Martin Maldovan and
Edwin L. Thomas

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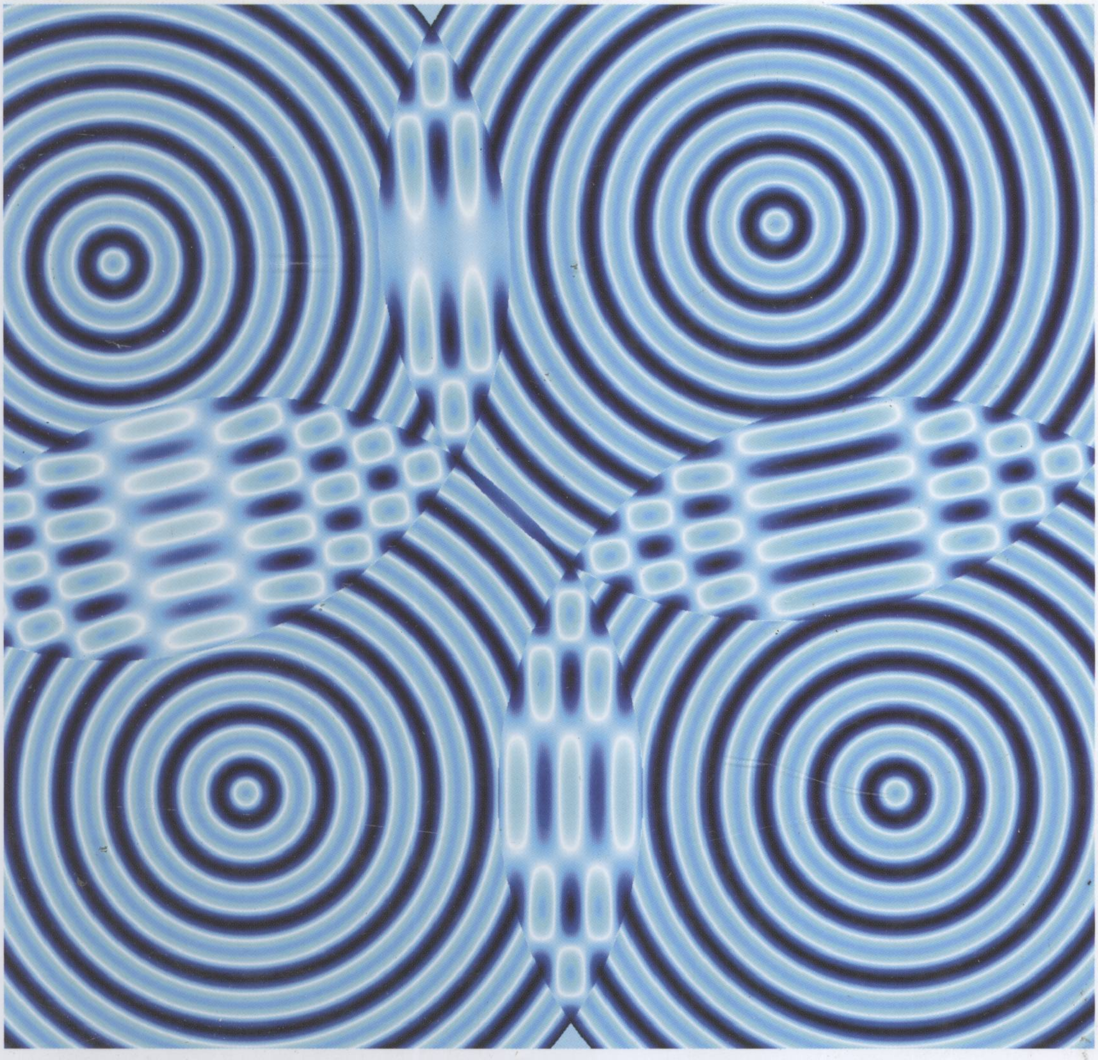
Periodic Materials and Interference Lithography

for Photonics, Phononics and Mechanics



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Preface

Periodic materials have been demonstrated to have unique physical properties due to their singular interaction with waves (which are also periodic). In recent years, the discovery of an experimental technique called *interference lithography*, which can create periodic materials at very small length scales, had a strong impact on the way we think about these materials. To rationally design and fabricate periodic materials by interference lithography, it is useful to perceive a periodic material as a sum of its Fourier series components. This book studies the fascinating and strong correlation between the analytical description of periodic materials by Fourier series and the experimental realization of these materials by interference lithography. We believe this mutual relation will have a deep influence in the development of new periodic materials since the convergence of theoretical and experimental methods allows for the theoretical design of structured materials that can be experimentally realized.

The book also attempts to comprehensively study the applications of periodic materials. For example, in spite of their strong similarities, to date, photonic and phononic crystals have been studied separately. In this book, we try to integrate these two research areas by proposing photonic–phononic crystals that can combine the physical properties of these materials and may even give rise to unique acousto-optical applications. The ubiquity of periodic materials in science and technology can be demonstrated by the large number of physical processes they can control. Several of these practical applications for periodic materials are discussed in this book, which include the control of electromagnetic and elastic waves, mechanics, fluids, and heat. The broad range of applications demonstrates the multifunctional character of periodic materials and the strong impact they can have if fabricated at small length scales.

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October, 2008 | *Martin Maldovan*
Cambridge, Massachusetts | *Edwin L. (Ned) Thomas*

Introduction

Rational Design of Materials

The control and improvement of the physical properties of materials is a central objective in many fields of science and technology. Indeed, one aspect of human evolution encompasses the ability of humans to understand, transform, and use natural materials, and our current advances in technology are a clear illustration of our deep understanding and ability to manipulate materials.

Scientists and engineers have been altering the physical properties of raw natural materials for years, from the simple combination of natural homogeneous materials to the complex fabrication of intricate structural designs that result in materials with effective properties significantly different from those corresponding to the constitutive material. Steel alloys and synthetic sponges are simple examples of the management of material properties by combination or structural design.

The history of the control of the properties of materials begins with the Stone age, the Iron age, and the Bronze age, where stone, iron, and bronze were the most sophisticated forms of materials, respectively. During the twentieth century, the control of the *mechanical* properties of materials had a significant impact on our world; buildings, highways, bridges, planes, ships, and rail-roads are just a few examples of how the understanding of the properties of materials can radically change our society. Moreover, in the last few decades, the managing of the *electrical* and *electronic* properties of materials have created an additional unpredictable revolution; radios, televisions, computers, cell-phones, digital cameras, and music players are now products that seem to have always existed.

"What is next?" ... is not a simple question to answer.

Undoubtedly, the reduction in material length scales emerges as a new frontier in science and technology since it has been demonstrated that as the intrinsic length scale is reduced, materials show different properties when compared to those exhibited at large length scales. Unfortunately, the reduction in the length scale brings difficulties in the fabrication process of these novel materials. That is,

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materials at small length scales bring new physical properties as well as fabrication challenges. This is where this book comes in.

Imagine creating a material that allows us to control the propagation of light. For example, envision a material that does not allow light with certain frequencies to propagate while allowing light with other frequencies to propagate freely. Moreover, imagine a material that can make a "ray of light" turn 90° and that "ray of light" has a cross-section area in the order of microns. Or a material where a "ray of light" can pass around little objects placed within the material. Furthermore, imagine that the material can also stop the propagation of light by confining the electromagnetic wave around certain spatial regions within the material. Actually, this material exists: it is called a *photonic crystal* and it is one of the main subjects in this book.

Assume also that you want to have all of the above physical phenomena but in the case of sound. That is, imagine controlling sound in such a way that you can selectively decide whether or not a particular frequency is allowed to propagate in the material, guide sound inside of the material, or localize it within a certain region in space. This special currently emerging class of material that allows us to control sound in such innovative forms is called a *phononic crystal* and is also studied in detail in this book.

A crucial and common characteristic between photonic and phononic crystals is the fact that they are *periodic* materials. These types of materials can be understood as made of an arrangement of a specific object (e.g. sphere, cylinder, etc.) that repeats regularly in space. Importantly, the materials from which the object is made are decisive in terms of the functionality of photonic and phononic crystals.

The task to design and fabricate such periodic materials is a formidable challenge. First, there are essentially an infinite set of possible periodic geometries, and second creating such structures actually requires sculpting specific materials into the resultant structures with typical feature sizes at and below the submicron length scale.

For example, to control the propagation of visible light, which has wavelengths between 400 and 700 nm, the size of the objects and the distance between them must be on the submicron scale. That is, the fabrication of a photonic crystal that controls the propagation of visible light is analogous to the construction of a building where the periodic supports are separated by distances smaller than a micron. Needless to say, this brings an enormous challenge in terms of the techniques needed to fabricate these materials.

To be able to develop these research areas, it is essential to design periodic materials that have useful photonic and phononic properties *and* that can be actually fabricated at small length scales. This is not a trivial assignment and is one of the main topics studied in this book. We particularly concentrate on the design, fabrication, and applications of *periodic materials* at small length scales. As previously mentioned, periodic materials show striking physical effects and have surprising properties as they interact with waves. Since they do not have preferences toward a particular type of wave, periodic materials can indistinctively control the propagation of both electromagnetic and elastic waves. As a result, we have an opportunity for a radical new departure on the management of material properties, which is the control of the *optical* and *acoustical* properties of materials.

In addition, periodic materials at small length scales can present a new twist to the *mechanical* properties of materials. In the past, much attention has been paid to the fabrication of periodic structures at the millimeter scale (and above) in order to obtain stiff-strong, light-weight structures. The reduction in the length scale brings new opportunities for the applications of periodic materials by exploiting, for example, length-scale-dependent mechanical properties.

We divide the book in three sections: theory, experiments, and applications. In the theoretical section, our objective is to design useful periodic materials that can be fabricated at small length scales by a fast, low-cost experimental technique known as *interference lithography*. One of the most important advantages of periodic materials is the fact that they can be described mathematically with high precision. For example, Fourier series is a mathematical approach that can be used to analytically describe structures that repeat periodically in space. In particular, we use a scheme to design periodic structures based on the manipulation of the coefficients of the Fourier series expansions describing periodic materials. The importance of this approach is that it allows us to obtain periodic structures described by the sum of a small number of Fourier terms, which can be fabricated at small length scales by interference lithography and have exceptional optical, acoustical, and mechanical properties. In addition, we explain in detail how periodic materials can be fabricated by the use of the interference lithography technique and show that this technique is intrinsically related to the Fourier series expansions describing the periodic materials.

The experimental section of the book is intended to provide guidelines for the fabrication of periodic materials at small length scales by interference lithography. In terms of the experimental realization of submicron structured materials, joint efforts of researchers from several fields such as chemistry, engineering, and materials science are leading to good success. From the perspective of experimental fabrication of periodic materials, it is highly desirable to be able to obtain large samples while still having control over the geometry of the resultant structure. Serial writing techniques, such as two-photon lithography, three-dimensional printing, or robotic micromanipulation allow one to create arbitrary structures but are usually slow and cover only small areas. In contrast, self-assembly of colloidal spheres and block-copolymers tends to be rapid and cover large areas, but the control over the geometry of the structure is quite restricted and it is difficult to avoid random defects. Interference lithography emerges as the fabrication method that allows one to control the geometry of the periodic structure while still creating large-area, defect-free single crystals. Important experimental aspects of the interference lithography technique are described in detail in this section.

In the last section of the book, we deal with the practical applications of periodic materials. The ability to be able to precisely describe periodic structures has important benefits: the properties of periodic materials can be calculated accurately. This contributes significantly to give feedback for the design of improved periodic materials with optimized specific functionalities. We not only concentrate on explaining fundamental applications of periodic materials by employing them as photonic and phononic crystals as well as microstructures for mechanics but also demonstrate how periodic materials can be used in a large number of practical applications in several different fields.

Outline of the Book

The introductory Chapter 1 presents the fundamental concepts of periodicity. Two- and three-dimensional periodic structures are described by an arrangement of regular points known as the *point lattices*. These sets of ordered points allow us to classify periodic structures based on how they repeat in space. In this chapter, we also show how periodic materials can be described by the use of analytical functions and introduce the *Fourier series* expansions of three-dimensional periodic functions. Fourier series expansion is a mathematical technique that allows us to describe periodic structures by the use of analytical formulas, which consist of the sum of trigonometric functions.

In Chapter 2, we introduce a systematic scheme based on Fourier series expansions to obtain a large set of *simple periodic structures*. These periodic structures are *simple* in the sense that they are described by Fourier series expansions made of the sum of a small number of trigonometric terms. This is achieved by the systematic manipulation of the coefficients of the Fourier series expansions. In subsequent chapters, we demonstrate that these simple periodic structures have important applications in optics, acoustics, and mechanics, and they are appropriate for fabrication via the interference lithography technique.

Chapter 3 provides an introduction to *wave-interference* phenomena. We first study the propagation of electromagnetic plane waves in homogeneous materials. Then, we examine the superposition of monochromatic electromagnetic plane waves in the same spatial region and the physical effects associated with the interference between the waves. Drawing upon these fundamental concepts, we describe in detail the interference lithography technique, which is the fabrication method that allows us to obtain the periodic structures presented in the previous chapter.

In Chapter 4, we introduce a general scheme that allows us to obtain the electromagnetic plane waves (or interfering beams) required to create desired periodic structures by using the interference lithography technique. This scheme is based on the connection between the Fourier series expansion of a periodic structure and the spatial distribution of energy corresponding to the interference of electromagnetic plane waves. In particular, by using this general scheme, we obtain all necessary information required to fabricate the simple periodic structures presented in Chapter 2.

Chapter 5 deals with *experimental* aspects associated with the fabrication of periodic structures by interference lithography. The key concept is the ability of photosensitive materials to change their solubility characteristics in regions of either high or low light intensity, such that a subsequent chemical development leads to a material having periodic features replicating the incident light interference pattern. We examine important considerations and experimental difficulties, such as conserving the correct beams needed to create the light intensity patterns as well as drying, shrinkage, backfilling, and volume fraction control of the transfer of the pattern to a photo resist material.

In Chapter 6, we study *photonic crystals*, which are periodic structures made of two different dielectric materials. We introduce the reader to basic solid state physics concepts such as reciprocal lattice, Bloch waves, Brillouin zones, and band diagrams in order to understand the fundamental property of photonic crystals, which is the fact that electromagnetic waves having frequencies within a specific range are not allowed to propagate within the crystal. These frequency ranges are also called *photonic band gaps*. We study photonic crystals in one, two, and three dimensions and present numerical data for photonic band gaps as a function of material volume fraction for a set of periodic structures that can be fabricated via the interference lithography route.

In Chapter 7, we study the acoustic version of photonic crystals, which are *phononic crystals*. These periodic structures are made of two different elastic materials and present *phononic band gaps*, that is, frequency ranges for which mechanical waves cannot propagate within the crystal. In the first part of the chapter, we discuss the difference between the propagation of mechanical waves in fluids and solid materials. In general, when mechanical waves propagate in fluid materials they are called *acoustic* waves, whereas when they propagate in solid materials they are called *elastic* waves. As in the previous chapter, we investigate phononic crystals in one, two, and three dimensions and present numerical data for phononic band gaps as a function of material volume fraction for a set of periodic structures that can be fabricated via interference lithography.

Chapter 8 deals with the *mechanical properties* of periodic structures fabricated by interference lithography. We first present an introduction to theoretical aspects of elastic mechanical properties of materials. We explain in detail fundamental concepts in mechanics, such as Hooke's law, stress and strain tensors, elastic constants of cubic crystals, Young's modulus, Poisson's ratio, shear modulus, and bulk modulus. In the second part of the chapter, we introduce the topological design of periodic structures with application in mechanics and provide numerical calculations for effective linear elastic properties of periodic solids fabricated by interference lithography. In the last section, we briefly comment on the plastic deformation of these structures.

Finally, in Chapter 9 we examine several potential applications of periodic materials in several emerging research areas. For example, we show how periodic materials can be used to control the spontaneous emission of light, guide and localize light, manage light and sound simultaneously, focus light without diffraction limits, maximize the transport of heat and electricity, regulate the flow of fluid, and enhance thermoelectric devices. All of the above examples demonstrate the *multifunctional* character and the huge technological impact of these periodic materials.

In addition, at the end of each chapter, we give relevant references/literature for additional reading as well as background material and specialist textbooks for further study. At the end of most of the chapters, we also provide problem sets for the reader to strengthen the concepts studied in the book.

Cambridge, Massachusetts *Martin Maldovan and Edwin L. (Ned) Thomas*
October, 2008

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