

**CHAPTER 1****Introduction****1.1 NANOPHOTONICS—AN EXCITING FRONTIER  
IN NANOTECHNOLOGY**

Nanophotonics is an exciting new frontier that has captured the imaginations of people worldwide. It deals with the interaction of light with matter on a nanometer size scale. By adding a new dimension to nanoscale science and technology, nanophotonics provides challenges for fundamental research and creates opportunities for new technologies. The interest in nanoscience is a realization of a famous statement by Feynman that “There’s Plenty of Room at the Bottom” (Feynman, 1961). He was pointing out that if one takes a length scale of one micrometer and divides it in nanometer segments, which are a billionth of a meter, one can imagine how many segments and compartments become available to manipulate.

We are living in an age of “nano-mania.” Everything nano is considered to be exciting and worthwhile. Many countries have started Nanotechnology Initiatives. A detailed report for the U.S. National Nanotechnology Initiative has been published by the National Research Council (NRC Report, 2002). While nanotechnology can’t claim to provide a better solution for every problem, nanophotonics does create exciting opportunities and enables new technologies. The key fact is that nanophotonics deals with interactions between light and matter at a scale shorter than the wavelength of light itself. This book covers interactions and materials that constitute nanophotonics, and it also describes their applications. Its goal is to present nanophotonics in a way to entice one into this new and exciting area. Purely for the sake of convenience, the examples presented are selected wherever possible from the work conducted at our Institute for Lasers, Photonics, and Biophotonics, which has a comprehensive program in nanophotonics.

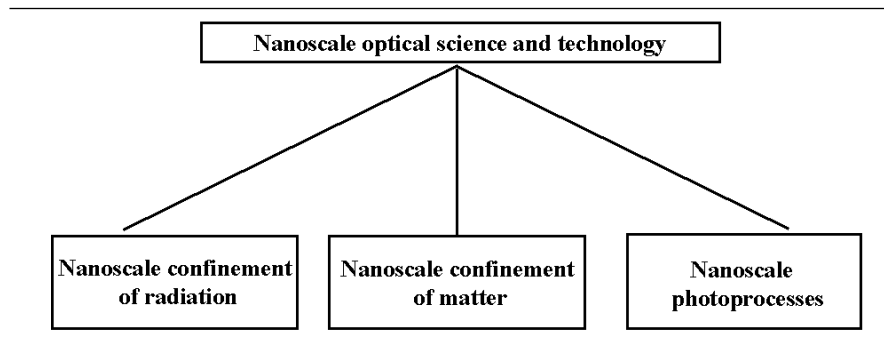
As a supplemental reference, a CD-ROM of the author’s SPIE short course on nanophotonics, produced by SPIE, is recommended. This CD-ROM (CDV 497) provides numerous technical illustrations in color in the PowerPoint format.

**1.2 NANOPHOTONICS AT A GLANCE**

Nanophotonics can conceptually be divided into three parts as shown in Table 1.1 (Shen et al., 2000). One way to induce interactions between light and matter on a

## 2 INTRODUCTION

Table 1.1. Nanophotonics



nanometer size scale is to confine light to nanoscale dimensions that are much smaller than the wavelength of light. The second approach is to confine matter to nanoscale dimensions, thereby limiting interactions between light and matter to nanoscopic dimensions. This defines the field of nanomaterials. The last way is nanoscale confinement of a photoprocess where we induce photochemistry or a light-induced phase change. This approach provides methods for nanofabrication of photonic structures and functional units.

Let's look at nanoscale confinement of radiation. There are a number of ways in which one can confine the light to a nanometer size scale. One of them is using near-field optical propagation, which we discuss in detail in Chapter 3 of this book. One example is light squeezed through a metal-coated and tapered optical fiber where the light emanates through a tip opening that is much smaller than the wavelength of light.

The nanoscale confinement of matter to make nanomaterials for photonics involves various ways of confining the dimensions of matter to produce nanostructures. For example, one can utilize nanoparticles that exhibit unique electronic and photonic properties. It is gratifying to find that these nanoparticles are already being used for various applications of nanophotonics such as UV absorbers in sunscreen lotions. Nanoparticles can be made of either inorganic or organic materials. Nanomers, which are nanometer size oligomers (a small number of repeat units) of monomeric organic structures, are organic analogues of nanoparticles. In contrast, polymers are long chain structures involving a large number of repeat units. These nanomers exhibit size-dependent optical properties. Metallic nanoparticles exhibit unique optical response and enhanced electromagnetic field and constitute the area of "plasmonics." Then there are nanoparticles which up-convert two absorbed IR photons into a photon in the visible UV range; conversely, there are nanoparticles, called quantum cutters, that down-convert an absorbed vacuum UV photon to two photons in the visible range. A hot area of nanomaterials is a photonic crystal that represents a periodic dielectric structure with a repeat unit of the order of wavelength of light. Nanocomposites comprise nanodomains of two or more dissimilar materials that are phase-separated on a nanometer size scale. Each nanodomain in

the nanocomposite can impart a particular optical property to the bulk media. Flow of optical energy by energy transfer (optical communications) between different domains can also be controlled.

Nanoscale photoprocesses can be used for nanolithography to fabricate nanostructures. These nanostructures can be used to form nanoscale sensors and actuators. A nanoscale optical memory is one of exciting concepts of nanofabrication. An important feature of nanofabrication is that the photoprocesses can be confined to well-defined nanoregions so that structures can be fabricated in a precise geometry and arrangement.

### 1.3 MULTIDISCIPLINARY EDUCATION, TRAINING, AND RESEARCH

We live in a complex world where revolutionary progress has been and continues to be made in communications, computer memory, and data processing. There is a growing need for new technologies that rapidly detect and treat diseases at an early stage or even pre-stage. As we get accustomed to these advances, our expectations will demand more compact, energy-efficient, rapidly responding, and environmentally safe technologies. Photonic-based technology, coupled with nanotechnology, can meet many of these challenges. In the medical area, new modes of photonic diagnostics, which are noninvasive and molecular-based, may recognize the pre-stages and onset of a disease such as cancer and thus provide a major leap (Prasad, 2003). Nanomedicine, combined with light-guided and activated therapy, will advance individualized therapy that is based on molecular recognition and thus have minimal side effects.

The past several decades have witnessed major technological breakthroughs produced by fusion of different disciplines. This trend is even more likely in this millennium. Nanophotonics in its broader vision offers opportunities for interactions among many traditionally disparate disciplines of science, technology, and medicine. As shall be illustrated in this book, nanophotonics is an interdisciplinary field that comprises physics, chemistry, applied sciences and engineering, biology, and biomedical technology.

A significant multidisciplinary challenge lies ahead for the broader nanophotonics visions to become reality. These challenges require a significant increase in the number of knowledgeable researchers and trained personnel in this field. This need can be met by providing a multidisciplinary training for a future generation of researchers at both undergraduate and graduate levels, worldwide. A worldwide recognition of this vital need is evident from the growing number of conferences and workshops being held on this topic, as well as from the education and training programs being offered or contemplated at various institutions. For example, the author has offered a multidisciplinary course in nanophotonics at Buffalo as well as a short course in this subject at the SPIE professional society meetings. Much of the material covered in this book was developed during the teaching of these courses and was refined by valuable feedback from these course participants.

## 4 INTRODUCTION

It is hoped that this book will serve both as an education and training text and as a reference book for research and development. Also, this book should be of value to industries and businesses, because the last chapter attempts to provide a critical evaluation of the current status of nanophotonic-based technologies.

### 1.4 RATIONALE FOR THIS BOOK

Naturally, for a hot area such as nanophotonics, many excellent reviews and edited books exist. Nanophotonics has meant different things to different people. Some have considered near-field interactions and near-field microscopy as the major thrust of nanophotonics, while others have considered it to be focused in photonic crystals. Another major direction has been nanomaterials, particularly the ones exhibiting size dependence of their optical properties; these are the quantum-confined structures. For engineers, nanoscale optical devices and nanolithography are the most relevant aspects of nanophotonics.

In terms of optical materials, the scientific community is often divided in two traditional groups: inorganic and organic, with very little cross-fertilization. The physics community focuses on inorganic semiconductors and metals, while shying away from complex organic structures. The chemical community, on the other hand, deals traditionally with organic structures and biomaterials and feels less comfortable with inorganic semiconductors, particularly with concepts defining their electronic and optical properties. Importantly, a new generation of hybrid nanomaterials, which involve different levels of integration of organic and inorganic structures, holds considerable promise for new fundamental science and novel technologies. For example, novel chemical routes can be utilized to prepare inorganic semiconductor nanostructures for nanophotonics. Engineers, who could exploit these new materials' flexibility for fabrication of components with diverse functionalities and their heterogeneous integration, often lack experience in dealing with these materials. Biologists have a great deal to offer by providing biomaterials for nanophotonics. At the same time, biological and biomedical researchers can utilize nanophotonics to study cellular processes and use nano-optical probes for diagnosis and to effect light-guided and activated therapy.

Often, a major hurdle is the lack of a common language to foster effective communication across disciplines. Therefore, much is to be gained by creating an environment that includes these disciplines and facilitates their interactions.

This book will address all these issues. It proposes to fill the existing void by providing the following features:

- A unifying, multifaceted description of nanophotonics that includes near-field interactions, nanomaterials, photonic crystals, and nanofabrication
- A focus on nanoscale optical interactions, nanostructured optical materials and applications of nanophotonics
- A coverage of inorganic, organic materials, and biomaterials as well as their hybrids

**1.5 OPPORTUNITIES FOR BASIC RESEARCH AND DEVELOPMENT OF NEW TECHNOLOGIES 5**

- A broad view of nanolithography for nanofabrication
- A coverage of nanophotonics for biomedical research and nanomedicine
- A critical assessment of nanophotonics in the market place, with future forecasts

**1.5 OPPORTUNITIES FOR BASIC RESEARCH AND DEVELOPMENT OF NEW TECHNOLOGIES**

Nanophotonics integrates a number of major technology thrust areas: lasers, photonics, photovoltaics, nanotechnology, and biotechnology. Each of these technologies either already generates or shows the potential to generate over \$100 billion per year of sales revenue. Nanophotonics also offers numerous opportunities for multidisciplinary research. Provided below is a glimpse of these opportunities, categorized by disciplines.

**Chemists and Chemical Engineers**

- Novel synthetic routes and processing of nanomaterials
- New types of molecular nanostructures and supramolecular assemblies with varied nanoarchitectures
- Self-assembled periodic and aperiodic nanostructures to induce multifunctionality and cooperative effects
- Chemistry for surface modifications to produce nanotemplates
- One-pot syntheses that do not require changing reaction vessels
- Scalable production to make large quantities economically

**Physicists**

- Quantum electrodynamics to study novel optical phenomena in nanocavities
- Single photon source for quantum information processing
- Nanoscale nonlinear optical processes
- Nanocontrol of interactions between electrons, phonons and photons
- Time-resolved and spectrally resolved studies of nanoscopic excitation dynamics

**Device Engineers**

- Nanolithography for nanofabrication of emitters, detectors, and couplers
- Nanoscale integration of emitters, transmission channels, signal processors, and detectors, coupled with power generators
- Photonic crystal circuits and microcavity-based devices
- Combination of photonic crystals and plasmonics to enhance various linear and nonlinear optical functions
- Quantum dot and quantum wire lasers

## 6 INTRODUCTION

- Highly efficient broadband and lightweight solar panels that can be packaged as rolls
- Quantum cutters to split vacuum UV photons into two visible photons for new-generation fluorescent lamps and lighting

### **Biologists**

- Genetic manipulation of biomaterials for photonics
- Biological principles to guide development of bio-inspired photonic materials
- Novel biocolloids and biotemplates for photonic structures
- Bacterial synthesis of photonic materials

### **Biomedical Researchers**

- Novel optical nanoprobe for diagnostics
- Targeted therapy using light-guided nanomedicine
- New modalities of light-activated therapy using nanoparticles
- Nanotechnology for biosensors

## 1.6 SCOPE OF THIS BOOK

This book is written for a multidisciplinary readership with the goal to provide introduction to a wide range of topics encompassing nanophotonics. A major emphasis is placed on elucidating concepts with minimal mathematical details; examples are provided to illustrate principles and applications. The book can readily enable a newcomer to this field to acquire the minimum necessary background to undertake research and development.

A major challenge for researchers working in a multidisciplinary area is the need to learn relevant concepts outside of their expertise. This may require searching through a vast amount of literature, often leading to frustrations of not being able to extract pertinent information quickly. By providing a multifaceted description of nanophotonics, it is hoped that the book will mitigate this problem and serve as a reference source.

The book is structured so that it can also be of value to educators teaching undergraduate and graduate courses in multiple departments. For them, it will serve as a textbook that elucidates basic principles and multidisciplinary approaches. Most chapters are essentially independent of each other, providing flexibility in choice of topics to be covered. Thus, the book can also readily be adopted for training and tutorial short courses at universities as well as at various professional society meetings.

Each chapter begins with an introduction describing its contents. This introduction also provides a guide to what may be omitted by a reader familiar with the specific content or by someone who is less inclined to go through details. Each chapter ends with highlights of the content covered in it. The highlights provide the take-home message from the chapter and serve to review the materials learned. Also, for researchers interested in a cursory glimpse of a chapter, the highlights provide an

overview of topics covered. For an instructor, the highlights may also be useful in the preparation of lecture notes or PowerPoint presentations.

Chapter 2 provides an introduction to the foundations of nanophotonics. The nanoscale interactions are defined by discussing similarities and differences between photons and electrons. Spatial confinement effects on photons and electrons are presented. Other topics covered are photon and electron tunneling, effect of a periodic potential in producing a bandgap, and cooperative effects. Ways to localize optical interactions axially and laterally on a nanoscale are described.

Chapter 3 defines near-field interactions and describes near-field microscopy. A brief theoretical description of near-field interactions and the various experimental geometries used to effect them are introduced. The theoretical section may be skipped by those more experimentally oriented. Various optical and higher-order nonlinear optical interactions in nanoscopic domains are described. Applications to the highly active field of single molecule spectroscopy is described.

Chapter 4 covers quantum-confined materials whose optical properties are size-dependent. Described here are semiconductor quantum wells, quantum wires, quantum dots, and their organic analogues. A succinct description of manifestations of quantum confinement effects presented in this chapter should be of significant value to those (e.g., some chemists and life scientists) encountering this topic for the first time. The applications of these materials in semiconductor lasers, described here, exemplify the technological significance of this class of materials.

Chapter 5 covers the topic of metallic nanostructures, now with a new buzzword “plasmonics” describing the subject. Relevant concepts together with potential applications are introduced. Guiding of light through dimensions smaller than the wavelength of light by using plasmonic guiding is described. The applications of metallic nanostructures to chemical and biological sensing is presented.

Chapter 6 deals with nanoscale materials and nanoparticles, for which the electronic energy gap does not change with a change in size. However, the excitation dynamics—that is, emission properties, energy transfer, and cooperative optical transitions in these nanoparticles—are dependent on their nanostructures. Thus nanocontrol of excitation dynamics is introduced. Important processes described are (i) energy up-conversion acting as an optical transformer to convert two IR photons to a visible photon and (ii) quantum cutting, which causes the down-conversion of a vacuum UV photon to two visible photons.

Chapter 7 describes various methods of fabrications and characterization of nanomaterials. In addition to the traditional semiconductor processing methods such as molecular beam epitaxy (MBE) and metal–organic chemical vapor deposition (MOCVD), the use of nanochemistry, which utilizes wet chemical synthesis approach, is also described. Some characterization techniques introduced are specific to nanomaterials.

Chapter 8 introduces nanostructured molecular architectures that include a rich class of nanomaterials often unfamiliar to physicists and engineers. These nanostructures involve organic and inorganic–organic hybrid structures. They are stabilized in a three-dimensional architecture by both covalent bonds (chemical) and noncovalent interactions (e.g., hydrogen bond). This topic is presented with a mini-

## 8 INTRODUCTION

imum amount of chemical details so that nonchemists are not overburdened. Nanomaterials covered in this chapter are block copolymers, molecular motors, dendrimers, supramolecules, Langmuir–Blodgett films, and self-assembled structures.

Chapter 9 presents the subject of photonic crystals, which is another major thrust of nanophotonics that is receiving a great deal of worldwide attention. Photonic crystals are periodic nanostructures. The chapter covers concepts, methods of fabrication, theoretical methods to calculate their band structure, and applications of photonic crystals. One can easily omit the theory section and still appreciate the novel features of photonic crystals, which are clearly and concisely described.

Chapter 10 covers nanocomposites. A significant emphasis is placed on the nanocomposite materials that incorporate nanodomains of highly dissimilar materials such as inorganic semiconductors or inorganic glasses and plastics. Merits of nanocomposites are discussed together with illustrative examples of applications, such as to energy-efficient broadband solar cells and other optoelectric devices.

Chapter 11 introduces nanolithography, broadly defined, that is used to fabricate nanoscale optical structures. Both optical and nonoptical methods are described, and some illustrative examples of applications are presented. The use of direct two-photon absorption, a nonlinear optical process, provides improved resolution leading to smaller photoproduced nanostructures compared to those produced by linear absorption.

Chapter 12 deals with biomaterials that are emerging as an important class of materials for nanophotonic applications. Bioderived and bioinspired materials are described together with bioassemblies that can be used as templates. Applications discussed are energy-harvesting, low-threshold lasing, and high-density data storage.

Chapter 13 introduces the application of nanophotonics for optical diagnostics, as well as for light-guided and light-activated therapy. Use of nanoparticles for bioimaging and sensing, as well as for targeted drug delivery in the form of nanomedicine, is discussed.

Chapter 14 provides a critical assessment of the current status of nanophotonics in the marketplace. Current applications of near-field microscopy, nanomaterials, quantum-confined lasers, photonic crystals, and nanolithography are analyzed. The chapter concludes with future outlook for nanophotonics.

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