 13.4.3 Space-Charge Electrets 752
- 13.4.4 Polymer-Dispersed Liquid Crystals 752
- 13.4.5 Nanomaterials 753
- 13.5 Summary and Outlook 753
- References 755

**Index** 759

