

# Nano-Optics and Nanophotonics

## *Editor-in-Chief*

Motoichi Ohtsu, Tokyo, Japan

## *Editorial Board*

Gunnar Björk, Kista, Sweden  
Hirokazu Hori, Kofu, Yamanashi, Japan  
Chennupati Jagadish, Canberra, ACT, Australia  
Christoph Lienau, Oldenburg, Germany  
Lih Y. Lin, Seattle, WA, USA  
Erich Runge, Ilmenau, Germany  
Frank Träger, Kassel, Germany  
Masaru Tsukada, Aoba-ku, Sendai, Japan

For further volumes:

<http://www.springer.com/series/8765>

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.

Makoto Naruse  
Editor

# Nanophotonic Information Physics

Nanointelligence and Nanophotonic  
Computing

 Springer

*Editor*  
Makoto Naruse  
Photonic Network Research Institute  
National Institute of Information and  
Communications Technology  
Tokyo  
Japan

ISSN 2192-1970                      ISSN 2192-1989 (electronic)  
ISBN 978-3-642-40223-4            ISBN 978-3-642-40224-1 (eBook)  
DOI 10.1007/978-3-642-40224-1  
Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2013953214

© Springer-Verlag Berlin Heidelberg 2014

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)

# Preface

This book contains nine review articles about nanophotonic information physics—with the subtitle nanointelligence and nanophotonic computing—and is the first publication of its kind.

Optical science and technologies have been experiencing tremendous advancements in recent years, especially at scales below the wavelength of light. Technological enablers have been cultivated both in top-down approaches such as nanoscale-precision lithography, and bottom-up ones, such as DNA-based self-assembly. The fundamental physical processes of light–matter interactions, such as energy transfer via near-field interactions, among others, have been extensively studied from the viewpoint of the basic science and enabling technologies of nanophotonics.

From an information standpoint, on the other hand, novel architectures should be considered so that we can fully utilize and benefit from the potential of the unique physical processes made possible by nanophotonics. There are plenty of degrees-of-freedom on the nanoscale, and a wide variety of physical processes and technologies exist. A comprehensive view covering diverse disciplines, including physics, materials, devices, systems, information, and architectures, is vitally important and will push the frontiers of physical and information sciences and technologies.

At the same time, such interdisciplinary and basic research areas that cover both physics and information—or real-world and abstract functions—will pave the way to gain fundamental insights and critical knowledge for implementing novel applications of nanophotonics that will be of key importance in our lives and for wider society, both today and in the future; these include computing, information systems, network systems, sensing and imaging, healthcare and welfare, safety and security, the environment and energy.

Such a research concept is represented by the title of this book. The nine selected articles in this book are based on presentations given at the First International Workshop on Information Physics and Computing in Nano-scale Photonics (IPCN), held in Orleans, France, in September 2012. The workshop aimed to bring researchers together and stimulate strong interest at the intersection of nanophotonics, nanoelectronics, and information science and technologies, a goal that is also shared by this book. It should be emphasized that novel architectural

ideas, concepts, and paradigms are discussed in each chapter, besides concrete technological realizations.

**Chapter 1** (Naruse et al.) discusses information physics fundamentals for nanophotonics. **Chapters 2** (Dwyer et al.), **3** (Tanida), and **4** (Ogura et al.) present the original concepts of the authors and some practical applications. The concepts described in these three chapters are all based on DNA and related self-assembly principles and technologies, but it should be remarked that a variety of system-level ideas and benefits result. **Chapters 5** (Kasai et al.) and **6** (Kawahito et al.) are based on nanoelectronics with unique device architectures for computing and imaging applications. **Chapter 7** (Tate et al.) discusses interfacing issues, and corresponding solutions, between the macro- and nano-scale worlds, which are of critical importance for nanophotonic systems. **Chapter 8** (Tait et al.) discusses photonic neuromorphic signal processing and computing, including both its fundamental theoretical concerns and photonic realizations. **Chapter 9** (Aono et al.) paves the way to new problem-solving and decision-making methods based on the spatiotemporal optical excitation transfer dynamics provided by optical near-field interactions.

Through these inter- and cross-disciplinary investigations covering optical, material, and information sciences, besides considering applications and architectures that will provide new value via state-of-the-art technologies, it is my sincere hope to convey the excitement and sense-of-wonder that emerges, and that researchers will harness the fruits of these investigations in creating a new research area that merges physical and information sciences and technologies.

I am deeply indebted to the committee members, speakers, and participants of the IPCN Workshop and its subsequent in-depth discussions, especially Dr. Y. Ogura (Osaka University) who served as the co-chair of the workshop, and Dr. M. Aono (Tokyo Institute of Technology) who greatly helped in the successful organization of the workshop. Also, I would like to thank Dr. J. Tanida (Osaka University) for his encouragement and discussions throughout the course of the workshop and the preparation of this book. In addition, I sincerely thank Dr. M. Ohtsu (The University of Tokyo), who is the Editor-in-Chief of Nano-Optics and Nanophotonics, for his great encouragement of researchers in nanophotonics science and technology and for his support and suggestions for this book. Finally, I am grateful to Dr. C. Acheron of Springer-Verlag for his guidance and suggestions throughout the preparation of this book.

Tokyo

Makoto Naruse

# Contents

<b>1 Nanointelligence: Information Physics Fundamentals for Nanophotonics</b> . . . . .	1
Makoto Naruse, Naoya Tate, Masashi Aono and Motoichi Ohtsu	
1.1 Introduction. . . . .	2
1.2 Optical Excitation Transfer to go Beyond the von Neumann Architecture . . . . .	4
1.2.1 Fundamentals . . . . .	5
1.2.2 Space-, Time-, and Energy-Related Basic Functions . . . . .	7
1.2.3 Going Beyond the von Neumann Architecture: Stochastic Solution Searching . . . . .	13
1.3 Nanophotonics for Security . . . . .	19
1.3.1 Theoretical Foundation . . . . .	20
1.3.2 Hierarchical Hologram for Information Hiding and its Theoretical Fundamentals. . . . .	22
1.3.3 Shape-Engineered Nanostructures for Authentication Functions. . . . .	26
1.4 Stochastic Modeling of Near-Field Processes for Intelligent Material Formation . . . . .	28
1.4.1 Light-Assisted Size-Regulation of Nanoparticles . . . . .	29
1.4.2 Light-Assisted Nanoparticle Array Formation . . . . .	31
1.5 Conclusion and Future Prospect. . . . .	35
References . . . . .	36
<b>2 DNA Self-Assembled Nanostructures for Resonance Energy Transfer Circuits</b> . . . . .	41
Chris Dwyer, Arjun Rallapalli, Mohammad Mottaghi and Siyang Wang	
2.1 Introduction. . . . .	41
2.2 Foundations for an Integrated Molecular System . . . . .	42
2.3 DNA Self-Assembly. . . . .	43
2.4 RET Circuits and Logic Devices . . . . .	45
2.4.1 Inputs and Outputs. . . . .	45

2.4.2	Signal Transport . . . . .	46
2.4.3	Non-linear Transfer . . . . .	46
2.4.4	RET-Based Logical Functions . . . . .	47
2.5	Design Flow . . . . .	48
2.5.1	Comparison with Other EDA Design Flows . . . . .	49
2.5.2	RET Network Design as a Type-and-Site Assignment Problem . . . . .	50
2.6	Metrics and Design Rules . . . . .	50
2.6.1	Metrics . . . . .	51
2.6.2	Design Rules . . . . .	51
2.7	Design Automation Process . . . . .	52
2.7.1	Scripting Language for Tool-Chain Control . . . . .	53
2.7.2	Spectral Analysis Tool . . . . .	53
2.7.3	Geometry Analysis Tool . . . . .	54
2.7.4	Linear Approximation Tool . . . . .	54
2.7.5	Physical Simulation . . . . .	55
2.7.6	Batch Evaluation Tools . . . . .	58
2.8	Design Examples . . . . .	59
2.8.1	Design Example 1: AND5 . . . . .	59
2.8.2	Design Example 2: Wavelength Sequence Detector . . . . .	62
2.9	Evaluation . . . . .	64
2.10	Conclusion . . . . .	65
	References . . . . .	65
<b>3</b>	<b>Smart Fold Architecture: A Nano Information System Based on a Hierarchical Structure . . . . .</b>	<b>67</b>
	Jun Tanida	
3.1	Introduction . . . . .	67
3.2	DNA Nano Information Systems . . . . .	68
3.2.1	Fundamental Concepts . . . . .	68
3.2.2	DNA Information Techniques . . . . .	69
3.2.3	Architectures . . . . .	73
3.3	Smart Fold Architecture . . . . .	77
3.3.1	Concept . . . . .	77
3.3.2	Constituent Layers . . . . .	79
3.3.3	System Operation . . . . .	81
3.4	Applications of Smart Fold Information Systems . . . . .	84
3.5	Discussion . . . . .	87
3.5.1	Implications of Smart Fold Computing . . . . .	87
3.5.2	Future Issues . . . . .	88
3.6	Conclusion . . . . .	89
	References . . . . .	90



<b>4 Photonic DNA Nano-Processor: A Photonics-Based Approach to Molecular Processing Mediated by DNA</b> . . . . .	91
Yusuke Ogura, Takahiro Nishimura, Hirotsugu Yamamoto, Kenji Yamada and Jun Tanida	
4.1 Introduction . . . . .	91
4.2 Photonic DNA Nano-Processor . . . . .	93
4.2.1 Concept . . . . .	93
4.2.2 Photonic DNA Nano-Processor as Mediator . . . . .	94
4.2.3 Types of Light Usage . . . . .	96
4.3 Light-Activatable DNA Nano-Processor . . . . .	97
4.3.1 Activation of Sensing Function Using Light . . . . .	97
4.3.2 Scheme . . . . .	98
4.3.3 Experiments . . . . .	100
4.4 DNA Scaffold Logic . . . . .	103
4.4.1 Fundamental Scheme of Logic Operation . . . . .	103
4.4.2 Features . . . . .	105
4.4.3 Experiments . . . . .	106
4.4.4 Analysis of Properties . . . . .	108
4.5 Conclusions and Outlook . . . . .	111
References . . . . .	112
<b>5 Boolean Logic Circuits on Nanowire Networks and Related Technologies</b> . . . . .	115
Seiya Kasai, Hong-Quan Zhao, Yuta Shiratori, Tamer Mohamed and Svetlana N. Yanushkevich	
5.1 Introduction . . . . .	115
5.2 BDD Logic Circuit on Nanowire Network . . . . .	118
5.2.1 Basic Concept and Nanoscale Implementation . . . . .	118
5.2.2 Circuit Design . . . . .	120
5.2.3 Fabrication . . . . .	123
5.2.4 Device Characteristics . . . . .	123
5.2.5 Circuit operation . . . . .	125
5.2.6 Performance . . . . .	127
5.3 Reconfigurable BDD Circuit . . . . .	129
5.3.1 Concept . . . . .	129
5.3.2 Fabrication and Characterization . . . . .	131
5.3.3 Implemented Functions and Circuit Aarea . . . . .	134
5.4 Error Correcting BDD Circuits . . . . .	135
5.4.1 Background . . . . .	135
5.4.2 Error Correction Scheme . . . . .	136
5.4.3 Implementation and Characterization . . . . .	137
5.5 Summary . . . . .	141
References . . . . .	141

<b>6</b>	<b>Single Photoelectron Manipulation and Detection with Sub-Nanosecond Resolution in CMOS Imagers . . . . .</b>	<b>145</b>
	Shoji Kawahito, Keita Yasutomi and Keiichiro Kagawa	
6.1	Introduction . . . . .	145
6.2	Single Photoelectron Manipulation by CMOS Active Pixel . . . . .	146
6.2.1	Single Photon Avalanche Diode . . . . .	146
6.2.2	Achieving High Quality in CMOS Image Sensors . . . . .	148
6.3	Our Method: Lateral Electric Field (LEF) Control . . . . .	150
6.3.1	Concept and Implementation of LEF Control . . . . .	150
6.3.2	Comparison with Transfer-Gate-Based Implementation . . . . .	152
6.3.3	Simple Implementation: Draining-Only Modulation . . . . .	153
6.4	Chip Implementation and Experiments . . . . .	154
6.4.1	Fluorescence Lifetime Imaging Microscopy (FLIM) Image Sensor . . . . .	154
6.4.2	Experimental Results . . . . .	154
6.5	Conclusions . . . . .	157
	References . . . . .	158
<b>7</b>	<b>Engineering of a Nanometric Optical System Based on Optical Near-Field Interactions for Macro-Scale Applications . . . . .</b>	<b>161</b>
	Naoya Tate, Makoto Naruse and Motoichi Ohtsu	
7.1	Introduction . . . . .	161
7.2	Nanometric Optical System . . . . .	162
7.2.1	Nanophotonics . . . . .	162
7.2.2	Basics of Nanometric Optical System . . . . .	163
7.3	Modulatable Nanophotonics . . . . .	165
7.3.1	Concept . . . . .	165
7.3.2	Basics of Optical Energy Transfer . . . . .	166
7.3.3	Modulated Emission Based on Optical Energy Transfer . . . . .	167
7.3.4	Numerical Demonstration . . . . .	168
7.3.5	Experimental Demonstration . . . . .	171
7.3.6	Conclusion . . . . .	174
7.4	Nanophotonic Droplet . . . . .	174
7.4.1	Concept . . . . .	174
7.4.2	Basics . . . . .	175
7.4.3	Experimental Demonstrations . . . . .	176
7.4.4	Conclusion . . . . .	180
7.5	Summary . . . . .	180
	References . . . . .	181

<b>8 Photonic Neuromorphic Signal Processing and Computing . . . . .</b>	<b>183</b>
Alexander N. Tait, Mitchell A. Nahmias, Yue Tian, Bhavin J. Shastri and Paul R. Prucnal	
8.1 Introduction . . . . .	183
8.2 Neuromorphic Processing in Electronics and Photonics . . . . .	185
8.3 Photonic Spike Processing . . . . .	186
8.3.1 Spiking Signals . . . . .	187
8.3.2 Spike Processor: Computational Primitive . . . . .	188
8.4 Spiking Neuron Model . . . . .	191
8.5 Photonic Neuron Bench-Top Model . . . . .	192
8.6 Lightwave Neuromorphic Circuits . . . . .	195
8.6.1 Barn Owl Auditory Localization Algorithm . . . . .	195
8.6.2 Crayfish Tail-Flip Escape Response . . . . .	197
8.7 Ultrafast Learning . . . . .	199
8.7.1 Synaptic Time Dependent Plasticity . . . . .	200
8.7.2 Intrinsic Plasticity . . . . .	201
8.7.3 Principal Component Analysis . . . . .	201
8.7.4 Independent Component Analysis . . . . .	202
8.7.5 Photonic STDP . . . . .	203
8.8 Excitable Laser Neuron . . . . .	205
8.8.1 Before Pulse Formation . . . . .	206
8.8.2 Pulse Generation . . . . .	207
8.8.3 LIF Analogy . . . . .	208
8.8.4 Excitable VCSELs . . . . .	209
8.8.5 Other Spiking Photonic Devices . . . . .	212
8.9 Cortical Spike Algorithms: Small-Circuit Demos . . . . .	213
8.9.1 Multistable System . . . . .	214
8.9.2 Synfire Chain . . . . .	215
8.9.3 Spatio-Temporal Pattern Recognition Circuit . . . . .	216
8.10 Summary and Concluding Remarks . . . . .	218
References . . . . .	221
<b>9 A Nanophotonic Computing Paradigm: Problem-Solving and Decision-Making Systems Using Spatiotemporal Photoexcitation Transfer Dynamics . . . . .</b>	<b>223</b>
Masashi Aono, Song-Ju Kim, Makoto Naruse, Masamitsu Wakabayashi, Hirokazu Hori, Motoichi Ohtsu and Masahiko Hara	
9.1 Introduction . . . . .	224
9.2 Photoexcitation Transfer . . . . .	226
9.3 Nanophotonic Problem Solver . . . . .	227
9.3.1 The Satisfiability Problem . . . . .	227
9.3.2 Spatiotemporal Dynamics of Photoexcitation Transfer . . . . .	228

- 9.3.3 Model of a Nanophotonic Problem Solver (NanoPS) . . . 230
- 9.3.4 WalkSAT Algorithm . . . . . 234
- 9.3.5 NanoPS versus WalkSAT . . . . . 234
- 9.4 Nanophotonic Decision Maker. . . . . 235
  - 9.4.1 Multi-Armed Bandit Problem (BP) . . . . . 235
  - 9.4.2 Model of a Nanophotonic Decision  
Maker (NanoDM) . . . . . 236
  - 9.4.3 Intensity Adjuster of NanoDM . . . . . 239
  - 9.4.4 Softmax Algorithm . . . . . 241
  - 9.4.5 NanoDM versus Softmax . . . . . 241
- 9.5 Discussion and Conclusion . . . . . 242
- References . . . . . 243
- Index** . . . . . 245

# Contributors

**Masashi Aono** Earth-Life Science Institute, Tokyo Institute of Technology, 201201 Ookayama, Meguro-ku, Tokyo 152-8850, Japan, e-mail: masashi.aono@elsi.jp

**Chris Dwyer** Department of Electrical and Computer Engineering, Department of Computer Science, Duke University, Durham, NC, USA, e-mail: dwyer@ece.duke.edu

**Masahiko Hara** Department of Electronic Chemistry, Interdisciplinary Graduate School of Science and Engineering, Tokyo Institute of Technology, 4259 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan, e-mail: masahara@echem.titech.ac.jp

**Hirokazu Hori** Interdisciplinary Graduate School of Medicine and Engineering, University of Yamanashi, 4-3-11 Takeda, Kofu, Yamanashi 400-8511, Japan, e-mail: hirohori@yamanashi.ac.jp

**Keiichiro Kagawa** Research Institute of Electronics, Shizuoka University, Hamamatsu, Japan, e-mail: kagawa@idl.rie.shizuoka.ac.jp

**Seiya Kasai** Graduate School of Information Science and Technology and Research Center for Integrated Quantum Electronics, Hokkaido University, N14, W9, Sapporo 060-0814, Japan, e-mail: kasai@rciqe.hokudai.ac.jp

**Shoji Kawahito** Research Institute of Electronics, Shizuoka University, Hamamatsu, Japan, e-mail: kawahito@idl.rie.shizuoka.ac.jp

**Song-Ju Kim** Atomic Electronics Group, WPI Center for Materials Nanoarchitectonics (MANA), National Institute for Materials Science (NIMS), 1-1 Namiki, Tsukuba, Ibaraki 305-0044, Japan, e-mail: KIM.Songju@nims.go.jp

**Tarmer Mohamed** Department of Electrical and Computer Engineering, University of Calgary, Calgary, Alberta, T2N 1N4, Canada, e-mail: tamer.mohamed@ucalgary.ca

**Mohammad Mottaghi** Department of Computer Science, Duke University, Durham, NC, USA, e-mail: mamad@cs.duke.edu

**Mitchell A. Nahmias** Lightwave Communications Laboratory, Department of Electrical Engineering, Princeton University, Princeton, NJ 08544, USA, e-mail: mnahmias@princeton.edu

**Makoto Naruse** Photonic Network Research Institute, National Institute of Information and Communications Technology, 4-2-1 Nukui-kita, Koganei, Tokyo 184-8795, Japan, e-mail: naruse@nict.go.jp

**Takahiro Nishimura** Graduate School of Information Science and Technology, Osaka University, 1-5 Yamadaoka, Suita, Osaka 565-0871, Japan, e-mail: t-nishimura@ist.osaka-u.ac.jp

**Yusuke Ogura** Graduate School of Information Science and Technology, Osaka University, 1-5 Yamadaoka, Suita, Osaka 565-0871, Japan, e-mail: ogura@ist.osaka-u.ac.jp

**Motoichi Ohtsu** Department of Electrical Engineering and Information Systems and Nanophotonics Research Center, Graduate School of Engineering, The University of Tokyo, 2-11-16 Yayoi, Bunkyo-ku, Tokyo 113-8656, Japan, e-mail: ohtsu@ee.t.u-tokyo.ac.jp

**Paul R. Prucnal** Lightwave Communications Laboratory, Department of Electrical Engineering, Princeton University, Princeton, NJ 08544, USA, e-mail: prucnal@princeton.edu

**Arjun Rallapalli** Department of Electrical and Computer Engineering, Duke University, Durham, NC, USA, e-mail: ar233@duke.edu

**Bhavin J. Shastri** Lightwave Communications Laboratory, Department of Electrical Engineering, Princeton University, Princeton, NJ 08544, USA, e-mail: bshastri@princeton.edu

**Yuta Shiratori** Graduate School of Information Science and Technology and Research Center for Integrated Quantum Electronics, Hokkaido University, N14, W9, Sapporo 060-0814, Japan

**Alexander N. Tait** Lightwave Communications Laboratory, Department of Electrical Engineering, Princeton University, Princeton, NJ 08544, USA, e-mail: atait@princeton.edu

**Jun Tanida** Graduate School of Information Science and Technology, Osaka University, 1-5 Yamadaoka, Suita, Osaka 565-0871, Japan, e-mail: tanida@ist.osaka-u.ac.jp

**Naoya Tate** Department of Electrical Engineering and Information Systems and Nanophotonics Research Center, Graduate School of Engineering, The University of Tokyo, 2-11-16 Yayoi, Bunkyo-ku, Tokyo 113-8656, Japan, e-mail: tate@nanophotonics.t.u-tokyo.ac.jp

**Yue Tian** Lightwave Communications Laboratory, Department of Electrical Engineering, Princeton University, Princeton, NJ 08544, USA, e-mail: yuetian@princeton.edu

**Masamitsu Wakabayashi** Department of Biomolecular Engineering, Tokyo Institute of Technology, 4259 Nagatsuta, Midori-ku, Yokohama 226-8501, Japan, e-mail: wakabayashi@riken.jp

**Siyang Wang** Department of Electrical and Computer Engineering, Department of Computer Science, Duke University, Durham, NC, USA, e-mail: siyang.wang@duke.edu

**Kenji Yamada** Graduate School of Medicine, Osaka University, 1-7 Yamadaoka, Suita, Osaka 565-0871, Japan, e-mail: k-yamada@sahs.med.osaka-u.ac.jp

**Hirotsugu Yamamoto** Department of Optical Science and Technology, The University of Tokushima, 2-1 Minamijyusanjima-cho, Tokushima 770-8506, Japan, e-mail: yamamoto@opt.tokushima-u.ac.jp

**Svetlana N. Yanushkevich** Department of Electrical and Computer Engineering, University of Calgary, Calgary, Alberta, T2N 1N4, Canada, e-mail: syanshk@ucalgary.ca

**Keita Yasutomi** Research Institute of Electronics, Shizuoka University, Hamamatsu, Japan, e-mail: kyasu@idl.rie.shizuoka.ac.jp

**Hong-Quan Zhao** Graduate School of Information Science and Technology and Research Center for Integrated Quantum Electronics, Hokkaido University, N14, W9, Sapporo 060-0814, Japan