

# NANO-OPTICS AND NANOPHOTONICS

---

For further volumes:  
[www.springer.com/series/8765](http://www.springer.com/series/8765)

# NANO-OPTICS AND NANOPHOTONICS

---

The Springer Series in Nano-Optics and Nanophotonics provides an expanding selection of research monographs in the area of nano-optics and nanophotonics, science- and technology-based on optical interactions of matter in the nanoscale and related topics of contemporary interest. With this broad coverage of topics, the series is of use to all research scientists, engineers and graduate students who need up-to-date reference books. The editors encourage prospective authors to correspond with them in advance of submitting a manuscript. Submission of manuscripts should be made to the editor-in-chief, one of the editors or to Springer.

## *Editor-in-Chief*

Motoichi Ohtsu

Department of Electrical Engineering and Informations Systems, School of Engineering  
The University of Tokyo  
Yayoi, Bunkyo-ku 2-11-16, 113-8656 Tokyo, Japan  
[ohtsu@ee.t.u-tokyo.ac.jp](mailto:ohtsu@ee.t.u-tokyo.ac.jp)

## *Editorial Board*

Gunnar Björk

Department of Electronics  
KTH, Electrum 229  
164 40 Kista, Sweden  
[gbjork@kth.se](mailto:gbjork@kth.se)

Chennupati Jagadish

Department of Electronic Materials Engineering  
Research School of Physics and Engineering  
Australian National University  
Canberra, ACT 0200, Australia  
[cxji09@rsphysse.anu.edu.au](mailto:cxji09@rsphysse.anu.edu.au)

Christoph Lienau

Institut für Physik, Fakultät V  
Carl von Ossietzky Universität Oldenburg  
Ammerländer Heerstraße 114-118  
26129 Oldenburg, Germany  
[christoph.lienau@uni-oldenburg.de](mailto:christoph.lienau@uni-oldenburg.de)

Lih Y. Lin

Electrical Engineering Department  
University of Washington  
M414 EEL Bldg., Box 352500  
Seattle, WA 98195-2500, USA  
[lylin@uw.edu](mailto:lylin@uw.edu)

Erich Runge

Technische Universität Ilmenau  
Curiebau, Weimarer Str. 25  
98693 Ilmenau, Germany  
[erich.runge@tu-ilmenau.de](mailto:erich.runge@tu-ilmenau.de)

Frank Träger

Experimentalphysik I, Universität Kassel  
Heinrich-Plett-Str. 40, 34132 Kassel, Germany  
[traeger@physik.uni-kassel.de](mailto:traeger@physik.uni-kassel.de)

Masaru Tsukada

WPI-AIMR Center, Tohoku University  
2-1-1 Katahira, Aoba-ku, Sendai, 980-8577 Japan  
[tsukada@wpi-aimr.tohoku.ac.jp](mailto:tsukada@wpi-aimr.tohoku.ac.jp)

Please view available titles in *Nano-Optics and Nanophotonics*  
on series homepage <http://www.springer.com/series/8765>

Motoichi Ohtsu

Editor

# Progress in Nanophotonics 2

 Springer

*Editor*

Motoichi Ohtsu  
Graduate School of Engineering  
The University of Tokyo  
Tokyo, Japan

ISSN 2192-1970  
Nano-Optics and Nanophotonics  
ISBN 978-3-642-35718-3  
DOI 10.1007/978-3-642-35719-0  
Springer Heidelberg New York Dordrecht London

ISSN 2192-1989 (electronic)  
ISBN 978-3-642-35719-0 (eBook)

Library of Congress Control Number: 2011934022

© Springer-Verlag Berlin Heidelberg 2013

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media ([www.springer.com](http://www.springer.com))

# Preface to *Progress in Nanophotonics*

As the first example, recent advances in photonic systems demand drastic increases in the degree of integration of photonic devices for large-capacity, ultrahigh-speed signal transmission and information processing. Device size has to be scaled down to nanometric dimensions to meet this requirement, which will become even more strict in the future. As the second example, photonic fabrication systems demand drastic decreases in the size of the fabricated patterns for assembling ultra-large-scale integrated circuits. These requirements cannot be met even if the sizes of the materials are decreased by advanced methods based on nanotechnology. It is essential to decrease the size of the electromagnetic field used as a carrier for signal transmission, processing, and fabrication. Such a decrease in the size of the electromagnetic field beyond the diffraction limit of the propagating field can be realized in optical near fields. Nanophotonics, a novel optical technology that utilizes the optical near field, was proposed by M. Ohtsu (the editor of this monograph series) in 1993 in order to meet these requirements. However, it should be noted that the true nature of nanophotonics involves not only its ability to meet the above requirements. It is also its ability to realize qualitative innovations in photonic devices, fabrication techniques, energy conversion, and information processing systems by utilizing novel functions and phenomena made possible by optical near-field interactions, which are otherwise impossible as long as conventional propagating light is used. Based on interdisciplinary studies on condensed-matter physics, optical science, and quantum field theory, nano-materials and optical energy transfer in the nanometric regime have been extensively studied in the last two decades. Through these studies, novel theories on optical near fields have been developed, and a variety of novel phenomena have been found. The results of this basic research have been applied to develop nanometer-sized photonic devices, nanometer-resolution fabrication, highly efficient energy conversion, and novel information processing, resulting in qualitative innovations. Further advancement in these areas is expected to establish novel optical sciences in the nanometric space, which can be applied to further progress in nanophotonics in order to support the sustainable development of peoples lives all over the world. This unique monograph series entitled *Progress in Nanophotonics* in the Springer Series in Nano-optics and Nanophotonics is being

introduced to review the results of advanced studies in the field of nanophotonics and covers the most recent topics of theoretical and experimental interest in relevant fields, such as classical and quantum optical sciences, nanometer-sized condensed matter physics, devices, fabrication techniques, energy conversion, information processing, architectures, and algorithms. Each chapter is written by leading scientists in the relevant field. Thus, this monograph series will provide high-quality scientific and technical information to scientists, engineers, and students who are and will be engaged in nanophotonics research. As compared with the previous monograph series entitled “Progress in Nano-Electro-Optics” (edited by M. Ohtsu, published in the Springer Series in Optical Science), this monograph series deals not only with optical science on the nanometer scale, but also its applications to technology. I am grateful to Dr. C. Ascheron of Springer-Verlag for his guidance and suggestions throughout the preparation of this monograph series.

Tokyo  
August 2010

Motoichi Ohtsu

## Preface to Volume II

This volume contains five review articles focusing on various but mutually related topics in nanophotonics written by the world's leading scientists. The first article describes near-field excitation dynamics in molecules. A generalized theoretical description of a light-matter interaction is given on the basis of the multipolar Hamiltonian. The second article is devoted to describing experimental results for wavelength up-converting a phonon-assisted excitation process with degenerate beams and non-degenerate beams in dye grains. Application to optical pulse-shape measurement is also reviewed. The third article describes a fabrication method of semiconductor quantum dots, including self-assembly of InAs quantum dots based on the Stranski-Krastanov growth mode. Fabrication and application of ultrahigh-density quantum dots by a strain compensation technique are also reviewed. The fourth article is devoted to single-nanotube spectroscopy and time-resolved spectroscopy for studying novel excitonic properties of single-walled carbon nanotubes. The striking features of excitons in the carbon nanotube, multiple-exciton states, charged exciton formation, and exciton-multiplication are reviewed. The last article describes microfluidic and extended-nano fluidic techniques. It claims that nanophotonics is used as a key technology since the space size becomes smaller than the wavelength in extended-nano space.

This volume is published with the support of Prof. Yatsui of the University of Tokyo, an associate editor. I hope that this volume will be a valuable resource for readers and future specialists in nanophotonics.

Tokyo  
February 2013

Motoichi Ohtsu

# Contents

<b>1</b>	<b>Near-Field Excitation Dynamics in Molecules: Nonuniform Light-Matter Interaction Theory Beyond a Dipole Approximation</b>	<b>1</b>
	Katsuyuki Nobusada	
1.1	Introduction	1
1.2	Theory	4
1.2.1	Multipolar Hamiltonian	4
1.2.2	A Molecule Interacting with a Nonuniform Near-Field	6
1.2.3	Near-Field Radiated from an Oscillating Dipole	8
1.2.4	Light-Matter Interaction in the Kohn-Sham DFT Approach	9
1.3	Computational Application	10
1.3.1	Time-Dependent Kohn-Sham Approach in Real Space	10
1.4	High-Harmonic-Generation Spectra Induced by the Near-Field Excitation	12
1.4.1	Molecular System and Computations	12
1.4.2	Near-Field Excitation Dynamics	13
1.4.3	Even and Odd Harmonics	18
1.4.4	Control of Harmonic Generation by Interference	19
1.4.5	Concluding Remarks	20
1.5	Near-Field Induced Optical Force in a Metal Nanoparticle and C <sub>60</sub>	21
1.5.1	Brief Review of Optical Force	21
1.5.2	Optical Force Exerted on a Particle	22
1.5.3	Model System and Computations	23
1.5.4	Optical Force on a Silver Nanoparticle	25
1.5.5	Optical Force on C <sub>60</sub>	29
1.5.6	Concluding Remarks	29
1.6	Summary	30
	References	30
<b>2</b>	<b>Novel Excitonic Properties of Carbon Nanotube Studied by Advanced Optical Spectroscopy</b>	<b>33</b>
	Kazunari Matsuda	



2.1	Basic Optical Properties of Carbon Nanotube . . . . .	33
2.1.1	Structure of Carbon Nanotube . . . . .	33
2.1.2	Electronic Structure of Graphene . . . . .	34
2.1.3	Electronic Structure of Carbon Nanotube . . . . .	35
2.1.4	Optical Spectroscopy of Carbon Nanotubes . . . . .	37
2.1.5	Exciton State in Carbon Nanotubes . . . . .	38
2.1.6	Exciton Structures in Carbon Nanotubes . . . . .	39
2.2	Novel Excitonic Properties of Carbon Nanotube . . . . .	40
2.2.1	Single Carbon Nanotube Spectroscopy for Revealing Exciton Structures . . . . .	40
2.2.2	Singlet-Bright and -Dark Exciton Revealed by Magneto-PL Spectroscopy . . . . .	42
2.2.3	Triplet and $K$ -Momentum Dark Exciton States . . . . .	45
2.2.4	Exciton-Complex in Carbon Nanotubes . . . . .	49
2.3	Novel Exciton Dynamics of Carbon Nanotube . . . . .	52
2.3.1	Exciton Relaxation Dynamics Between Bright and Dark State . . . . .	52
2.3.2	Radiative Lifetime of Bright Exciton States . . . . .	55
2.3.3	Exciton-Exciton Interaction in Carbon Nanotube . . . . .	60
2.3.4	Multi-Exciton Generation in Carbon Nanotube . . . . .	64
2.4	Summary . . . . .	67
	References . . . . .	67
<b>3</b>	<b>Fabrication of Ultrahigh-Density Self-assembled InAs Quantum Dots by Strain Compensation . . . . .</b>	<b>71</b>
	Kouichi Akahane	
3.1	Semiconductor Quantum Dot . . . . .	71
3.1.1	Self-assembled Semiconductor Quantum Dot . . . . .	73
3.1.2	Fabrication of Ultrahigh-Density QDs Using Strain-Compensation Technique . . . . .	75
3.1.3	Applications Using Ultrahigh-Density QDs . . . . .	83
3.1.4	Summary . . . . .	95
	References . . . . .	95
<b>4</b>	<b>Wavelength Up-Conversion Using a Phonon-Assisted Excitation Process and Its Application to Optical Pulse-Shape Measurement . . . . .</b>	<b>97</b>
	Hiroyasu Fujiwara	
4.1	Introduction . . . . .	97
4.2	Multi-step Phonon-Assisted Processes with Degenerate Beams . . . . .	98
4.2.1	Principles of Multi-step Phonon-Assisted Process . . . . .	99
4.2.2	Sample Preparation . . . . .	102
4.2.3	Comparison Between Fluorescence and Emitted Spectra Induced by Phonon-Assisted Process . . . . .	103
4.2.4	Excitation Intensity Dependence . . . . .	104
4.2.5	Lifetime of the Intermediate Excited State . . . . .	105

- 4.3 Multi-step Phonon-Assisted Process with Two Nondegenerate Beams . . . . . 108
  - 4.3.1 Emitted Spectra Induced by Phonon-Assisted Process with Nondegenerate Beams . . . . . 109
  - 4.3.2 Excitation Intensity Dependence . . . . . 111
  - 4.3.3 Dependence of the Difference in Polarization Angle Between Two Nondegenerate Beams . . . . . 114
- 4.4 Application to Optical Pulse Shape Measurement . . . . . 115
  - 4.4.1 Experimental Setup . . . . . 116
  - 4.4.2 Experimental Results . . . . . 117
- 4.5 Summary . . . . . 119
- References . . . . . 120
- 5 Micro and Extended-Nano Fluidics and Optics for Chemical and Bioanalytical Technology . . . . . 121**  
Kazuma Mawatari, Yuriy Pihosh, Hisashi Shimizu, Yutaka Kazoe, and Takehiko Kitamori
  - 5.1 Introduction . . . . . 121
  - 5.2 Technology and Applications by Microfluidics . . . . . 123
    - 5.2.1 Integration Methods . . . . . 123
    - 5.2.2 Optical Detection Method for Single Molecule Detection . . . . . 127
    - 5.2.3 Applications . . . . . 132
  - 5.3 Extended-Nano Fluidics and Optics . . . . . 136
    - 5.3.1 Introduction . . . . . 136
    - 5.3.2 Optical Detection Methods . . . . . 138
    - 5.3.3 Liquid and Optical Properties . . . . . 147
    - 5.3.4 Applications . . . . . 160
  - 5.4 Summary . . . . . 162
  - References . . . . . 162
- Index . . . . . 165**

# Contributors

**Kouichi Akahane** National Institute of Information and Communications Technology, Koganei, Tokyo, Japan

**Hiroyasu Fujiwara** Central Research Laboratories, Hamamatsu Photonics K.K., Hamamatsu, Shizuoka, Japan

**Yutaka Kazoe** Department of Applied Chemistry, School of Engineering, The University of Tokyo, Tokyo, Japan

**Takehiko Kitamori** Department of Applied Chemistry, School of Engineering, The University of Tokyo, Tokyo, Japan

**Kazunari Matsuda** Institute of Advanced Energy, Kyoto University, Uji, Kyoto, Japan

**Kazuma Mawatari** Department of Applied Chemistry, School of Engineering, The University of Tokyo, Tokyo, Japan

**Katsuyuki Nobusada** Department of Theoretical and Computational Molecular Science, Institute for Molecular Science, Okazaki, Aichi, Japan

**Yuriy Pihosh** Department of Applied Chemistry, School of Engineering, The University of Tokyo, Tokyo, Japan

**Hisashi Shimizu** Department of Applied Chemistry, School of Engineering, The University of Tokyo, Tokyo, Japan