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Physics of Negative Refraction and Negative Index Materials: Optical and Electronic Aspects and Diversified Approaches

负折射和负折射率材料物理
——光电性质和不同实现方法

（影印版）

〔美〕克罗恩(C. M. Krowne)
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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

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。

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2010 年 5 月于燕园

C.M. Krowne Y. Zhang (Eds.)

Physics of Negative Refraction and Negative Index Materials

Optical and Electronic Aspects and Diversified Approaches

With 229 Figures

Springer

Preface

There are many potentially interesting phenomena that can be obtained with wave refraction in the "wrong" direction, what is commonly now referred to as negative refraction. All sorts of physically new operations and devices come to mind, such as new beam controlling components, reflectionless interfaces, flat lenses, higher quality lens or "super lenses," reversal of lenses action, new imaging components, redistribution of energy density in guided wave components, to name only a few of the possibilities. Negative index materials are generally, but not always associated with negative refracting materials, and have the added property of having the projection of the power flow or Poynting vector opposite to that of the propagation vector. This attribute enables the localized wave behavior on a subwavelength scale, not only inside lenses and in the near field outside of them, but also in principle in the far field of them, to have field reconstruction and localized enhancement, something not readily found in ordinary matter, referred to as positive index materials.

Often investigators have had to create, even when using positive index materials, interfaces based upon macroscopic or microscopic layers, or even heterostructure layers of materials, to obtain the field behavior they are seeking. For obtaining negative indices of refraction, microscopic inclusions in a host matrix material have been used anywhere from the photonic crystal regime all the way into the metamaterial regime. These regimes take one from the wavelength size on the order of the separation between inclusions to that where many inclusions are sampled by a wavelength of the electromagnetic field. Generally in photonic crystals and metamaterials, a Brillouin zone in reciprocal space exists due to the regular repetitive pattern of unit cells of inclusions, where each unit cell contains an arrangement of inclusions, in analogy to that seen in natural materials made up of atoms. Only here, the arrangements consist of artificial "atoms" constituting an artificial lattice.

The first two chapters of this book (Chaps. 1 and 2) address the use of uniform media to generate the negative refraction, and examine what happens to optical waves in crystals, electron waves in heterostructures, and guided waves in bicrystals. The first chapter also contrasts the underlying physics in various approaches adopted or proposed for achieving negative refraction and examines the effects of anisotropy, as does the second chapter for negative index materials (left-handed materials). Obtaining left-handed material behavior by utilizing a permeability tensor modification employing magnetic material inclusions is investigated in Chap. 3. Effects of spatial dispersion in the permittivity tensor can be important to understanding excitonic–electromagnetic interactions (exciton–polaritons) and their ability to generate negative indices and negative refraction. This and other polariton issues are discussed in Chap. 4.

The next group of chapters, Chaps. 5 and 6, in the book looks at negative refraction in photonic crystals. This includes studying the effects in the microwave frequency regime on such lattices constructed as flat lenses or prisms, in two dimensional arrangements of inclusions, which may be of dielectric or metallic nature, immersed in a dielectric host medium, which could be air or vacuum. Even slight perturbations or crystalline disorder effects can be studied, as is done in Chap. 7 on quasi-crystals. Analogs to photonic fields do exist in mechanical systems, and Chap. 8 examines this area for acoustic fields which in the macroscopic sense are phonon fields on the large scale.

Finally, the last group of chapters investigates split ring resonator and wire unit cells to make metamaterials for creation of negative index materials. Chapter 9 does this as well as treating some of the range between metamaterials and photonic crystals by modeling and measuring split ring resonators and metallic disks. Chapter 10 looks at the effects of the split ring resonator and wire unit cells on left-handed guided wave propagation, finding very low loss frequency bands. Designing and fabricating split ring resonator and wire unit cells for lens applications is the topic of Chap. 11. This chapter has extensive modeling studies of various configurations of the elements and arrangements of their rectangular symmetry system lattice. The last chapter in this group and of the book, Chap. 12, delves into the area of nonlinear effects, expected with enhanced field densities in specific areas of the inclusions. For example, field densities may be orders of magnitude higher in the vicinity of the gaps in the split rings, than elsewhere, and it is here that a material could be pushed into its nonlinear regime.

The chapters here all report on recent research within the last few years, and it is expected that the many interesting fundamental scientific discoveries that have occurred and the applications which have resulted from them on negative index of refraction and negative index materials, will have a profound effect on the technology of the future. The contributors to this book prepared their chapters coming from very diversified backgrounds, and as such, provide the reader with unique perspectives toward the subject matter. Although the chapters are presented in the context of negative refraction and related phenomena, the contributions should be found relevant to broad areas in fundamental physics and material science beyond the original context of the research. We expect this area to continue to yield new discoveries, applications, and insertion into devices and components as time progresses. Evidence of this is already available in recent developments for repetitive metal patterns on surfaces of thin films and plasmonic based metallic-dielectric hybrid structures showing focusing (some with magnification) or even negative refraction and negative refractive index into the infrared and optical regimes. These polariton based phenomena do not necessarily require double negativity, which represents another alternative to achieve sub-wavelength imaging in addition to photonic crystals and metamaterial split ring resonator type configurations.

Washington and Golden, June 2007

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