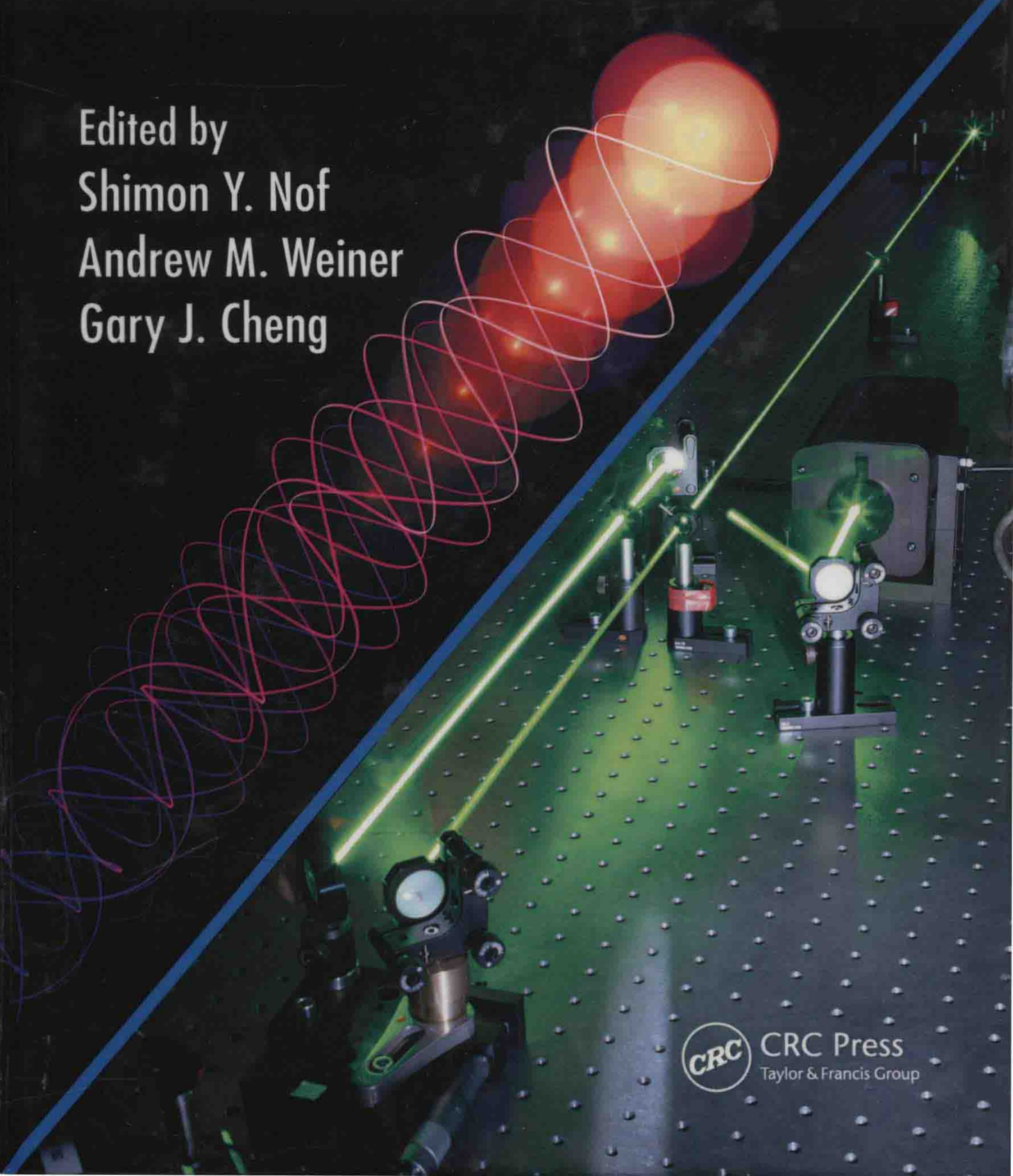
LASER AND PHOTONIC SYSTEMS

Design and Integration

Edited by
Shimon Y. Nof
Andrew M. Weiner
Gary J. Cheng



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LASER AND PHOTONIC SYSTEMS

Design and Integration

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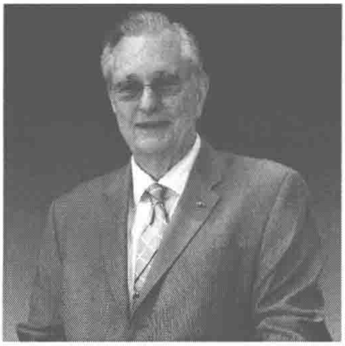
This book is dedicated to the scientists, engineers, explorers, and inventors of light, laser, and photonics throughout human history. May we always be enlightened.

Foreword

Laser and Photonic Systems: Dreams and Visions that Come True



As someone with a nearly 60-year career in materials research, I welcome the opportunity to write this foreword for a book on a visionary subject that is dear to me. I have been blessed by knowing many of the visionaries in this field who have propelled it forward and made it come true: Charles Townes, discoverer of stimulated emission from masers and lasers; Theodore Maiman, inventor of the first laser; Amnon Yariv, pioneer in lightwave communications and nonlinear and phase conjugate optics; Zhores Alferov, developer of semiconductor heterojunctions; Nick Holonyak, inventor of the practical LED; and Jerry Woodall, developer of compound heterojunctions and inventor of the red LED, among others.

Lasers and photonics also have a 60-plus year history starting from 1951 when Charles Townes conceived of the idea for the maser. Our lives before the many transformations in all aspects of our life that have resulted from these discoveries must be bewildering to most young students who today take these transformations for granted.

Our role as scientist-engineers and innovators is to integrate new concepts to find new solutions that will improve our security and quality of life. Experience has taught us that innovations usually derive from ideas that come from challenging old paradigms and probing into how best to do things differently. Contributors to this book have done just that and have asked not just *why* and *how* but *why not* in looking beyond the technological frontiers of our known world.

Consequently, this book will appeal to members of the STEM community of all ages in exploring how critical *grand challenge* problems of the twenty-first century can be addressed by lasers and photonics.

This book addresses such transformative applications of laser and photonic systems as in medicine, communications, security, sustainable energy, advanced manufacturing, and the synthesis and modification of new materials, especially the nanoprocessing of nanomaterials. Contributors to the book describe a few well-chosen samples of the many discoveries and developments currently underway that will have a substantial impact on our lives in the remainder of the twenty-first century.

Let me offer a walk through my own history in this field since the 1970s involving many distinguished colleagues.

In 1976, I joined DARPA (Defense Advanced Research Projects Agency) as head of the Materials Research Office, where along with Richard Reynolds, Ed van Reuth, Harry Windsor, and Michael Buckley, DARPA funded pioneering research at both universities and industries in compound semiconductor heterojunctions, rapidly solidified metals, laser-assisted machining of ceramics, integrated optic flight systems, ring laser gyros, optical fiber sensors, nonlinear optic frequency doubling and phase conjugation, LIDAR (light detection and ranging, or laser imaging detection and ranging) systems, and hardening against directed high-energy weapons (to include the effects of laser-induced plasmas on seeker performance). Most of this effort at the time was early-stage 6.1 (basic) and 6.2 (applied) research according the Department of Defense research budget categories; however, it preceded the early acceleration of nanotechnology.

In the 1990s, we worked on laser beam lithography of metal oxide electrodes for PZT memory applications. Traditional metal/metal oxide patterning techniques typically involved photolithography, which is a relatively expensive and time-consuming process. As an improvement, the fabrication of metal oxide upper electrodes by metallorganic decomposition (MOD) was integrated with laser beam patterning. A variety of patterns were prepared, which demonstrates the suitability of laser patterning for many applications.

During my directorship at NIST (National Institute of Standards and Technology), I enjoyed discussing laser quantum physics with Bill Phillips, Eric Cornell, Jan Hall, Dave Wineland, Deborah Jin, and Jun Ye. Bill Phillips shared the Nobel Prize in Physics in 1997 for "developing methods to cool and trap atoms with laser light." Eric Cornell shared the Nobel Prize in Physics in 2001 for synthesizing the first Bose–Einstein condensate in 1995. Jan Hall shared the Nobel Prize in Physics in 2005 for his work in precision laser spectroscopy and the optical frequency comb technique. David Wineland shared the Nobel Prize in Physics in 2012 for groundbreaking experimental methods on manipulating quantum systems that form the building blocks for a practical quantum computer.

The work accomplishments of Deborah Jin and Jun Ye are likewise groundbreaking. Deborah Jin and her group have achieved a fermionic condensate and discovered fermionic condensates of Cooper pairs at the BCS (Bardeen–Cooper–Schrieffer) and BEC (Bose–Einstein condensate) crossover regime. Jun Ye and his group have demonstrated precision manipulation of atomic states in ultracold strontium, resulting in the most accurate atomic clock in the world (will neither gain nor lose a second in 200 million years).

These discoveries of new states of condensed matter and their quantum behavior will lead to transformative quantum information and communications technologies in the twenty-first century. In addition, they will provide precise metrology techniques that will permit the engineering of materials at the atomic level with novel properties through the manipulation of their bonding states and band structures.

During my years with NIST, an important effort was to overcome the problems associated with LADAR (laser radar) systems. The NIST Construction Metrology and Automation Group (CMAG), cooperating with the NIST Intelligent Systems Division (ISD), developed performance metrics and researched issues related to the design and delivery of a next-generation LADAR sensor that will enable general automation in structured and unstructured environments. The physics and implementation of various LADAR technologies were studied. Worldwide state-of-the-art research was compared, and the results pointed to the general trends in advanced LADAR sensor research. Interestingly, their evaluation of likely impact on manufacturing, autonomous vehicle mobility, and on construction automation has been largely materialized with LADAR and also with LIDAR.

From my memories at the National Science Foundation (NSF), I recall our efforts to sustain and advance the Laser Interferometer Gravitational Wave Observatory (LIGO). LIGO is a large-scale physics experiment to directly detect and observe gravitational waves of cosmic origin. It is a joint project between scientists at many colleges and universities and is the largest and most ambitious project ever funded by the NSF. The international LIGO Scientific Collaboration (LSC) is a growing group of researchers, over 800 individuals at roughly 50 institutions, working to analyze the data from LIGO and other detectors. Beyond its immense scientific role, LIGO is a symbol of global scientific collaboration, which is both educational and inspirational. Teachers and educators are at the frontline of generating a high-quality workforce for any nation. Many students learning at universities and sophisticated labs participate in hands-on research experiments and internships made possible by federal grants in facilities such as the LIGO. These experiences are an effective way to excite, inspire, and train future generations of scientists, engineers, and technologists who will continue innovating. An important role of this book on design and integration of laser and photonic systems is to inspire teachers, educators, and students, as well as entrepreneurs and managers, to learn and innovate.

There are other public policies that will require input from scientists and engineers to policy makers because of their complexity and contextual nature (to include technical, social, and economic factors and their interrelationships). The relevant policy alternatives will require extensive analysis and research to identify the relative advantages and disadvantages of each alternative. Examples of challenging policy issues include the following:

- Crafting certification requirements for medical practitioners and manufacturing specialists involved in the safe operation of laser and photonics systems

- Working with OSHA and EPA in setting standards and regulations for safe, environment-friendly applications of additive manufacturing and surface modifications involving nanomaterials
- Establishing physical standards (with NIST research) through ANSI and ISO for new technologies entering commercialization and use
- Determining equitable standards for broadband spectrum auctions and allocations for laser and photonics communications (especially in the quantum regime)
- Establishing privacy and equity standards for the use of cloud computing, especially where open systems are desired using HubZero capabilities

The scientific and engineering communities in the field of laser and photonics systems must take a responsible stance in working with policy makers to assure that new policies are workable and meet fairness and equity principles in the context of their intended application. This view is increasingly important as complexity escalates when we progress from local and regional to national and global regimes.

Looking to the future, one can expect additional transformative developments in how research and education in laser and photonics will be conducted, as discussed in this book. This vision provides hope that as distances continue to shrink worldwide and virtual engagement is further facilitated, scientists and engineers will collaboratively find solutions to the daunting global challenges confronting the world today and lead us to a better quality of life.

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Preface

Laser and photonic systems and innovations are increasingly proliferating, resulting in significant advancements in many areas. Often, they offer better approaches in addressing important and difficult problems. It is necessary to understand their emerging discoveries and systems perspectives and learn how they can improve the quality of our life by overcoming serious obstacles.

This book brings together multiple perspectives on the topic of laser and photonic systems and innovations. Such systems are of growing interest to many organizations and individuals, given their promise and potential solutions of grand societal challenges.

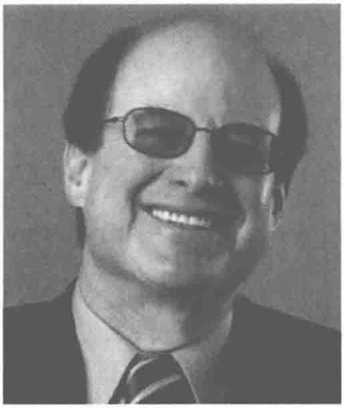
The book contains insights from leading researchers, inventors, and innovators. We discuss and explain a variety of techniques, models, technologies, and proven experience with laser and photonic systems, as well as their development, design, and integration.

We realize that laser and photonic technologies have already impacted solutions across many critical sectors. In this book, we are seeking to answer several questions. First, how can industrial and systems engineering knowledge (systems improvement and integration, optimization, process simulation, cyber-supported collaboration, and human supervisory control, among others) accelerate the systematization of laser and photonic systems and innovations? Can we inspire new concepts, models, scale-up methods, and significant quality improvements? Included are implications of cutting-edge laser and photonics technologies for industry and academia, scientists, engineers, students, and industry leaders. Materials are presented in terms of near-term and long-term methodological innovations, research and action agenda, and educational programs.

By bringing together chapters from multidisciplinary leading scientists and technologists as well as industrial and systems engineers and managers, we aim to stimulate new thinking that would bring a systems, networks, and system-of-systems perspective to bear on laser and photonic systems applications. Throughout the chapters, we challenge ourselves to explore opportunities for revolutionary and broader advancements. A particular emphasis throughout the book is the identification of emerging research and application frontiers where there are promising contributions to lasers, optics, and photonics applications in fields such as manufacturing, healthcare, security, and communications. The last chapter provides a summary of the subjects discussed in the previous chapters, pointing out important developments and implications to education.

The coeditors and coauthors appreciate and acknowledge the contributions of many individuals and organizations that took part in this effort and helped us bring this book to fruition. We hope that you, the readers, will benefit from this book and leverage the knowledge to exciting new frontiers of successful solutions.

Editors



Shimon Y. Nof, PhD, DHC, is professor of industrial engineering, Purdue University, and has held visiting positions at MIT and at universities in Chile, the European Union, Hong Kong, Israel, Japan, Mexico, and Taiwan. His research interests include collaborative control theory and collaborative robotics. He is the director of the NSF and the industry-supported PRISM Center (Production, Robotics and Integration Software for Manufacturing and Management) linked with PGRN (PRISM Global Research Network); recent chair of the IFAC (International Federation of Automatic Control) Coordinating Committee, Manufacturing & Logistics Systems; recent president and current board member of IFPR (International Foundation of Production Research); fellow of the Institute of Industrial Engineers; fellow of the IFPR; and inaugural member of Purdue's *Book of Great Teachers*. He teaches courses on integrated production systems design, computing in Industrial Engineering (IE), design of e-work and e-service systems, industrial robotics and assembly, and research in computer and communication methods for supply networks. He is coinventor of four patents; has published over 500 articles on production and manufacturing systems, robotics, and automation; and is the author, coauthor, and editor of 12 books, including the *Handbook of Industrial Robotics* (first and second editions) and the *International Encyclopedia of Robotics*, both winners of the Most Outstanding Book in Science and Engineering Award, as well as *Information and Collaboration Models of Integration*, *Industrial Assembly*, and the *Springer Handbook of Automation*. Dr. Nof was a cochair of the inaugural Gavriel Salvendy International Symposium on Frontiers in Industrial Engineering in 2010, on the topic "Cultural Factors in Decision Making and Action," which resulted in the publication of the CRC Press book entitled *Cultural Factors in Systems Design* (2012).

Andrew M. Weiner earned an ScD in electrical engineering from MIT, worked at Bellcore and joined Purdue University in 1992.

He is the Scifres Family Distinguished Professor of Electrical and Computer Engineering. His research focuses on ultrafast optics signal processing and applications to high-speed optical communications and ultrawideband wireless communication. He is especially well known for his pioneering work on programmable generation of arbitrary ultrashort pulse waveforms, which has found application both in fiber-optic networks and in ultrafast optical science laboratories around the world. He authored the textbook *Ultrafast Optics* (Wiley, 2009), eight book chapters, and approximately 270 journal articles and is the inventor of 15 US patents. Professor Weiner is a fellow the Optical Society of America and of the Institute of Electrical and Electronics Engineers (IEEE) and is a member of the US National Academy of Engineering. He has won numerous awards for his research, including the Hertz Foundation Doctoral Thesis Prize (1984), the Adolph Lomb Medal of the Optical Society of America (1990), the Curtis McGraw Research Award of the American Society of Engineering Education (1997), the International Commission on Optics Prize (1997), the Alexander von Humboldt Foundation Research Award for Senior US Scientists (2000), and the IEEE Photonics Society Quantum Electronics Award (2011). He is joint recipient, with J.P. Heritage, of the IEEE LEOS William Streifer Scientific Achievement Award (1999) and the OSA R.W. Wood Prize (2008) and has been recognized by Purdue University with the inaugural Research Excellence Award from the Schools of Engineering (2003), with the Provost's Outstanding Graduate Student Mentor Award (2008), and with the Herbert Newby McCoy Award for outstanding contributions to the natural sciences (2013). In 2009, Professor Weiner was named a US Department of Defense National Security Science and Engineering Faculty Fellow. Dr. Weiner recently served a three-year term as chair of the National Academy's US Frontiers of Engineering Meeting. He currently serves as the editor-in-chief of *Optics Express*, an all-electronic, open-access journal that publishes more than 3000 papers a year, emphasizing innovations in all aspects of optics and photonics.

Gary J. Cheng earned a PhD in mechanical engineering from Columbia University (2002), is an associate professor of industrial engineering and mechanical engineering (by courtesy), Purdue University. His research area is advanced functional materials, scalable micro/nanomanufacturing processes, laser–matter interaction, and mechanical/

physical property enhancement of materials. His research work is highly interdisciplinary, covering nanotechnology, materials science, biomedical, solid mechanics, and manufacturing. His research has been awarded an NSF CAREER award (2006), an ONR Young Investigator Award (2007), an SME K.K. Wang Outstanding Young Manufacturing Engineer Award (2007), and an ASME Chao and Trigger Young Manufacturing Engineer Award (2012). He has also been selected to serve as a faculty scholar at Purdue University (2013–2018), and was elected a fellow of the ASME in 2013. He has published more than 120 peer-reviewed papers, including more than 70 journal papers, and has 6 US patents awarded, with 9 other US patents filed.