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Electrodynamics of Metamaterials

超颖材料电动力学

（影印版）

〔俄〕萨雷切夫（A. K. Sarychev）
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序　言

物理学是研究物质、能量以及它们之间相互作用的科学。她不仅是化学、生命、材料、信息、能源和环境等相关学科的基础，同时还是许多新兴学科和交叉学科的前沿。在科技发展日新月异和国际竞争日趋激烈的今天，物理学不仅囿于基础科学和技术应用研究的范畴，而且在社会发展与人类进步的历史进程中发挥着越来越关键的作用。

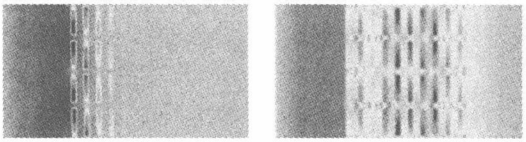
我们欣喜地看到，改革开放三十多年来，随着中国政治、经济、教育、文化等领域各项事业的持续稳定发展，我国物理学取得了跨越式的进步，做出了很多为世界瞩目的研究成果。今日的中国物理正在经历一个历史上少有的黄金时代。

在我国物理学科快速发展的背景下，近年来物理学相关书籍也呈现百花齐放的良好态势，在知识传承、学术交流、人才培养等方面发挥着无可替代的作用。从另一方面看，尽管国内各出版社相继推出了一些质量很高的物理教材和图书，但系统总结物理学各门类知识和发展，深入浅出地介绍其与现代科学技术之间的渊源，并针对不同层次的读者提供有价值的教材和研究参考，仍是我国科学传播与出版界面临的一个极富挑战性的课题。

为有力推动我国物理学研究、加快相关学科的建设与发展，特别是展现近年来中国物理学者的研究水平和成果，北京大学出版社在国家出版基金的支持下推出了《中外物理学精品书系》，试图对以上难题进行大胆的尝试和探索。该书系编委会集结了数十位来自内地和香港顶尖高校及科研院所的知名专家学者。他们都是目前该领域十分活跃的专家，确保了整套丛书的权威性和前瞻性。

这套书系内容丰富，涵盖面广，可读性强，其中既有对我国传统物理学发展的梳理和总结，也有对正在蓬勃发展的物理学前沿的全面展示；既引进和介绍了世界物理学研究的发展动态，也面向国际主流领域传播中国物理的优秀专著。可以说，《中外物理学精品书系》力图完整呈现近现代世界和中国物理

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 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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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

科学发展的全貌，是一部目前国内为数不多的兼具学术价值和阅读乐趣的经典物理丛书。

《中外物理学精品书系》另一个突出特点是，在把西方物理的精华要义"请进来"的同时，也将我国近现代物理的优秀成果"送出去"。物理学科在世界范围内的重要性不言而喻，引进和翻译世界物理的经典著作和前沿动态，可以满足当前国内物理教学和科研工作的迫切需求。另一方面，改革开放几十年来，我国的物理学研究取得了长足发展，一大批具有较高学术价值的著作相继问世。这套丛书首次将一些中国物理学者的优秀论著以英文版的形式直接推向国际相关研究的主流领域，使世界对中国物理学的过去和现状有更多的深入了解，不仅充分展示出中国物理学研究和积累的"硬实力"，也向世界主动传播我国科技文化领域不断创新的"软实力"，对全面提升中国科学、教育和文化领域的国际形象起到重要的促进作用。

值得一提的是，《中外物理学精品书系》还对中国近现代物理学科的经典著作进行了全面收录。20 世纪以来，中国物理界诞生了很多经典作品，但当时大都分散出版，如今很多代表性的作品已经淹没在浩瀚的图书海洋中，读者们对这些论著也都是"只闻其声，未见其真"。该书系的编者们在这方面下了很大工夫，对中国物理学科不同时期、不同分支的经典著作进行了系统的整理和收录。这项工作具有非常重要的学术意义和社会价值，不仅可以很好地保护和传承我国物理学的经典文献，充分发挥其应有的传世育人的作用，更能使广大物理学人和青年学子切身体会我国物理学研究的发展脉络和优良传统，真正领悟到老一辈科学家严谨求实、追求卓越、博大精深的治学之美。

温家宝总理在 2006 年中国科学技术大会上指出，"加强基础研究是提升国家创新能力、积累智力资本的重要途径，是我国跻身世界科技强国的必要条件"。中国的发展在于创新，而基础研究正是一切创新的根本和源泉。我相信，这套《中外物理学精品书系》的出版，不仅可以使所有热爱和研究物理学的人们从中获取思维的启迪、智力的挑战和阅读的乐趣，也将进一步推动其他相关基础科学更好更快地发展，为我国今后的科技创新和社会进步做出应有的贡献。

《中外物理学精品书系》编委会 主任

中国科学院院士，北京大学教授

王恩哥

2010 年 5 月于燕园

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Contents

Chapter 1

Introduction

Current developments in optical technologies are being directed toward nanoscale devices with subwavelength dimensions, in which photons are manipulated using nano-scale optical phenomena. Although light is clearly the fastest means to send information to and from the nanoscale, there is a fundamental incompatibility between light at the microscale and devices and processes at the nanoscale. For most materials, light–matter interactions decrease as $(a/\lambda)^2$, where a is the structure size and λ is the wavelength. However, metals, which support surface plasmon modes, can concentrate electromagnetic (em) fields to a small fraction of a wavelength while enhancing local field strengths by several orders of magnitude. For this reason, plasmonic nanostructures can serve as optical couplers across the nano–micro interface: metal–dielectric and metal–semiconductor nanostructures can act as optical nanoantennas and enhance efficiency such that the optical cross-sections increase in magnitude from $\sim a^2$ to $\sim \lambda^2$.

As electronics shrinks to the nanoscale, photonics must follow to maintain the speed and parallelism necessary for nanoelectronics to achieve their full potential. Nanophotonics, united with nanoelectronics, is destined to be a vital technology in the global high-tech economy. Nanophotonics with plasmonic structures promises to create entirely new prospects for manipulating light, some of which may have revolutionary impact on present-day optical technologies. However, our understanding of the interplay between light and plasmonic nanostructures is still incomplete, and techniques to synthesize nanophotonic devices and circuits based on plasmonic materials are still relatively primitive. Full integration of light with nanoscale plasmonic devices and processes will require fundamental advances at this research interface.

In this book, we will describe the electrodynamics of metal-dielectric metamaterials, which form a large class of nanostructured composite materials. Nanostructured metal-dielectric composites exhibit fascinating optical properties at visible and near-infrared frequencies due to excitation of surface plasmon modes. The technology drift of adopting these properties for applications in photonics and chemical sensing have led to exponentially growing activity in the actual design of plasmonic materials with subwavelength dimensions. Strongly amplified electromagnetic fields can be generated both in a broad spectral range for disordered metal–dielectric composites and at selected frequencies for periodically ordered metal nanostructures. Periodicity of metamaterial geometry plays a crucial role in tuning the optical response: Such phenomena have been observed in numerous experimental and theoretical studies of enhanced plasmon effects in left-handed materials (also referred to as negative-index materials, NIMs), in surface-enhanced Raman scattering, extraordinary optical transmission and photonic band-gap structures, both in the visible and near-infrared wavelengths. Microstrucured analogues of nano-metamaterials also exhibit very interesting and unusual properties, particularly in the microwave band range, where such phenomena as artificial magnetism, negative refractive index, and plasmonic bandgap have been also observed.

1.1 Surface Plasmon Resonance

To give a reader a quick insight to the wonderland of metamaterials let us consider a relatively simple plasmonic system, such as two-dimensional (2D) arrays of metal nanoparticles embedded in a dielectric medium. We then provide numerical calculations and a simple analytical theory for electromagnetic (EM) field enhancements in such systems. The obtained numerical and analytical results are in good agreement, yielding values for the enhancement of surface-enhanced Raman scattering (SERS) signal as large as 10^{11} for arrays of silver or gold nano-disks. SERS enhancement factor is described by $G_R = \left\langle \left| E(\mathbf{r}) / E_0 \right|^4 \right\rangle$ equation, where $E(\mathbf{r})$ is the local electric field in Cartesian coordinates $\mathbf{r} = (x, y, z)$, E_0 is the amplitude of incident field. Such field enhancements for the nanostructured arrays are strongly dependent on the ratio of composing particle diameter a and inter-particle spacing δ, which determines both the intensity of local fields and the characteristic cross-section for sampling chemical and biomolecular analytes. Our numerical simulations further illustrate how the interplay between field enhancement and particle spacing can affect the design of array-based SERS sensors for tracing chemical analytes.