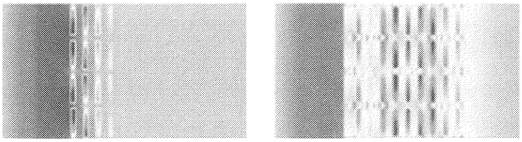
Electrodynamics of Metamaterials



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To Dima and Margarita

Preface

The current electronic techniques, as many believe, are running out of steam due to issues with RC-delay times, meaning that fundamentally new approaches are needed to increase data processing operating speeds to THz and higher frequencies. There is an undeniable and ever-increasing need for faster information processing and transport. The photon is the ultimate unit of information because it packages data in a signal of zero mass and has unmatched speed. The power of light is driving the photonic revolution, and information technologies, which were formerly entirely electronic, are increasingly enlisting light to communicate and provide intelligent control. Today we are at a crossroads in this technology. Recent advances in this emerging area now enable us to mount a systematic approach towards the goal of full system-level integration.

The mission that researchers are currently trying to accomplish is to fully integrate photonics with nanotechnology and to develop novel photonic devices for manipulating light on the nanoscale, including molecule sensing, biomedical imaging, and processing information with unparalleled operating speeds. To enable the mission, one can use the unique property of metal nanostructures to "focus" light on the nanoscale. Metal nanostructures supporting collective electron oscillations — plasmons — are referred to as plasmonic nanostructures, which act as optical nanoantennas by concentrating large electromagnetic energy on the nanoscale.

There is ample evidence that photonic devices can be reduced to the nanoscale using optical phenomena in the near-field, but there is also a scale mismatch between light at the microscale and devices and processes at the nanoscale that must be addressed first. Plasmonic nanostructures can serve as optical couplers across the nano–micro interface. They also have the unique ability to enhance local electromagnetic fields for a number of ultra-compact, sub-wavelength photonic devices. Nanophotonics is not only about very small photonic circuits and chips, but also about new ways of sculpting the flow of light with nanostructures and nanoparticles exhibiting fascinating optical properties never seen in the macro-world.

Plasmonic nanostructures utilizing surface plasmons (SPs) have been extensively investigated during the last decade and show a plethora of amazing effects and fascinating phenomena, such as extraordinary light transmission, giant field enhancement, SP nano-waveguides, and recently emerged metamaterials that are often based on plasmonic nanostructures. Metamaterials are expected to open a new gateway to unprecedented electromagnetic properties and functionality unattainable from naturally occurring materials. The structural units of metamaterials can be tailored in shape and size, their composition and morphology can be artificially tuned, and inclusions can be designed and placed at desired locations to achieve new functionality.

Light is in a sense "one-handed" when interacting with atoms of conventional materials. This is because out of the two field components of light, electric and magnetic, only the electric "hand" efficiently probes the atoms of a material, whereas the magnetic component remains relatively unused because the interaction of atoms with the magnetic field component of light is normally weak. Metamaterials, i.e., artificial materials with rationally designed properties, can enable the coupling of both the field components of light to meta-atoms, enabling entirely new optical properties and exciting applications with such "two-handed" light. Among the fascinating properties is a negative refractive index. The refractive index is one of the most fundamental characteristics of light propagation in materials. Metamaterials with negative refraction may lead to the development of a superlens capable of imaging objects and their fine structures that are much smaller than the wavelength of light. Other exciting applications of metamaterials include novel antennae with superior properties, optical nano-lithography and nano-circuits, and "meta-coatings" that can make objects invisible.

The word "meta" means "beyond" in Greek, and in this sense, the name "metamaterials" refers to "beyond conventional materials." Metamaterials are typically man-made and have properties not available in nature. What is so magical about this simple merging of "meta" and "materials" that has attracted so much attention from researchers and has resulted in exponential growth in the number of publications in this area?

The notion of metamaterials, which includes a wide range of engineered materials with pre-designed properties, has been used, for example, in the microwave community for some time. The idea of metamaterials has been quickly adopted in optics research, thanks to rapidly-developing nanofabrication and sub-wavelength imaging techniques. One of the most exciting opportunities for metamaterials is the development of "*left handed metamaterials*" (LHMs) with negative refractive index. These LHMs bring the concept of refractive index into a new domain of exploration and thus promise to create entirely new prospects for manipulating light, with revolutionary impacts on present-day optical technologies.

It is a rather unique opportunity for researchers to have a chance to reconsider and possibly even revise the interpretation of very basic laws. The notion of a negative refractive index is one such case. This is because the index of refraction enters into the basic formulae for optics. As a result, bringing the refractive index into a new domain of negative values has truly excited the imagination of researchers worldwide.

The refractive index gives the factor by which the phase velocity of light is decreased in a material as compared to vacuum. LHMs have a negative refractive index, so the phase velocity is directed against the flow of energy in a LHM . This is highly unusual from the standpoint of "conventional" optics. Also, at an interface between a positive and a negative index material, the refracted light is bent in the "wrong" way with respect to the normal. Furthermore, the wave-vector and vectors of the electric and magnetic fields form a left-handed system.

This book reviews the fundamentals of plasmonic structures and metamaterials based on such structures, along with their exciting applications for guiding and controlling light. Both random and geometrically ordered metamaterials are considered. Introductory Chapter 1 outlines the basic properties of surface plasmon resonances (SPRs) in metal particles and metal-dielectric composites along with the percolation model used for their description. Chapter 2 is focused on metal rods and their applications for LHMs . Chapters 3 and 4 describe the unique properties of metal-dielectric films, also referred to as semicontinuous metal films, and their important applications.

We also present there the general theory of the surface enhancement of the Raman signal and the theory of nonlinear optical phenomena in metal-dielectric metamaterials. At the end of Chapter 4 we discuss the analytical theory of the extraordinary optical transmittance (linear and nonlinear). Finally, Chapter 5 deals with electromagnetic properties of geometrically ordered metal-dielectric crystals.

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