

PREFACE

This volume combines two “hot” directions of current research in optics and photonics. *Plasmonic* effects — collective oscillations of electrons in metals coupled with electromagnetic waves (in optics, the waves of light) — play a dominant role in confinement, guiding and strong local enhancement of waves, which may be difficult or even impossible to achieve by any other means. *Metamaterials* are artificial structures judiciously designed, on a subwavelength scale, to control the propagation of electromagnetic waves and to devise physical properties not available otherwise. One striking example is artificial magnetism at high frequencies — a physical effect that does not exist in nature.

This book is a collective effort of many leading researchers in plasmonics, metamaterials and related areas. Fourteen chapters cover all aspects of the problems involved: analysis, fabrication, simulation and applications of various plasmonic structures and metamaterials. Reviews of recent developments, as well as new advances, are presented.

In the Analysis section, Khurigin & Sun deal with the fundamental questions of plasmon-enhanced absorption and emission of optical radiation: how the optical properties of atoms, molecules or other quantum-size objects are affected by plasmonic particles nearby. Khurigin & Sun develop an analytical model for surface plasmon modes of the particle and estimate the impact of these modes on the enhancement of optical radiation absorbed or emitted by the optically active objects, electroluminescence, and photoluminescence. Due to its analytical nature and relative simplicity, Khurigin & Sun’s model opens up new avenues for optimization of optical nanostructures.

In Chapter 2, Fung *et al.* investigate very rich and intriguing properties of chiral plasmonic media with twisted anisotropic elements. The band structures and transmission properties of such media are analyzed.

Interestingly, chirality offers a way to achieve negative refraction — light bending the “wrong” way at material interfaces. (This happens when phase and group velocities of the wave are at an obtuse angle to one another in one of the materials.) Fung *et al.* show that chiral plasmonic media can support both positive and negative refraction; criteria for achieving negative refraction are established.

In Chapter 3, Petschulat *et al.* transfer the multipole analysis of classical electrodynamics to the field of optical metamaterials. The authors argue that artificial metamaterials “can be treated as ordinary matter but featuring beyond the electric dipole interaction also second order multipole interactions”. As an example, the near-field response of split-ring resonators and other structures is used to reveal the multipolar contributions of the “meta-molecules”. The review of classical multipole analysis and averaging procedures is useful in its own right.

Experimental studies and applications — a major part of this book — starts with Chapter 4 by De Leon and Berini, “Amplification and Lasing with Surface Plasmon Polaritons”. Surface plasmon polaritons (SPPs) are light waves coupled with electron oscillation in metals at metal-dielectric interfaces. Losses in the metal, however, hamper many practical applications of SPP; thus amplification of these waves is of great practical interest. De Leon and Berini review major theoretical and experimental accomplishments in this field, in connection with amplified spontaneous emission, stimulated emission, and lasing. This contribution belongs to the general area of *active plasmonics* that is developing very rapidly.

Yu & Capasso, in Chapter 5, review recent work on plasmonic beam shaping of mid-infrared and far-infrared quantum cascade lasers (QCL). The reader unfamiliar with QCL will undoubtedly find an introductory review in the chapter useful. The authors explain how “metal and semiconductor microstructures can effectively tailor the dispersion properties of mid- and far-infrared surface plasmon polaritons”. Plasmonic Bragg gratings, spoof surface plasmon polariton structures, and channel polariton structures are discussed along with their various applications. Yu & Capasso also identify future directions in wavefront engineering with plasmonics: producing diffraction-free Bessel beams and beams with orbital angular momentum that can be used to rotate small particles. New materials and systems in the mid-IR and THz ranges are also identified — for example, semiconductors for THz light and conductive oxides such as indium tin oxide (ITO) and aluminum zinc oxide (AZO) for the near-infrared wavelengths and beyond.

Chapter 6 by Altug *et al.* is devoted to integrated plasmonic systems for ultrasensitive infrared nanospectroscopy and biodetection. Infrared spectroscopy has exceptional identification capabilities via vibrational fingerprints of the bio- and chemical molecules in the mid-IR. Altug *et al.* show that diffractively coupled plasmonic nanoantennas provide strong plasmonic field enhancement leading to surface-enhanced spectroscopy with zepto-mole level sensitivities. A low-cost fabrication technique for high-throughput fabrication of infrared plasmonic antenna arrays is also introduced. Finally, Altug *et al.* describe a novel biosensing system merging nanoplasmonics and nanofluidics to overcome fundamental mass transport limitations imposed by conventional microfluidic approaches.

We already mentioned surface plasmon polaritons (SPPs) in connection with Chapter 4. Chapter 7 by Leosson and others deals with fabrication and optical characterization of long-range SPP devices. The design involves thin metal stripes or nanowires in a polymer matrix, and the devices include thermo-optically controlled interferometers, compact extinction modulators with low polarization-dependent loss and optically pumped plasmonic amplifiers.

Chapter 8 by Lin *et al.* is, like Chapter 6, devoted to biosensing, more specifically to highly sensitive label-free sensing. The high sensitivity is afforded by 3D plasmonic crystals, and the team has been able to distinguish surface sensitivity from bulk sensitivity. Plasmonic crystal structures that support both surface plasmon polaritons and localized surface plasmons can be used to provide complementary information about bulk and surface properties at the same time, which could make label-free, multi-modal readout systems possible for high throughput biodiagnostics.

Over the last decade, the curious and peculiar phenomenon of negative refraction (already mentioned in connection with Chapter 2) has generated unprecedented interest and excitement in applied physics, optics and engineering. In Chapter 9, Xiao & Shalaev review and report significant recent advancements that push the operational wavelengths of negative-index metamaterials into the optical range, allow tunability, and alleviate losses by introducing active media in the design. This research should facilitate practical applications of negative-index materials.

Future computing systems will increasingly include optical interconnections that can be expected to rely on the plasmonic confinement and guidance of light. In Chapter 10, Feng & Fainman deal with the design and fabrication of plasmonic chips capable of manipulating light from nano- to microscale. The authors use standard micro- and nanofabrication

tools to create complex geometries of composite metal-dielectric plasmonic structures and to realize the integration of plasmonics with the CMOS-compatible Silicon-On-Insulator (SOI) platform.

Integration of nanophotonic and electronics components on the same chip is also a major goal pursued by Holmgaard & Bozhevolnyi (Chapter 11). They consider modeling, design, and characterization of dielectric-loaded plasmonic waveguide components at telecommunication wavelengths. Holmgaard & Bozhevolnyi show that such waveguides may allow propagation of a single surface plasmon polariton mode with sub-wavelength confinement and low propagation loss. Coupling between two parallel waveguides, as well as modulation and wavelength-separation of signals are investigated.

Chapter 12 deals with an entirely different aspect of plasmonics: strong field enhancement and confinement may lead to strong electrodynamic forces acting on nanoparticles. Crozier *et al.* show in this chapter how such forces can be used to propel and manipulate nanoparticles on surfaces. The focus is on the applications to surface enhanced Raman spectroscopy.

The final part of this volume is devoted to methods of computer simulation in plasmonics, metamaterials, and in related problems of photonics. The numerical method described by Eremina *et al.* in Chapter 13 involves a superposition of fields due to discrete sources. Two illustrative application examples of light scattering by nano-objects are considered.

Finally, in Chapter 14 Hafner *et al.* review key computational techniques for electromagnetic problems, with a focus on plasmonics. Particular attention is paid to various symmetries that may be exploited in practical simulations. Several complicated problems are solved using the finite element method (FEM) as well as the multiple multipole program (MMP) developed by the authors.

We do hope that this book will prove useful to researchers and developers in industry and academia, as well as to graduate and advanced undergraduate students specializing in photonics, optics and related areas of applied physics. Thoughtful comments and critique from these readers will be greatly appreciated.

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Most of all, we are grateful to all the authors for their timely and inspirational research that is advancing the fields of plasmonics and metamaterials.

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