Principles of Nano-Optics

First published in 2006, this book has become the standard reference on nano-optics. Now in its second edition, the text has been thoroughly updated to take into account new developments and research directions. While the overall structure and pedagogical style of the book remain unchanged, all existing chapters have been expanded and a new chapter has been added.

Adopting a broad perspective, the authors provide a detailed overview of the theoretical and experimental concepts that are needed to understand and work in nano-optics, across subfields ranging from quantum optics to biophysics. New topics of discussion include optical antennas, new imaging techniques, Fano interference and strong coupling, reciprocity, metamaterials, and cavity optomechanics.

With numerous end-of-chapter problem sets and illustrative material to expand on ideas discussed in the main text, this is an ideal textbook for graduate students entering the field. It is also a valuable reference for researchers and course teachers.

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Second Edition

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To our families
(Jessica, Leonore, Jakob, David, Rahel, Rebecca, Nadja, Jan)

and our parents
(Annemarie, Werner, Miloslav, Vera)

. . . it *was* worth the climb
(B. B. Goldberg)

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Preface to the first edition

Why should we care about nano-optics? For the same reason we care about optics! The foundations of many fields of the contemporary sciences have been established using optical experiments. To give an example, think of quantum mechanics. Blackbody radiation, hydrogen lines, or the photoelectric effect were key experiments that nurtured the quantum idea. Today, optical spectroscopy is a powerful means to identify the atomic and chemical structure of different materials. The power of optics is based on the simple fact that the energy of light quanta lies in the energy range of electronic and vibrational transitions in matter. This fact is at the core of our abilities for visual perception and is the reason why experiments with light are very close to our intuition. Optics, and in particular optical imaging, helps us to consciously and logically connect complicated concepts. Therefore, pushing optical interactions to the nanometer scale opens up new perspectives, properties and phenomena in the emerging century of the nanoworld.

Nano-optics aims at the understanding of optical phenomena on the nanometer scale, i.e. near or beyond the diffraction limit of light. It is an emerging new field of study, motivated by the rapid advance of nanoscience and nanotechnology and by their need for adequate tools and strategies for fabrication, manipulation and characterization at the nanometer scale. Interestingly, nano-optics predates the trend of nanotechnology by more than a decade. An optical counterpart to the scanning tunneling microscope (STM) was demonstrated in 1984 and optical resolutions had been achieved that were significantly beyond the diffraction limit of light. These early experiments sparked a field initially called *near-field optics*, since it was realized quickly that the inclusion of near-fields in the problem of optical imaging and associated spectroscopies holds promise for achieving arbitrary spatial resolutions, thus providing access for optical experiments on the nanometer scale.

The first conference on near-field optics was held in 1992. About seventy participants discussed theoretical aspects and experimental challenges associated with near-field optics and near-field optical microscopy. The subsequent years are characterized by a constant refinement of experimental techniques, as well as the introduction of new concepts and applications. Applications of near-field optics soon covered a large span ranging from fundamental physics and materials science to biology and medicine. Following a logical development, the strong interest in near-field optics gave birth to the fields of *single-molecule spectroscopy* and *plasmonics*, and inspired new theoretical work associated with the nature of optical near-fields. In parallel, relying on the momentum of the flowering nanosciences, researchers started to tailor nanomaterials with novel optical properties. Photonic crystals, single-photon sources and optical microcavities are products of this effort. Today, elements of nano-optics are scattered across the disciplines. Various review articles and books capture the state-of-the-art in the different subfields but there appears to be no dedicated textbook that introduces the reader to the general theme of nano-optics.

This textbook is intended to teach students at the graduate level or advanced undergraduate level about the elements of nano-optics encountered in different subfields. The book evolved from lecture notes that have been the basis for courses on nano-optics taught at the Institute of Optics of the University of Rochester, and at the University of Basel. We were happy to see that students from many different departments found interest in this course, which shows that nano-optics is important to many fields of study. Not all students were interested in the same topics and, depending on their field of study, some students needed additional help with mathematical concepts. The courses were supplemented with laboratory projects that were carried out in groups of two or three students. Each team picked the project that had most affinity with their interest. Among the projects were: surface enhanced Raman scattering, photon scanning tunneling microscopy, nanosphere lithography, spectroscopy of single quantum dots, optical tweezers, and others. Towards the end of the course, students gave a presentation on their projects and handed in a written report. Most of the problems at the end of individual chapters have been solved by students as homework problems or take-home exams. We wish to acknowledge the very helpful input and inspiration that we received from many students. Their interest and engagement in this course is a significant contribution to this textbook.

Nano-optics is an active and evolving field. Every time the course was taught new topics were added. Also, nano-optics is a field that easily overlaps with other fields such as physical optics or quantum optics, and thus the boundaries cannot be clearly defined. This first edition is an initial attempt to put a frame around the field of nano-optics. We would be grateful to receive input from our readers related to corrections and extensions of existing chapters and for suggestions of new topics.

Acknowledgments

We wish to express our thanks for the input we received from various colleagues and students. We are grateful to Dieter Pohl who inspired our interest in nano-optics. This book is a result of his strong support and encouragement. We received very helpful input from Andreas Lieb, Scott Carney, Jean-Jacques Greffet, Stefan Hell, Carsten Henkel, Mark Stockman, Gert Zumofen, Jer-Shing Huang, Paolo Bragioni, and Jorge Zurita-Sanchez. It was also a great pleasure to discuss various topics with Miguel Alonso, Joe Eberly, Robert Knox, and Emil Wolf at the University of Rochester.

Preface to the second edition

We are very pleased that this textbook found wide use and reasonably high demand. Since the first printing of the first edition in 2006, the field of nano-optics has gained considerable momentum and new research directions have been established. Among the new topics are metamaterials, optical antennas, and cavity optomechanics, to name but a few. The high field localization associated with metals at optical frequencies has given rise to the demonstration of truly nanoscale lasers and the high nonlinearity of metals is being used for frequency conversion in subwavelength volumes. These new trends define a clear motivation for a second edition of *Principles of Nano-Optics*.

The overall structure of the book has been left unchanged with the exception of a new chapter on optical antennas (Chapter 13). Chapter 2 (Theoretical foundations) has been adjusted to include topics such as reciprocity and energy density in lossy media, and Chapter 4 (Resolution and localization) has been extended by including new microscopy techniques, such as structured illumination and localization microscopy. Chapter 5 received a major polish: optical microscopy is now classified in terms of interaction orders between probe and sample. On the other hand, Chapter 6 has been condensed since some near-field techniques are no longer of general interest. Several new topics have been included in Chapter 8, which covers the theory of localized light–matter interactions. Among the new sections is a discussion of Fano interference, strong coupling between modes, and level crossing. Chapters 9 and 10 received only minor revisions, while Chapter 11 has been extended by a section on metamaterials and cavity optomechanics. Chapter 12 (Surface plasmons) has also been restructured: metals are discussed from a perspective of plasma physics leading to screening and to ponderomotive forces, which give rise to a wide range of optical nonlinearities. The chapter on optical forces (Chapter 14) has been adjusted to provide a more self-consistent perspective on dipole forces. Finally, various typos have been fixed. We thank our critical readers for pointing out several errors and for suggesting valuable changes.

Despite the changes and additions it is not possible to account for all the new results and directions in the field. However, the purpose of this book is not to provide a comprehensive review, but to present the necessary foundations and concepts to understand what's going on. In this sense, the book has remained a textbook and a reference for those seeking a conceptual understanding of the working principles of nano-optics.