Space–time transformations as a design tool for a new class of composite materials (metamaterials) have proved successful recently. The concept is based on the fact that metamaterials can mimic a transformed but empty space. Light rays follow trajectories according to Fermat's principle in this transformed electromagnetic, acoustic, or elastic space instead of laboratory space. This allows one to manipulate wave behaviors with various exotic characteristics such as (but not limited to) invisibility cloaks.

This book is a collection of works by leading international experts in the fields of electromagnetics, plasmonics, elastodynamics, and diffusion waves. The experimental and theoretical contributions will revolutionize ways to control the propagation of sound, light, and other waves in macroscopic and microscopic scales. The potential applications range from underwater camouflaging and electromagnetic invisibility to enhanced biosensors and protection from harmful physical waves (e.g., tsunamis and earthquakes). This is the first book that deals with transformation physics for all kinds of waves in one volume, covering the newest results from emerging topical subjects such as transformational plasmonics and thermodynamics.

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Transformation Wave Physics
Transformation Wave Physics
Electromagnetics, Elastodynamics, and Thermodynamics

edited by
Mohamed Farhat
Pai-Yen Chen
Sebastien Guenneau
Stefan Enoch
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*Nasim Mohammadi Estakhri and Andrea Alù*

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*Zhi Hao Jiang, Anastasios H. Panaretos, and Douglas H. Werner*

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Preface

The theory of composites is a vast and highly interdisciplinary topic that can be traced back to Lord Rayleigh’s work on effective medium formulae. John William Strutt, 3rd Baron Rayleigh, who earned the Nobel Prize in Physics in 1904 for his discovery of argon, is most famous among the wave community for Rayleigh scattering (for the layperson, this explains why the sky is blue) and Rayleigh waves that are, with Love waves, responsible for much of earthquake disasters in human infrastructures. Rayleigh’s textbook, *The Theory of Sound*, has been, together with Augustus Edward Hough Love’s monograph *Some Problems of Geodynamics*, an invaluable source of inspiration for generations of physicists, engineers, and mathematicians. Rayleigh waves are both longitudinal and transverse motions that decrease exponentially in amplitude as distance from the surface increases, so they are also known as surface Rayleigh waves, while Love waves are horizontally polarized surface waves.

Metamaterials are composites with extraordinary properties and were introduced in the context of electromagnetic waves by Sir John Pendry and his colleagues toward the end of the twentieth century, following the advent of photonic crystals. To achieve this tour de force Pendry proposed to combine split ring resonators and thin, straight wires, which exhibit, respectively, a negative permeability and a negative permittivity, the square root of which turns negative upon resonance (hence the negative refractive index!). The first experimental proof of negative refraction came in 2000 with the team of David Smith. Inspired by Victor Veselago’s 1968 proposal of a flat convergent lens via negative refraction, Pendry further proposed at the turn of the millennium a lens whose resolution is not limited by the wave wavelength, that is, with a resolution not limited by Rayleigh’s criterion on
resolution of optical instruments. Finally, 10 years ago, Pendry proposed, together with David Smith and David Schurig, a route toward invisibility, using coordinate changes in Maxwell’s equations, which leads to anisotropic heterogeneous tensors of permittivity and permeability. Ulf Leonhardt independently proposed to use conformal mappings to design invisibility cloaks without resorting to anisotropy. The paradigms of negative refraction, transformation optics, and conformal optics have revolutionized the field of photonics, as we have known it since the time of Snell and Descartes.

The present book explores theories and applications of metamaterials not limited to the control of electromagnetic waves. It is a collection of works by leading international experts in the fields of electromagnetics, plasmonics, hydrodynamics, elastodynamics, and diffusion waves.

It starts by a survey (by the world-famous theoretical physicist Leonhardt) of space–time transformations as a design tool for metamaterials underpinning intimate connections between Maxwell’s equations and Einstein’s theory of relativity, and then the book moves on to practical applications in the control of radio frequency and microwaves, water waves, mechanical waves, and even heat and mass diffusion. We stress that all these contributions promise to revolutionize ways of controlling the propagation of sound, light, and any particular form of waves at macroscopic and microscopic scales. Indeed, potential applications range from subwavelength lensing and time reversal, to underwater camouflaging and electromagnetic invisibility, to enhanced biosensors and protection from harmful physical waves (e.g., tsunamis and earthquakes). This volume covers theoretical as well as experimental aspects in these different areas that include nanoscale (plasmonics) and meter-scale (geophysics) media.

The outline of the chapters is as follows:

As mentioned earlier, the book starts with a chapter by Leonhardt, which describes how theoretical ideas arising from Einstein’s general theory of relativity in optical and electrical engineering for designing devices can do the (almost) impossible: invisibility cloaks, perfect imaging, levitation, and the creation of
analouges of the event horizon. This chapter gives an introduction to this field requiring minimal prerequisites.

The second chapter, by the group of Liu, reviews the fundamentals and applications of conformal mapping in transformation optics. It first introduces the basics of conformal mapping and how this subset of transformations in the complex plane can eliminate the undesired anisotropy in 2D systems. It then presents metamaterials with minimized anisotropy derived by quasi-conformal mapping; it addresses the promising applications for plasmonics, where conformal mapping manifests its versatility when dealing with the surface plasmon polaritons (SPPs) and localized surface plasmons (LSPs). Interestingly, an attempt is made at applying conformal mapping to the construction of 3D devices.

The third chapter, by the group of Li, further investigates quasi-conformal map as a useful tool for minimizing anisotropy, while the index range can be further minimized by avoiding sharp corners at boundaries. Analytic and numerical approaches show that the corresponding map generation can be simplified by taking an electrostatic analogy. Extension to acoustic and elastic waves is proposed for carpet cloaks. These considerations are useful in a wide class of applications such as invisibility cloaks and optimized integrated devices at the optical wavelengths.

The fourth chapter, by the group of Chan, introduces a mechanism to control the spatial distribution of either an electric or a magnetic field instead of both fields, which can be controlled in an almost arbitrary manner in wavelength and subwavelength scales. Interestingly, the principle of flux control does not rely on surface waves as in the field of plasmonics, but relies on the evanescent waves induced by the strong anisotropy and designed inhomogeneity of media. Such inhomogeneous anisotropic media exhibit surprisingly robust high transmittance. Combined with transformation optics, such high transmittance property can be utilized to build waveguide devices with almost arbitrary shapes and bending angles.

The fifth chapter, by the group of Itoh, reviews progress on radio frequency and microwave beam-forming techniques using planar metamaterials and metamaterial surfaces (metasurfaces). Principles
and physics of guided- and leaky-wave characteristics of periodic planar structures are discussed, such as transmission-line-based metamaterials, followed by their active versions that enable novel smart antennas with beam-steering functions. Practical realizations are discussed, as well as the integration with active elements and circuits, which enables adaptively tailoring electromagnetic waves. Planar metamaterial-/metasurface-based beam-forming techniques are clarified through a critical assessment and comparative analysis in the radio-frequency and microwave bands. These techniques offer promising applications in modern wireless communication, radar, remote sensing, and medical and security imaging.

The sixth chapter, by the group of Alù, aims at providing a comprehensive insight into recent developments and applications of gradient metasurfaces to control and engineer the propagation of electromagnetic waves. Various aspects of this technology are explored, starting from miniaturized metasurface building blocks at the lowest level, moving to primary optical elements for radiation patterning, and ultimately incorporating graded metasurfaces into more complex optical devices.

The seventh chapter, by Douglas and Werner, presents scattering manipulation of objects using anisotropic metasurfaces in the microwave range and plasmonic loadings at optical wavelengths. Different from previously reported transformation optics–enabled coatings, they are achieved on the basis of modifying the complex Mie scattering coefficients of an object. The nonvanishing radial response of an anisotropic metasurface is exploited to accomplish near-perfect cloaking and angle-tolerant illusion for objects beyond the quasi-static limit. It is also demonstrated how plasmonic core–shell particles can provide a compact and robust solution toward the realization of nanocircuit loads that offer unprecedented flexibility in tuning the response of a nanodipole-type antenna. Indicative examples are provided that demonstrate the tuning range that core–shell particles are capable of offering.

The eighth chapter, by some of this book’s editors, emphasizes that metamaterials can mimic a transformed space in many wave physics areas. The light rays follow trajectories according to Fermat’s principle in transformed electromagnetic, acoustic,
hydrodynamic, or elastic space, instead of the laboratory space. Homogenization techniques are used to approach such media. This allows one to ultimately manipulate electromagnetic, water, and mechanical wave behaviors, with various exotic characteristics, such as (but not limited to) invisibility cloaks and flat convergent lenses.

The ninth chapter, by the group of Puvirajesinghe, investigates transformational techniques applied to diffusion phenomena. Coordinates transform in the Fourier and Fick’s equations bridges transformational thermodynamics to control of mass diffusion. Potential applications range from invisibility cloaks and concentrators for control of heat flux in electronics to biocloaks enabling delayed drug delivery for medical applications.

The tenth chapter, by the group of Wegener, points out that cloaking can be seen as a look-alike contest: the goal is to make some object A appear like another object B with respect to some physical observable. Early mathematical literature has indeed spoken of the nonuniqueness of the tomography (inverse) problem with the works of Calderon (1980), Kohn and Vogelius (1984), and Greenleaf et al. (2003). The experiments discussed in this chapter concern the observables light, sound, elastic waves, static elasticity, electric conduction, heat conduction, and particle diffusion.

The eleventh chapter, by the group of Sato, refreshes our mind with geometrical interpretation to required material parameters through linear-algebraic operations, before moving on to a systematic approach for designing a single functionality in a given physical domain. In this chapter, an extension of the transformation optics formalism is proposed to go beyond a single functionality to independently manipulate multiple physical phenomena simultaneously. A multifunctional shell behaving as an electrical invisibility cloak and a thermal concentrator opens a route to transformation multiphysics.

The twelfth, and last, chapter of the book, by the group of Maurel and Fink, takes us on a journey to the wonderland of time reversal of acoustic, elastic, and electromagnetic waves. In a standard time reversal experiment, waves generated by a source are first measured by an array of antennas positioned around the source and then time-reversed and simultaneously rebroadcasted
by the same antenna array. Due to the time invariance of the wave process, the reemitted energy will focus back on the original source, whatever the complexity of the propagation medium. This chapter concentrates on the application of time reversal to the focusing and manipulation of water waves both in linear and nonlinear regimes. Applications are sought in water waves that are scalar waves referring to the evolution of small perturbation of the height of fluid under the action of gravity and surface tension. They are dispersive by nature, nonlinear when generated with standard wave makers, and they experience strong damping at the scale of laboratory experiments. The evolution dynamics in time and space of nonlinear wave trains in deep water can be modeled using the focusing nonlinear Schrödinger equation. The implication of the time reversal invariance on the nonlinear Schrödinger equation is discussed and a way to experimentally focus, both in time and space, rogue waves using the principles of time reversal mirrors is demonstrated.

As you can see, this book therefore touches upon many hot subjects in the physics of metamaterials, which were discovered less than 20 years ago. The first direct experimental evidence of gravitational waves that are ripples in the curvature of space–time that propagate like waves traveling outward from a source (say, two black holes falling onto one another) came in January 2016, that is, one century after Einstein foresaw their existence as a solution to his equations of general relativity. The experimental evidence of Higg’s boson came just over two years ago. Graphene was discovered just over a decade ago. We have therefore lived an exciting new millennium of advances in physics thus far, and needless to say that this would already be even to fill with joy the life of any human being, but we believe that metamaterials offer a playground for many new discoveries. We hope that the present book will help foster theoretical and experimental efforts toward a brave new physics world!

We would like to convey our warmest thanks to all chapter authors for their excellent scientific contributions and their willingness to share their knowledge of metamaterials with a general readership. The assistance and professionalism of the Pan Stanford Publishing team is also greatly acknowledged.
We hope that you’ll enjoy reading these chapters and find them as informative as we did!

Mohamed Farhat
Pai-Yen Chen
Stefan Enoch
Sebastien Guenneau
Thuwal, Detroit, and Marseille