Contents

Preface *xiii*
List of Abbreviations *xv*

1 Preparation of 2D Materials *1*
Yue Tang and Hua Xu
1.1 Mechanical Exfoliation of 2D Materials *2*
1.2 Liquid-Phase Exfoliation of 2D Materials *4*
1.3 Chemical Vapor Deposition Growth of 2D Materials *6*
1.4 CVD Growth of Wafer-Scale Single Crystal 2D Materials *8*
1.5 Thickness Control in CVD Growth of 2D Materials *10*
1.6 Phase Control in CVD Growth of 2D Materials *12*
1.7 Summary and Prospect *14*
References *15*

2 An Introduction to the Nonlinear Optical Properties of 2D Materials *21*
Bolong Wang and Hao-Li Zhang
2.1 Introduction *21*
2.2 Nonlinear Optics of 2D Materials *22*
2.2.1 SHG, THG, and HHG Setups *24*
2.2.2 Four-Wave Mixing *26*
2.2.3 Z-Scan Techniques *27*
2.2.4 Nonlinear Optical Imaging *29*
2.2.5 Pump–Probe Techniques *32*
2.3 Application of 2D Nonlinear Materials *35*
2.3.1 Optical Limiting *35*
2.3.2 Q-Switched and Mode-Locked Lasers *38*
2.3.3 Optical Switch and Modulation *40*
2.3.4 Other Nonlinear Optical Phenomena *41*
2.4 Prospect *43*
2.4.1 Precise Fabrication and Functionalization of 2D Materials *43*
2.4.2 High Resolution Spatiotemporal Characterizing Techniques *44*

2.4.3 New Physics of 2D Materials *44*
2.4.4 Ever-Lasting Expansion of Applications *44*
Acknowledgment *45*
References *45*

3 Modulation and Enhancement of Optical Nonlinearity in 2D Materials *55*
Xinglin Wen and Qihua Xiong
3.1 Introduction *55*
3.2 Nonlinear Optics in 2D Materials *57*
3.2.1 Basics of Nonlinear Optics *57*
3.2.2 Parametric Nonlinear Optics *58*
3.2.3 Nonparametric Nonlinear Optics *59*
3.3 Nonlinearity Modulation in 2D Materials *60*
3.3.1 Structural Engineering *60*
3.3.1.1 Layer Number *60*
3.3.1.2 Twisted Angle *62*
3.3.1.3 Stacking Order *64*
3.3.1.4 Edge States *65*
3.3.2 Optical Modulation *66*
3.3.2.1 Excitonic Effects Enhanced Nonlinearity *66*
3.3.2.2 Valley-Dependent Nonlinearity *69*
3.3.2.3 Optical Cavity-Enhanced Nonlinearity *71*
3.3.2.4 All-Optical Modulation *73*
3.3.3 Electrical Modulation *75*
3.3.4 Magnetic Modulation *78*
3.3.5 Perspectives *78*
Author Contributions *78*
Notes *79*
Acknowledgment *79*
References *79*

4 Characterizing the Nonlinear Optical Properties of 2D Materials by Double 4f Nonlinear Imaging System with Phase Object and Four-Wave-Mixing Microscopy *87*
Zhongguo Li and Yinglin Song
4.1 Introduction *87*
4.2 Principle of NLO Measurement Technique *88*
4.2.1 Nonlinear Optical Interaction in 2D Materials *88*
4.2.2 Typical NLO Measurement Method in 2D Material Research *89*
4.2.2.1 Self-Phase Modulation (SPM) *89*
4.2.2.2 Z-Scan *89*
4.2.2.3 Third-Harmonic Generation (THG) *90*
4.2.2.4 Two-Photon-Induced Photoluminescence (TPL) *90*

4.3 Characterizing NLO Response of 2D Materials via Double 4f Nonlinear Imaging System with Phase Object (NIT-PO) Microscopy *91*
4.4 Characterizing NLO Response of 2D Materials via Four-Wave-Mixing Microscopy *95*
4.5 Outlook and Perspective *97*
References *98*

5 Ultrafast Carrier Dynamics in Emerging 2D Materials *103*
Jiawei Huang, Ningning Dong, and Jun Wang
5.1 Introduction *103*
5.2 Ultrafast Time-Resolved Spectroscopy *104*
5.2.1 Principle of Pump–Probe Measurement *104*
5.2.2 Experiment for Ultrafast Spectroscopy *107*
5.2.3 Fundamental Mechanism of Recombination Dynamics *107*
5.3 Ultrafast Optics in van der Waals 2D Materials *109*
5.3.1 Graphene *109*
5.3.2 Transition Metal Dichalcogenides (TMDC) *109*
5.3.3 Black Phosphorus *115*
5.4 Ultrafast Optics in Emerging Quasi-2D Materials *118*
5.4.1 2D Perovskite *118*
5.4.2 Non-Layered 2D Platinum Sulfide *120*
5.5 Perspectives on Ultrafast Optics for 2D Material *124*
Author Contributions *125*
Notes *125*
Acknowledgment *125*
References *125*

6 Transient Terahertz Spectroscopy for 2D Materials *131*
Jingyin Xu, Kai Zhang, Hong Li, and Tianwu Wang
6.1 Introduction *131*
6.2 Generation and Detection of THz Radiation *132*
6.2.1 Generation of THz Radiation Based on Nonlinear Optical Processes *132*
6.2.1.1 Photoconductive Antennas (PCAs) *133*
6.2.1.2 Electro-optic (EO) Crystals *135*
6.2.1.3 Air Plasma *136*
6.2.1.4 THz Emission of 2D Semiconductor Materials *140*
6.2.2 Typical THz Time-Domain Spectroscopy Setup *141*
6.2.2.1 Time-Domain THz Spectroscopy Under Pressure *143*
6.2.3 Photoinduced Changes of the Dielectric Function in 2D via THz Spectroscopy *147*
6.3 Nanoscale THz Scanning Probe Microscopy of 2D Materials *149*
6.3.1 Scanning Near-Field THz Microscopy for Polariton in 2D Materials *150*
6.3.2 THz-STM *151*
6.4 Perspectives *154*
6.4.1 Transient THz Spectroscopy *154*

6.4.2 High-Resolution Spatial and Temporal THz Spectroscopies *155*
Acknowledgment *155*
References *155*

7 Graphene Glass for Nonlinear Optics *163*
Qi Xiao, Jingyu Sun, and Hao-Li Zhang
7.1 Light Absorption of Graphene *163*
7.2 Nonlinear Optical Properties of Graphene *164*
7.2.1 Third-Order Nonlinear Optical Properties of Graphene *164*
7.2.2 Saturable Absorption of Graphene *165*
7.2.3 High-Order Harmonic Generation of Graphene *165*
7.3 Nonlinear Optical Properties of Graphene Glass *167*
7.3.1 Graphene-Doped Glass *167*
7.3.2 Graphene Glass Fabricated by Spin Coating *167*
7.3.3 Graphene Glass Fabricated by Transfer Method *168*
7.3.4 Directly Growth Graphene on Glass *168*
7.3.4.1 Graphene Growth on High-Temperature-Resistant Glass *168*
7.3.4.2 Graphene Growth on Molten Glass *171*
7.3.4.3 Metal-Catalyst-Assisted Graphene Growth *173*
7.3.4.4 Plasma-Enhanced Low-Temperature Graphene Growth *176*
7.4 Perspectives *179*
Acknowledgment *180*
References *180*

8 2D Materials for Nonlinear Optical Limiting *185*
Wen Shang, Bolong Wang, and Qiang Wang
8.1 Introduction *185*
8.2 Nonlinear Optical Limiting Mechanism *186*
8.2.1 Reverse Saturable Absorption *186*
8.2.2 Two-Photon/Multiphoton Absorption *187*
8.2.3 Free Carrier Absorption *188*
8.2.4 Nonlinear Refraction *188*
8.2.5 Nonlinear Scattering *189*
8.3 2D Materials for Optical Limiting *189*
8.3.1 Graphene and Analogs *190*
8.3.1.1 Graphene *190*
8.3.1.2 Transition Metal Dichalcogenides *194*
8.3.1.3 Black Phosphorus *196*
8.3.1.4 Hexagonal Boron Nitride (h-BNS) *197*
8.3.2 Novel 2D Materials *197*
8.3.2.1 Antimonene *197*
8.3.2.2 Tellurene *198*
8.3.2.3 2D Perovskites *200*
8.3.2.4 2D Metal–Organic Frameworks (2D-MOFs) *201*
8.3.3 Materials with New Structures and Mechanism *203*

8.3.3.1 Nonlinear Photonic Metamaterials *203*
8.3.3.2 Plasmonic Effect-Enhanced Nonlinearity *205*
8.3.4 Multifunctional Optical Limiting Devices *206*
8.4 Conclusions and Prospects *209*
Acknowledgments *210*
References *210*

9 The Saturable Absorbers Based on 2D Materials *221*
Xin-Hai Yan, Lei Zhang, and Kai-Ge Zhou
9.1 Introduction *221*
9.2 The Fundaments in the 2D Materials-Based Saturable Absorbers *222*
9.2.1 SA Theory *222*
9.2.2 Slow- and Fast-Saturable Absorber *223*
9.2.2.1 Slow-Saturable Absorber *224*
9.2.2.2 Fast-Saturable Absorber *225*
9.3 The Family of 2D Material-Based Saturable Absorbers *225*
9.3.1 Mono-Elemental 2D Materials *226*
9.3.1.1 Group IVA-Elemental 2D Materials *226*
9.3.1.2 Group VA-Elemental 2D Materials *230*
9.3.2 Dual-Elemental 2D Materials *234*
9.3.2.1 TMDs *234*
9.3.2.2 Topological Insulators (TIs) *235*
9.3.3 Multi-Elemental 2D Materials *237*
9.3.3.1 MOFs *237*
9.3.3.2 MXenes *237*
9.3.3.3 2D Perovskites *239*
9.4 Applications *239*
9.4.1 Fabrication of SA Device Based on 2D Materials *239*
9.4.1.1 Scotch Tape Exfoliation *240*
9.4.1.2 CVD, PVD *240*
9.4.1.3 LPE *240*
9.4.2 Q-Switched Laser *242*
9.4.2.1 Q-Switched Fiber Laser *243*
9.4.3 Mode-Locked Laser *246*
9.5 Perspectives and Outlook *248*
Acknowledgment *249*
References *249*

10 Second-Harmonic and Third-Harmonic Generations in 2D Layered Materials *257*
Xudong Jin and Min Zhao
10.1 Introduction *257*
10.1.1 Fundamentals of SHG and THG *258*
10.1.2 2DLM-Based SHG *259*
10.1.3 Graphene *260*

10.1.4 Transition Metal Dichalcogenides *262*
10.1.5 Other 2DLMs *266*
10.1.6 2DLM-Based THG *268*
10.1.6.1 Graphene *268*
10.1.7 Transition Metal Dichalcogenides *268*
10.1.7.1 Other 2DLMs *270*
10.2 Conclusions and Outlook *274*
References *274*

11 2D Perovskites for Nanolasers *281*
Wei Yuan and Chuanjiang Qin
11.1 Introduction *281*
11.2 Laser Formation Principle and Performance Parameters *283*
11.2.1 Basic Optical Physical Process *283*
11.2.2 Laser Formation Condition *283*
11.2.3 Performance Parameters *284*
11.2.4 Optical Cavities *285*
11.3 The Application of 2D Perovskites in Nanolasers *286*
11.3.1 Microplates *287*
11.3.2 Microrods *287*
11.3.3 Microcrystals *291*
11.3.4 Nanowires *291*
11.3.5 Microrings *293*
11.3.6 Thin Films *294*
11.3.7 Thin Flakes *298*
11.4 Prospect *299*
References *300*

12 2D Materials for Space Use *303*
Shuyan Wang and Qiang Wang
12.1 Introduction *303*
12.2 Space Radiation and Two-Dimensional Materials *305*
12.2.1 Space Radiation Environment *305*
12.2.2 2D Materials Under Irradiation *307*
12.2.2.1 Electron Irradiation *307*
12.2.2.2 Ion Irradiation *307*
12.2.2.3 Proton Irradiation *308*
12.2.2.4 γ-Ray Irradiation *308*
12.3 2D Materials for Space Use *309*
12.3.1 Emerging Nonlinear Optical Applications *309*
12.3.1.1 Laser Protection and Mode Locking *310*
12.3.1.2 Other Nonlinear Phenomena *313*
12.3.2 Space X-ray Detection and Imaging *314*
12.3.3 Perovskite Solar Cells (PSCs) *316*
12.3.4 2D Single-Photon Sources *317*

12.3.5 Integrated Optoelectronic Platform *318*
12.3.5.1 Field-Effect Transistor and Photodetectors *318*
12.3.5.2 Sensors *320*
12.3.6 Other Applications: Lubricants *320*
12.4 Perspectives *321*
Acknowledgment *322*
References *322*

Index *333*