Optical Antennas

This consistent and systematic review of recent advances in optical antenna theory and practice brings together leading experts in the fields of electrical engineering, nano-optics and nano-photonics, physical chemistry, and nanofabrication.

Fundamental concepts and functionalities relevant to optical antennas are explained, together with key principles for optical antenna modeling, design and characterization. Recognizing the tremendous potential of this technology, practical applications are also outlined.

Presenting a clear translation of the concepts of radio antenna design, near-field optics and field-enhanced spectroscopy into optical antennas, this interdisciplinary book is an indispensable resource for researchers and graduate students in engineering, optics and photonics, physics, and chemistry.

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"A thorough introduction into the field of optical nanoantennas, and a wide-ranging survey of the current state of the art in this exciting field of photonics nanotechnology."

STEFAN MAIER, Imperial College London

"This book provides a comprehensive and up-to-date overview of optical antennas, a subject of fundamental scientific and technological importance, written by the key players in the field. It will no doubt become an indispensable reference for all students, researchers, and engineers concerned with optics and photonics at the nanoscale."

THOMAS W. EBBESEN, University of Strasbourg

"Optical antennas were long regarded as a downscale from the familiar designs of radio physics; however, recently it was found that smaller scales and higher frequencies bring an exciting new physics and many novel effects and opportunities. The study of optical antennas and nanoantennas is the new emerging field of photonics, and this book presents the first systematic and comprehensive summary of the reviews written by the pioneers and top-class experts in the field of optical antennas. The book makes fascinating reading, addressing many grand challenges of the cutting-edge research for creating smaller and more efficient photonic structures and devices."

YURI KIVSHAR, Australian National University

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To Pietro, Matteo, Marta and Suzanne

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Preface

Recent years have witnessed a tremendous progress in nanofabrication, as well as in the theoretical and experimental understanding of light–matter interaction at the nanoscale. The field of nano-optics has thrived during these times and one of the most exciting related advances in this area has been the concept, design and application of *optical antennas*, or *nanoantennas*. Starting within the onset of field-enhanced spectroscopy and near-field optics, the concept has rapidly evolved into a sophisticated tool to enhance and direct spontaneous emission from quantum light sources, boost light–matter interaction and optical nonlinearities at the nanoscale, as well as implement realistic optical communication links. The amount of research activity on optical antennas has grown very rapidly in the last few years, and currently spans a broad range of areas, including optics, physics, chemistry, electrical engineering, biology and medicine, to cite a few. The rapid progress and inherent multidisciplinarity of nanoantennas have produced a situation in which the involved research communities do not necessarily speak the same language. If electrical engineers have an established formalism based on circuit and radiation concepts developed over decades of antenna engineering and design, in optics, physics or chemistry many of the same phenomena are described in very different terms. It is exactly this interdisciplinarity, however, that may lead to groundbreaking findings and applications in a variety of fields of modern science.

It is generally accepted that nanoantennas may take great advantage from decades of radio-frequency antenna research, as many of the problems currently faced in optics have been approached and solved in the twentieth century by the giants of radio-frequency antennas, including G. Marconi, S.A. Schelkunoff, R.W.P. King and E. Hallén. Indeed, translating some of these concepts to optics has been shown to be very beneficial, but it is not a trivial task, due to the different nature of many of the involved phenomena. For example, the existence of surface-plasmon-polaritons at the interface between real metals and insulators gives rise to peculiar resonant phenomena not available at radio-frequencies. In addition, the quantum nature of light and matter becomes significantly important when dealing with nanoscale features and optical fields.

The following chapters have been written by leading experts in each subfield of the area. Each contribution has been carefully selected and edited to shape a complete book structured in a coherent manner, with the goal of guiding the reader through the different languages and diverse approaches in design, fabrication, characterization and applications of optical antennas. Our aim has been not only to provide a consistent and well-organized survey of recent advances in the field, but also to help set a common playground for exciting future work in the area.

The book is divided into three parts and twenty-one chapters, covering fundamental and applied aspects of optical antennas. The first part outlines the central features and functionalities of optical antennas, using concepts and techniques from nano-optics, electrical engineering and physical chemistry. It aims at showing how an interdisciplinary approach is essential to capture the full potential of the optical antenna concept and it attempts to lay down a common language that may help the interaction among scientists and engineers working on different aspects of this topic. The book opens with an overview on the genesis of optical antennas, emphasizing their origin from near-field optical microscopy. The following two chapters aim at translating familiar radio-frequency concepts for antenna analysis and design to nano-optics. Concepts like antenna impedance, matching and radiation are revisited in the framework of optical antennas. Analogies and differences between the two fields are highlighted and the radio-frequency formalism is expanded to model the coupling between quantum emitters and optical antennas. Chapter 4 also connects engineering and optics approaches analyzing how nanoparticles with gain may operate analogously to conventional antenna elements. The next two chapters are dedicated to topics familiar to field-enhanced spectroscopy and describe them using the antenna concept. The peculiar field enhancement near optical antennas and the corresponding design rules for improving a variety of spectroscopic signals are discussed in Chapter 5. Chapter 6 is focused on the modification of fluorescence by optical antennas, acting on the excitation and emission channels and providing control over polarization and directionality. Chapters 7 and 8 expand the antenna concept toward quantum and nonlinear optics, emphasizing some unique features. For example, the possibility of enhancing the radiative decay rate of a quantum emitter by orders of magnitude across a broad spectral range or of obtaining an efficient nonlinear response without the need for phase matching. Finally, the last chapter of this first part addresses dynamical aspects in optical antennas, paying particular attention to the coherent control of nano-optical fields and its implications for spectroscopy.

The second part of the book is focused on modeling, design and characterization. Here the goal is to present a detailed survey of the state-of-the-art and of the challenges associated with the investigation of optical antennas. The first three chapters are focused on theoretical and numerical approaches to model nanostructures and their interaction with light. Chapter 10 is centered on computational electrodynamics for nano-optics, presenting advantages and pitfalls of various numerical methods. Chapter 11 deals with first-principle simulations of near-field effects, providing a deeper understanding of light–matter interaction at the nanoscale and of the relevance of quantum processes in this context.

In Chapter 12, the analysis of optical antennas is presented in the electrostatic approximation. This facilitates the analysis of the antenna properties and it may also provide interesting insights that are difficult to capture with full electrodynamic models. The next chapters discuss the challenges and available solutions for the fabrication and characterization of nanoantennas. Chapter 13 reviews how the microscopic structure of nanofabricated antennas may affect their optical properties, together with the most common optical techniques for their characterization. Chapter 14 introduces photoelectron emission microscopy (PEEM) as an essential tool to map and control the optical near-field with nanometer spatial resolution. Chapter 15 is fully dedicated to the study of optical antenna arrays and the possibility of controlling directionality and radiation pattern of the emitted light. Chapter 16 focuses on novel fabrication methods for optical antennas, with an emphasis on soft lithography. Finally, Chapter 17 is centered on nanoparticle clusters, which may exhibit exotic optical properties and may be fabricated using unconventional methods, like DNA-based assembly.

The book is concluded with four chapters on applications, spanning optical communications and energy harvesting, to sensing, imaging and biophotonics. This list is by no means exhaustive of the relevant applications of optical antennas at the moment, but it aims at providing a flavor of the breadth of exciting opportunities that nanoantennas may provide across a broad range of areas. Chapter 18 discusses how optical antennas may be deployed in a variety of semiconductor technologies for the next generation of optoelectronic devices and solar cells. Chapter 19 focuses on the use of optical antennas as refractive-index optical sensors. Imaging applications of optical antennas are presented in Chapter 20, ranging from the recent developments in scanning-probe nanoscopy to the concept of a nanolens. The final chapter describes aperture antennas and their use in bio and nanophotonics.

Optical Antennas represents an attempt at presenting a thorough and complete overview of an emerging and evolving field. We hope that the book will help towards crystallizing current achievements and future trends in the area, and bringing closer together the different approaches and disciplines involved. We wish the book to become a fundamental resource, not only for experienced researchers in the areas of nano-optics, but also to the curious scientists, postdocs and graduate students who want to get closer to this exciting field of research.

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More information

Notation

AFM	atomic force microscopy (microscope)
Al, Ag, Au, ...	aluminum, silver, gold, ... (chemical elements)
DDA	discrete dipole approximation
EBL	electron beam lithography
EHD	electric Hertzian dipole
FDTD	finite-difference time-domain
FIB	focused ion beam
FWHM	full width at half maximum
IR	infrared
LDOS	local density of states
LSPR	localized surface plasmon–polariton resonance
NA	numerical aperture
NP	nanoparticle
PEEM	photoemission electron microscopy (microscope)
QD	quantum dot
RF	radio frequency
SEF	surface-enhanced fluorescence
SEIRA	surface-enhanced infrared absorption
SEM	scanning electron microscopy (microscope)
SERRS	surface-enhanced resonance Raman scattering
SERS	surface-enhanced Raman scattering
SHG	second harmonic generation
SNOM	scanning near-field optical microscopy (microscope)
SPP	surface plasmon–polariton
SPR	surface plasmon–polariton resonance
TDDFT	time-dependent density functional theory
TE	transverse electric
TEM	transmission electron microscopy (microscope)
TERS	tip-enhanced Raman scattering
TLS	two-level system
TM	transverse magnetic
TPL	two-photon photoluminescence
UV	ultraviolet
$\sim$	*asymptotically* equal (in scaling sense)

$\approx$	*approximately* equal (in numerical value)
1D	one-dimensional (one dimension)
2D	two-dimensional (two dimensions)
2PPE	two-photon photoemission
3D	three-dimensional (three dimensions)