Preface

Electromagnetic simulation is an established tool across many scientific and technological disciplines, buoyed by the development of high-power computer platforms. This holds true in the field of photonics, where recent years have seen major advances in theoretical, numerical, and computational techniques. These advances have been driven by the emergence of sophisticated integrated photonic systems, on the one hand, and sub-wavelength device structuring to enhance light–matter interactions on the other, all aimed towards the generation, transmission, localisation, manipulation, detection, and use of light.

The annual Optical Wave and Waveguide Theory and Numerical Modelling (OWTNM) Workshop has, since 1992, provided a forum for lively debates, intended to bring forward new ideas in the field of theoretical and computational photonics. This book brings together some of the cutting-edge work on computational methods in photonics presented at recent OWTNM meetings and addresses the physical understanding, mathematical description, and the computational treatment of guided optical waves, and related optical effects in micro- and nanostructures, including multi-physics effects.

The first section of this book describes some numerical methodologies for computational photonics. Chapter 1 discusses the development of a finite-element-based time-domain approach; the use of a perforated mesh increases numerical efficiency, which is compared against the well-established finite-difference time-domain (FDTD) method. Mid-infrared light sources have been intensively investigated in recent years since they can enable many applications, for example in remote sensing and medicine. Chapter 2 describes numerical investigations of some of the possibilities for obtaining mid-infrared laser action in rare earth-doped chalcogenide glass fibres, starting from some basic laser physics and progressing through the development of powerful numerical fibre laser models and the experimental techniques used to extract the model parameters. Chapter 3 then describes a hybrid analytical–numerical approach to coupled mode theory which leads to quantitative, computationally efficient and readily interpretable models for photonic integrated circuits. The application of these models is illustrated for components such as single and parallel waveguides, waveguide crossings, micro-resonators with circular elements, and photonic molecules excited by straight waveguides. Chapter 4 provides a rigorous analysis of acousto-optic interactions in optical waveguides using a vector finite-element approach, in particular of nonlinear Stimulated Brillouin Scattering (SBS). The numerical approach presented can be used for the study of a wide range of practical optical waveguides with either co- or anti-guiding acoustic modes

The twenty-first century has seen a remarkable growth within the field of photonics in the understanding, realisation, and use of novel materials, such as photonic crystals (PCs) and metamaterials (MMs), the electromagnetic properties of which are engineered to obtain properties that are unattainable in naturally existing materials. This is often achieved by using structuring on a sub-wavelength scale. Chapter 5 provides a theoretical examination of photonic crystals and metamaterials coupled with gain and explains how the incorporation of a gain material in such systems can be treated numerically with the FDTD technique. The following two chapters (Chaps. 6 and 7) describe the theory and numerical modelling of Parity-Time (PT)-symmetric structures in photonics, starting with the study of a PT-symmetric Bragg grating structure in which unique scattering phenomena have been discovered. A dispersive and saturable gain model, implemented within the time-domain Transmission-Line Modelling (TLM) method, is then introduced which enables the impact of realistic (non-ideal) material properties on the behaviour of these devices to be investigated. A further extended TLM model, including material nonlinearity, is then used to study the behaviour of nonlinear PT Bragg gratings as an innovative all-optical memory device. The second of the two chapters describing PT-symmetric structures in photonics investigates the spectral behaviour, and real-time operation, of PT-symmetric coupled resonators. A Boundary Integral Equation (BIE) model is developed to study these structures in the frequency domain. Then, the TLM method is used to study the impact of realistic gain/loss material properties on the operation of PT-symmetric coupled resonators.

Nonlinear optics is another topic that has triggered the discovery of important phenomena and developed deep understandings of fundamental optical effects, and which has enabled a large variety of applications. As described in Chap. 8, nonlinear optical interactions can be significantly enhanced using the local electromagnetic field enhancement achievable with plasmonic effects and metallic nanostructures. The chapter reviews coherent nonlinear plasmonic effects due to intrinsic electronic metallic nonlinearities, which are rigorously described by a hydrodynamic model, focusing on harmonic generation and related phenomena. An illustrative analytical solution of the hydrodynamic equations reveals the important role of resonance symmetries and establishes a criterion for the generation of nanoscale localised second harmonic generation (the analogue of macroscale phase-matching at the nanoscale). A further example predicts the formation of cascaded surface plasmon solitons. Then, a comprehensive non-perturbative numerical implementation of the hydrodynamic model is presented that allows the investigation of nonlinear optical interactions in metallic nanostructures without any approximations. Nonlinear harmonic and broadband white light supercontinuum generation in metallic nanorods and metallic nanospirals is considered; this is significantly enhanced by the interplay between the topology of the nanostructure and the non-local response of the metal. Chapter 9 continues the nonlinear optics theme and applies a Discontinuous Galerkin Time-Domain (DGTD) method to the numerical simulation of the second harmonic generation from various metallic nanostructures. A Maxwell–Vlasov hydrodynamic model is used to describe the nonlinear effects in the motion of the excited free electrons in a metal. Results are compared with experimental measurements for split-ring resonators and plasmonic gap antennas. Chapter 10 extends the nanophotonic theme to the study of high refractive index dielectric nanoparticles and presents several basic approaches for the numerical study of their collective optical response. It is shown that these dielectric nanoparticles offer new phenomena for the manipulation of directional light scattering and nano-antenna applications, and advantages over their plasmonic counterparts in terms of reduced losses and the resonant enhancement of both electric and magnetic fields which can bring novel functionalities to simple nanoparticle geometries.

The following two chapters give further detail on the field of computational plasmonics. The first of these, Chap. 11, covers essential theoretical background material and provides some simple models of light–matter interactions. The focus is on the physical properties of bulk plasmons, surface plasmon polaritons, and localised plasmons. Analytical and numerical examples are given, and plasmon-enhanced solar cells and other exciting new research directions are introduced. These applications provide motivation for the more detailed numerical studies described in Chap. 12, which include modern *ab initio* methods, and the standard frequency-domain and time-domain methods of computational electromagnetics. Some applications in the fields of photovoltaics and plasmonic–photonic crystals are studied; the chapter closes with a discussion of some open problems that show that there is still room for new and exciting methods and further discoveries in the future. The final chapter of the book, Chap. 13, investigates the engineering of hybrid photonic–plasmonic devices for enhanced light–matter interactions. The focus is on the design and characteristics of a hybrid photonic–plasmonic nanoresonator using 3D finite-difference time-domain simulations. The structure is uniquely capable of the localisation of high-intensity light in a sub-wavelength hot spot, whilst maintaining a high-quality factor. This makes it suitable for applications such as near-field optical trapping and manipulation, sensing and spectroscopy. Clear pathways to the practical realisation and optimisation of the device are also established. The device is designed for operation in the telecommunication wavelength range, making it compatible with the existing telecommunication technology and photonic crystal fabrication processes.

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