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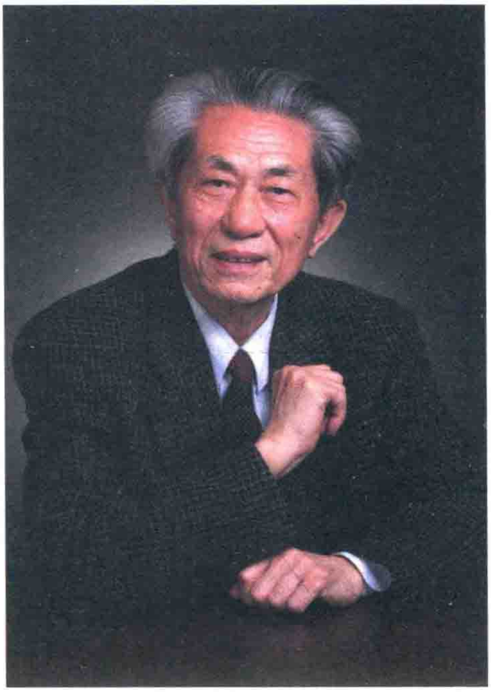
——谨以此书献给我们尊敬的老师闵乃本先生

庆祝闵先生八十华诞！



闵乃本，男，汉族，1935 年 8 月生，江苏如皋人，日本东北大学理学博士，南京大学教授，中国科学院院士，第三世界科学院院士。曾任南京大学固体微结构国家重点实验室主任、学术委员会主任，江苏省自然科学基金会主任，教育部科学技术委员会副主任，教育部“材料科学与工程教学指导委员会”主任，中国晶体学会理事长，全国政协第九、十、十一届常委，江苏省政协第八、九届副主席，九三学社第十、十一届中央副主席，江苏省九三学社第四、五届主委。于 1998 年获“何梁何利科学与技术进步奖”，1999 年获第三世界科学院基础科学奖——物理奖，2000 年获美国科学信息研究所(ISI)经典引文奖，2006 年获国家自然科学一等奖，1982 年、2005 年、2007 年，三次获得国家自然科学二等奖。1995 年获“全国优秀教师”称号及奖章，2001 年获“全国模范教师”称号及奖章，2009 年被评为“新中国成立以来江苏省十大杰出科技人物”。

Foreword

The properties of bulk materials are understood and controlled by the chemical elements and bonds in the material. The development in ab initio solid state science allows the study of the electronic, optical, thermal and mechanical properties starting from the atom-or molecule-level, and has helped expand the range of materials accessible to us.

In last few decades, advanced nanofabrication and computational techniques has offered a new route to design material properties at will. Through controlled interactions with electromagnetic (EM) waves, it became possible to produce fascinating physical properties unavailable in naturally occurring or chemically synthesized materials. Photonic crystals and metamaterials are good examples of employing structural design to manipulate electromagnetic wave propagation in an unprecedented way.

Over last thirty years, Professor Naiben Min of Nanjing University, has developed the novel concept of "dielectric superlattices". Analogous to the superlattice for electrons in semiconductors, (for instance, an array of coupled quantum wells that have controllable electronic characteristics), dielectric superlattices are composited of a periodic of dielectric media processing unprecedented optical properties. For example, electro-optic and acoustic-optic modulation of optical superlattices can be used for compact solid-state pulsed lasers. Since optical superlattices have the advantage of high nonlinear gain and phase shift over broad wavelengths, they can act as mode locking devices, generating high repetition rate semiconductor laser pulses. In quantum optics, optical superlattices can exhibit higher photon single photon yield, and entangled photon pair production compared with conventional nonlinear crystals. Min's scientific contributions have greatly influenced the science of functional optical materials, and has shaped modern Optical Physics in China.

This book is based on representative publications on dielectric superlattices by Prof. Min's research team in Nanjing University. His original work has had a profound impact in science and technology. The team was honored by the First-Class State Natural Science Award (the highest award in scientific research in China) in 2006, for their significant achievements on the fundamental and applied nonlinear optics, laser physics, and technology. Prof. Min has extended the optical superlattice concept from periodic structures to quasi-periodical, multi-periodic, and even completely random structures, in 1D, 2D, and 3D.

The phase matching techniques developed by Min were extended from the original single quasi-phase matching; to multiple quasi-phase matching; local quasi-phase matching; and, eventually the nonlinear "Huygens principle", a generic rule for phase matching in complex nonlinear optical nanostructures. In 30 years of effort, three kinds of dielectric superlattices have been systematically developed for different functionalities, including, optical superlattices, acoustic superlattices, and ionic-type phononic crystals. It is noteworthy that soon after I proposed the idea of photonic crystals in 1987, Professor Min's team had proposed and demonstrated phononic crystals for acoustic waves. The acoustic forbidden band is similar to photonic bands. In addition, ionic-type phononic crystals with superlattices of piezoelectric materials can efficiently couple acoustic waves with electromagnetic wave. Such dielectric superlattices have now been used in microwave electromagnetic devices and electronic devices.

As we enter the new age of "designer's materials", this book provides a reference source for scientists or engineers practicing in the field of optical materials and device applications. I believe the readers in both academic and industrial sectors will find this book helpful and beneficial to their understanding of the exciting research in material science and photonics.

Eli Yablonovitch

Berkeley, August 2016

序

介电体超晶格是一种在光电子学、声电子学、量子信息学领域有重大应用前景的新型功能材料，是我们南京大学介电体超晶格研究团队经过近30年的努力开拓出来的研究领域。我们团队在围绕介电体超晶格材料体系开展的基础研究和应用探索过程中，还为畴工程学的建立做出了奠基性的贡献。本书从我们团队发表的数百篇论文中精选出90篇代表论文，根据研究内容整理、编辑成九个章节。第一章是绪论，第二至第八章分别介绍了介电体超晶格研究的七个分支领域。为了方便读者，编者在每章前都增加了中英文序言作为导读。第九章为“总结与展望”。全书的编辑力图能清晰地描绘出该领域的发展轨迹、学术系统和科学内涵，期待本书出版后能成为为在该领域和相关领域从事基础研究和应用研究科技人员提供借鉴的有益读物。

光波或超声波在介电晶体中传播，其波长甚大于晶格常数，或者说，其波矢甚小于晶格倒格矢，光波或声波/超声波在介电晶体中的行为完全等价于在连续介质中的行为，晶格的周期性对其没有任何影响。如果在介电晶体中引入可与光波或声波/超声波波长比拟的超周期－超晶格，亦即引入可与光波或声波/超声波的波矢比拟的倒格矢，则情况迥然不同。铁电晶体是一种介电晶体。对铁电晶体的铁电畴进行人为的调制，调制周期与光波或声波/超声波波长可比拟，形成超周期，我们称之为介电体超晶格。在介电体超晶格中，除了非线性光学系数外，压电系数和电光系数等也相应地被调制。依据研究对象的不同，介电体超晶格也被称为光学超晶格、声学超晶格和离子型声子晶体等。

我们对介电体超晶格的研究按两条思路展开。其一是由于超晶格的倒格矢可以参与光波（光子）、声波（声子）的波矢量守恒（动量守恒），在无法满足动量守恒的所有物理过程中，如存在折射率色散的光参量过程中，倒格矢的引入必然产生新颖的物理效应。其二是光波（光子）、声波（声子）在超晶格的周期结构中传播，可类比于电子在晶格周期势场中运动，这种周期结构必然导致不同类型能带，于是可通过能带的设计与裁剪，实现对作为信息载体的光波或光子、声波或声子的调控。

介电体超晶格研究可追溯到1986年，经过19年的努力，该项研究于2006年获国家自然科学一等奖。获奖后我们曾写过一篇总结性论文：“介电体超晶格的研究”（物理 37 (2008) 1-10）。在这之前，我也曾应英文刊物“先进材料”之约写过一篇综述文章，“Superlattices and Microstructures of Dielectric Materials”（Adv. Mater. 11 (1999) 1079-1090）。这两篇文章分别用中、英文发表，虽然年代不同，都在一定程度上系统地介绍了介电体超晶格的研究内容与学术体系。本书将这两篇论文选作第一章，代“绪论”。

介电晶体中折射率色散造成了发生在其中的光参量过程的位相失配，即动量守恒

(波矢量守恒)不能满足。而介电体超晶格中超晶格结构所提供的倒格矢可以补偿折射率色散所引起的位相失配,使参量光通过相长干涉(相干叠加)得到有效增强,这被称之为准相位匹配,或准波矢量守恒。一维周期超晶格具有一组倒格矢,其初基倒格矢可以满足一个单一光参量过程的准位相匹配。一维准周期超晶格具有多组倒格矢,可高效地同时实现多个相互独立的或相互耦合的光参量过程的准位相匹配,于是多个参量光能同时有效输出,这被称之为多重准位相匹配。我们发展了多重准位相匹配理论及其应用,拓展了非线性光学的研究领域。我们还研究了二维光学超晶格,实现了共线、非共线准位相匹配,获得了弹性散射、非弹性散射(拉曼散射)以及Čerenkoverenkov 辐射的非线性增强。这部分工作放在第二章介绍,并标以题目"准相位匹配概念的拓展和非线性光学新效应"。

在二维正方对称性介电常数(或折射率)周期调制的超晶格中,利用两组倒格矢,能激发四个 Floquet-Bloch 波,据此我们发展了四(多)波动力学理论,并在此基础上进一步考虑介电常数的 Kerr 非线性,发现了新的光学双稳机制-折射率调制机制,让多束光同时进入双稳态。这部分工作以及后续发展的用折射率调制的光子晶体工作放在第三章"克尔非线性光学超晶格与光子晶体"中介绍。

超声波可以在正负铁电畴交替排列的声学超晶格中被激发,由于相邻电畴压电常数符号相反,畴界处可看为 δ 声源。声学超晶格中适当选取相邻 δ 声源的间距即电畴单元的宽度,可使所有 δ 声源发出的超声波相长干涉。用声学超晶格研制成的声学器件不仅输出强度高、插入损耗低,还填补了超声工程中体波声学器件从几百兆周到几千兆周的空白频段。这部分工作在第四章"声学超晶格与声子晶体"中介绍。

对于像铌酸锂、钽酸锂等仅具有 180 度畴界的铁电晶体,如果以一对自发极化相反的铁电畴作为超晶格的基本构造单元,可以造成在两种畴的构型:畴界平行于自发极化矢量,畴界上不存在束缚电荷;畴界垂直于自发极化矢量,则畴界上存在等效束缚电荷,且相邻畴界的等效束缚电荷符号相反。对于第二种情况,形式上可以将超晶格看为一维正、负离子链,电磁波通过超晶格必然引起畴界(束缚电荷)振动。这就是说,电磁波能激发超晶格集体振动,畴界(束缚电荷)的振动将激发电磁波,于是超晶格振动和电磁波的耦合导致了极化激元的产生。这种情况类似于 1951 年黄昆提出的离子晶体中电磁波与晶格振动耦合所激发的极化激元。我们将这类超晶格称之为离子型声子晶体。不过在离子晶体中的极化激元波长是在红外波段,而这里发生在微波波段。研究表明,超晶格中的光、声耦合实际上源于压电效应。即使对于畴界处不存在束缚电荷的超晶格,电磁波在其中传播,亦可能存在纵向超晶格声子与光子耦合形成的声子极化激元,这就扩展了传统的极化激元的概念。而且,由于我们可以通过对压电或压磁超晶格的结构进行人工设计,使得超晶格在特定波段的介电常数或磁导率为负,这与新近提出的电磁超构材料出现了有趣的一致,因而可看作一种压电或压磁超构材料。这部分工作放在第五章"离子型声子晶体与超构材料"中介绍。

自 1986 年到 2006 年,我们关于超晶格的研究,其基本构造单元的材料仅限于介电体,其研究的思路主要是沿着准波矢量守恒所产生的相干叠加增强效应展开。2006 年前后,我们一方面将超晶格构造单元的材料由介电体扩展到金属和半导体,这就包括了表面等离激元和超构材料(metamaterials),使介电体超晶格内涵有所拓展。另一方面,研究的思路由通过准波矢量守恒产生相干叠加的增强效应,扩展到通过能带结构研究来发现新效应和新应用。如研究了离子型声子晶体中极化激元的能带结构,发现了两种类型的极化激元,即寻常极化激元和异常极化激元。极化激元的带隙禁止寻常极化激元通过,而异常极化激元则可以部分地通过极化激元带隙。又如,对以金属棱柱体和空气棱柱体为构造单元的声学超晶格(声超构材料,声子晶体),发展了声子能带的计算和设计方法,实现了第一和第二能带的负折射效应,提出并验证了"能带交叠"导致的双负折射效应。关于光、声和极化激元能带研究的相关工作分别在第三、四、五章中有所介绍。

当代信息技术中,用于信息处理与运算的信息载体是电子的电荷属性(电荷流量密度,电流密度),用于信息远程传输的是光的波动属性(频率、振幅、位相、偏振态)。信息处理与运算和信息远程传输使用了不同的信息载体,这成了当代信息技术发展的瓶颈。另一方面,集成电路愈做愈小,终究要达到它的物理极限。这表明用电子的电荷属性作为信息载体的时代,即摩尔时代的终结。后摩尔时代信息处理、运算以及传输的信息载体是什么?这是新一轮信息革命所面临的基本问题。电子的属性有电荷、自旋、质量、能量、动量,除了电荷,电子自旋也可作为的信息载体。总的说来,当前人们开始关注粒子(电子、光子),准粒子(声子、极化激元、等离激元……)的量子态。量子信息是以量子态作为信息载体的,量子信息在增大信息传输容量、提高信息处理和运算速度、确保信息安全等方面将突破经典信息的瓶颈。另一方面,纠缠的光子作为信息载体的研究引人注目,这是由于产生纠缠光子的全固态光子芯片技术和远程传输纠缠光子的光纤技术日趋成熟。我们在光的量子信息领域的工作放在第六章"准位相匹配量子光学和光子芯片"中介绍。

基础科学中的物质科学(凝聚态物理学与化学)的研究路径是,化合物的合成和材料的制备→组分、结构的测定→化学性能和物理效应的揭示→其间内在联系和客观规律的阐明。工程学则相反,从应用目的出发,瞄准某种性能和效应,利用组分、结构与性能、效应间的内在联系与规律,设计并制备出具有所需结构和性能的材料或器件。当前,分子设计与组装以及微结构设计与制备就具有工程学研究的特征。畴工程学是微结构设计与制备的分支领域。畴工程学始于铁电畴工程学,稍后扩展到铁磁畴和铁弹畴等。但由于精确控制铁磁畴和铁弹畴组态和稳定性问题一直没有得到解决,迄今,只有铁电畴工程学发展得较为完善。通过铁电畴工程学,可以实现具有设定功能的光电子声电子材料、器件和量子信息器件等。铁电畴工程学也为研制全固态集成的铌酸锂光量子芯片开拓了全新的技术途径。我们在第七章"介电体超晶格与畴工程学"中着重介绍铁电畴工程学。

光学超晶格作为激光频率转换晶体可用于研制新型全固态激光器件。我们将准位相匹配、多重准位相匹配理论与全固态激光技术相结合，拓展了全固态激光器件的研究领域。通过准位相匹配，光学超晶格可以在晶体的整个透明波段实现参量光的高效输出。另外，对于具有 3m 点群的非线性光学晶体如铌酸锂、钽酸锂等，它们最大的非线性光学常数 d_{33} 是不能位相匹配的，但可以实现准相位匹配。与普遍采用的 d_{31} 位相匹配相比，利用晶体 d_{33} 的准位相匹配转换效率能增加数十倍。利用准相位匹配和多重准位相匹配，我们研制出同时输出多个波长的激光器及红绿蓝三基色激光器，研制出高功率、宽调谐光学超晶格中红外激光系统，以及芯片上的多波长激光器阵列。这部分工作将在第八章"光学超晶格的应用研究"中介绍。

第九章则是对全书的简略总结和对介电体超晶格研究的展望。

本书的编辑与出版是祝世宁和朱永元博士策划的，编者中还有王振林、陈延峰、陆延青博士。南京大学出版社的领导给予大力支持，王南雁、吴汀等编辑提出了许多有益的建议与帮助。该书内容是团队成员集体努力的结晶，反映了我学术研究工作的一个重要方面，该书的整理过程也让我有机会回顾了我的科研生涯以及那令人难忘的挑战与机遇，因此我十分感谢促成本书完成的我的学生和同事。我真诚地感谢我的团队成员及合作者，虽然在此序言中我没有一一列出他们的名字，但读者可以通过阅读本书所选文章了解他们对这一学术体系所做的贡献，可以说没有他们出色的研究工作就没有此书。我要借此机会向我的同事和朋友表示敬意，感谢他们长期以来对我们的工作给予的热情鼓励和积极支持。

闵乃本

2015 年 8 月 9 日，于南京碧树园

Preface

Dielectric superlattice has been extensively explored by the research team from Nanjing University for more than 30 years. With a series of breakthrough, it has been developed into a variety of novel functional materials with significantly potential applications in photo-electronics, acousto-electronics and quantum informatics. Meanwhile, in order to designing and preparing the dielectric superlattice, a new research field, domain engineering, has been developed. This book is a collection of original papers from more than hundreds of works that we have published in peer reviewed journals. These papers are classified into the first 8 chapters according to their contents, with a summary and outlook provided in Chapter 9. With this organization, we try to provide a solid and detailed description on the intrinsic characteristics and the scientific framework of dielectric superlattice. We expect this book to be helpful to various audiences, including scientists, engineers and graduates in physics, material science, optics and optical engineering, and other related fields.

Electromagnetic waves and ultrasonic waves can be excited and propagate in a dielectric crystal. The wavelengths of these waves are much larger than the lattice constants of a dielectric crystal, i.e., their wave vectors are much smaller than the reciprocal lattice vectors of a crystal. Thus their propagation in a dielectric crystal is completely equivalent to in a continuous medium, not being affected by the lattice periodicity. Among the dielectric crystals, ferroelectric crystals show excellent nonlinear optical, electro-optical, piezoelectric properties. By artificial modulation of ferroelectric domains, that is, introducing a periodicity comparable to the wavelength of the light or ultrasonic waves into the dielectric crystals to create an artificial reciprocal lattice vector to compensate the dispersion of wave vectors, a dielectric superlattice (sometimes we also call it optical superlattice or acoustic superlattice or ionic-type phononic crystal, depending on which physical process is involved) can be fabricated. Thus the scenario of wave propagation in a dielectric superlattice would be totally different from that in a homogeneous dielectric crystal.

Our study on dielectric superlattices can be divided into two categories: one is known as quasi-phase matching engineering, the other is the artificial energy band gap engineering. Both of them can bring some novel physical effects those are not able to be produced in homogeneous dielectric crystals. We begin Chapter 1 in which two invited review papers are included. The first one with the title of "介电体超晶格的研究" was published in a Chinese journal ("物理"(Physics), 37, 1 - 10 (2008)). The other one titled "Superlattices and Microstructures of Dielectric Materials" appeared in an international journal (Adv. Mater. 11, 1079 - 1089 (1999)).

In a dielectric crystal, the refractive index dispersion usually causes a phase mismatch and therefore breaks the momentum conservation (the wave vector conservation) in an optical parametric process, which results in a destructive interference parametric waves, therefore, low conversion efficiency. The reciprocal lattice vectors in dielectric superlattices can provide a phase compensation for this mismatch process, converting the destructive interference into a constructive interference (coherent superposition). This is called quasi-phase matching (QPM) or quasi-wave vector conservation. An one-dimensional (1D) periodic superlattice has a set of reciprocal lattice vectors in which the largest primary reciprocal lattice vector can efficiently implement a QPM optical parametric process. An 1D quasi-periodic superlattice has two or more sets of reciprocal lattice vectors, some of them can efficiently support several independent or mutually coupled QPM optical parametric processes. This process, involving the intervention of multiple reciprocal lattice vectors, is called multiple quasi-phase-matching (MQPM). MQPM may also take place in a two-dimensional (2D) ferroelectric optical superlattice. For example, we designed a 2D superlattice with a hexagonal symmetry, in which three sets of reciprocal lattice vectors simultaneously participate in the different nonlinear processes in some geometries. Using such a 2D superlattice, we respectively demonstrated three kinds of novel nonlinear effects: non-collinear QPM enhanced elastic scattering, QPM enhanced in elastic scattering (Raman Scattering) and QPM enhanced Čerenkov radiations. These works above are involved in Chapter 2 with title "Nonlinear Optical Phenomena in Optical Superlattice and Some Concepts Extended".

In Chapter 3, we describe another type of 2D superlattice with the periodic modulation of dielectric constant (or refractive index). For example, a 2D superlattice with a square symmetry offers two sets of reciprocal lattice vectors, leading to the excitation of four Floquet-Bloch waves. The phenomenon was explained by the multi-wave dynamics theory we developed. On this basis, with further consideration of nonlinear Kerr effect, we proposed a new kind of optically bistable mechanism modulated by index. It leads to a unique multi-beam optical bistability. This part of the work is introduced in Chapter 3, with the title of "Kerr-type Nonlinear Optical Superlattices and Photonic Crystals".

The dielectric superlattice that can excite ultrasonic waves by piezoelectric effect is called as an acoustic superlattice. In an acoustical superlattice, there is an abrupt change for the sign of the piezoelectric constants of crystal at the boundary of two adjacent domains, therefore, each domain's boundary is equivalent to a δ sound source. By appropriate selection of the interval between the adjacent domains, one can effectively engineer all δ sound sources in-phase to generate constructive interference and coherent superposition for ultrasonic exciting and propagating inside. The emergence of acoustic superlattices not only promises novel ultrasound devices with high output power and low insertion losses, but also unprecedentedly covers the ultrasonic frequency spectrum from several hundred MHz to a few GHz. This part of the work is described in Chapter 4 with the title "Acoustic Superlattices and Sonic Crystals".

In dielectric superlattices with 180° antiphase domain boundary, only there are two different kinds of domain configurations: one with the domain boundaries parallel to the spontaneous polarization, therefore, no charge bounded at the boundaries; the other with the domain boundaries perpendicular to the spontaneous polarization, with bounded charges of opposite signs accumulated alternately at the domain boundaries across the superlattice. In this case, the 1D superlattice effectively serves as an ionic chain with positive and negative ions. While electromagnetic waves propagating through the superlattice induce the vibrations of the charged domain boundaries, i. e., the electromagnetic waves excite the superlattice vibrations. The vibrations of the domain boundaries (bounded charges) also simultaneously excites and radiates electromagnetic waves. Such superlattice vibrations and electromagnetic waves consequently couple with each other, leading to the emergence of polaritons, which shares similar fundamentals with the coupling of electromagnetic waves and lattice vibrations excited by polarization in an ionic crystal proposed by Huang Kun in 1951. Therefore, we named it ionic-type phononic crystal. In conventional ionic crystals, the polaritons are excited in the far-infrared regime. However, they occur in the microwave regime in the ionic-type phononic crystals we defined. Further studies demonstrated that, for the superlattices without the bound charges at the domain boundaries, a transverse polarization still can be induced by a longitudinal wave due to piezoelectric effect. This type of polariton does not exist in a real ionic crystal. Furthermore, even negative permittivity or permeability could be achieved in some frequency regimes by the couple of piezoelectric and piezomagnetic effects in a few composite superlattices. These phenomena just coincide with the properties of metamaterials in some extent. This part of the work is presented in Chapter 5 with the title "Ionic-Phononic Crystals and Metamaterials".

From 1986 to 2006, the study on superlattices was limited to dielectric materials. The fundamental principle depends mainly on the enhanced coherent superposition effects originated from the conservation of quasi-wave vectoror quasi-phase-matching. Since 2006, two explorations on the study of superlattice have appeared: the first one is that, the superlattice structure has been extend to be used to metals and semiconductors, which means that the study has penetrated into the fields of surface plasmonics and metamaterials; the second one is that the artificial band gap engineering is used to various superlattices. These two explorations have brought the study of superlattice many intriguing effects and applications. For the research on the polariton band structure of ionic-type phononic crystals, we found two types of polaritons: ordinary polaritons and extraordinary polaritons. The band gap prohibits ordinary polaritons, but partially permits to extraordinary polaritons. For another example, in an acoustic superlattice (phonon crystal), whose structural unit is composed of metallic cylinders in an air matrix or air cylinders in a solid-state matrix, we developed the corresponding calculation and design methodologies for effective manipulation of sound/ultrasound. In experiment, we observed the negative refraction effects in the first and second energy bands and further proposed and validated a negative birefraction effect caused by "band overlapping". Related works on the band structures of light, sound and polariton are introduced in Chapters 3, 4 and 5, respectively.

In the modern information technology, the operation and processing of information utilize the charges of electrons (charge flow density, current density), while the information remote transfer relies on light or photon, relying on their wave properties, such as frequency, amplitude, phase and polarization etc. This creates a significant barrier due to the fact that different information carriers are utilized for information network. On the other hand, currently the integrated circuits are eventually approaching its physical limits. This suggests the end of the Moore era in which the electron charges serve as the information carriers. We face an open question in fundamentals: what will become the information carriers for the next round of information revolution? The intrinsic properties of electrons at the quantum level include charge, spin, mass, energy and momentum, in which electron spin is being frequently investigated as a potential information carrier. Overall, the quantum states of particles (electron, photon) and quasi-particles (polariton, phonon, plasmon, and so on) have drawn significant efforts in the exploration of quantum information. By exploiting quantum states as information carriers, quantum information technology can break through the bottleneck of classical information technology in several aspects: increasing information transmission capacity, increasing the speed of the information processing and computing, and enhancing the information security and so on. It is compelling that the entangled photons serve as information carriers instead of classic light. Benefiting from the well-developed solid-state photon chip and optical fiber technologies, we may realize the generation and the remote transfer of entangled photons, respectively. The photonics-based quantum information technology can in further eliminate the fundamental flaw of using two different carriers in information processing and remote transfer in current information technology. Our work about quantum information based on single or entangled photon is presented in Chapter 6 with the title "Review Article: Quasi-phase-matching Engineering of Entangled Photons".

The research strategy in basic sciences, such as in condensed matter physics, material science, and chemistry, is divided into different layers, that is, the sample preparation or compound synthesis, the identification of constituent and structure, the characterization of physical and chemical properties and the clarification of the intrinsic links between them and the objective laws. On the contrary, the engineering is originated from the application goals, aiming at the performance and corresponding effects, thus designing and preparing the useful materials and devices with the desired structures and properties. During this process, one must obey the intrinsic links and objective laws among constituents, structures, properties, and performances. At this moment, molecular design and assembly as well as micro-structural design and preparation bear such essential characteristics of engineering. As a branch of micro-structural engineering, domain engineering started from the study on ferroelectric domains and extended later to the ferromagnetic and ferroelastic domains. Due to the difficulty for accurately controlling the configuration and stability of the ferromagnetic and ferroelastic domains, so far, only the ferroelectric domain engineering is sophisticatedly developed. By ferroelectric domain engineering and other modern state-of-the-art technologies, one can integrate various functions for the manipulation of photon on a $LiNbO_3$ chip, which promises a new venue towards solid-state integrated optical quantum chips. We emphatically describe domain engineering of ferroelectrics in Chapter 7 with the title "Domain Engineering for Dielectric Superlattice".

Chapter 8 deals with the synergy of QPM, MQPM and solid-state laser technology to tremendously explore and advance the research of solid-state laser and other photo-electronic devices. Using the MQPM scheme, we have developed novel solid-state lasers with simultaneous output of the three-primary colors (RGB) and multi-wavelength output on-demand. Based on QPM, we achieved highly efficiently optically parametric outputs, which may almost cover the entire transparent region of the implemented nonlinear optical crystals. Moreover, based on conventional technologies, for the nonlinear optical crystals with 3m point group, such as $LiNbO_3$ crystals, their largest nonlinear optical coefficient d_{33} cannot be used to realize conventional birefringence phase matching, but can be utilized by QPM. This will increase the output power several tens of times more than that of the widely used phase matching of d_{31}. By means of the optical superlattice and QPM, we have developed high-power widely-tunable mid-infrared laser systems. We have also efficiently integrated multi-functional entangled photonic sources on the $LiNbO_3$ chips by utilizing domain engineering. This part of works is highlighted in Chapter 8 with the title "Engineered Quasi-phase-matching for Laser Techniques".

Chapter 9 is a summary and outlook for the whole book. It briefly looks back on the history about the research of dielectric superlattice, and predicts possible applications and intriguing development directions in future. Of course, these predictions are based on the authors' own opinionsand do not represent a formal recommendation.

Dr. Shi-Ning Zhu and Dr. Yong-Yuan Zhu conceived the editing and publishing of this book.The editorial team also includes Dr. Zhen-Lin Wang, Dr. Yan-Feng Chen, and Dr. Yan-Qing Lu. I very much appreciate their efforts as well as the contributions from many others in editing and publishing of this book, such as Dr. Nan-Yan Wang and Dr. Ting Wu, the executive editors of this book. This event gives me a chance to recall my scientific career and my own life, as the old saying goes: it is a special time in which opportunity and challenge coexist. I wish to sincerely thank my students and coauthors for their excellent works presented in this book, and my colleagues and friends for their invaluable advices and assistance as well.

Nai-Ben Ming

August 9, 2015, in Nanjing Bishu Park