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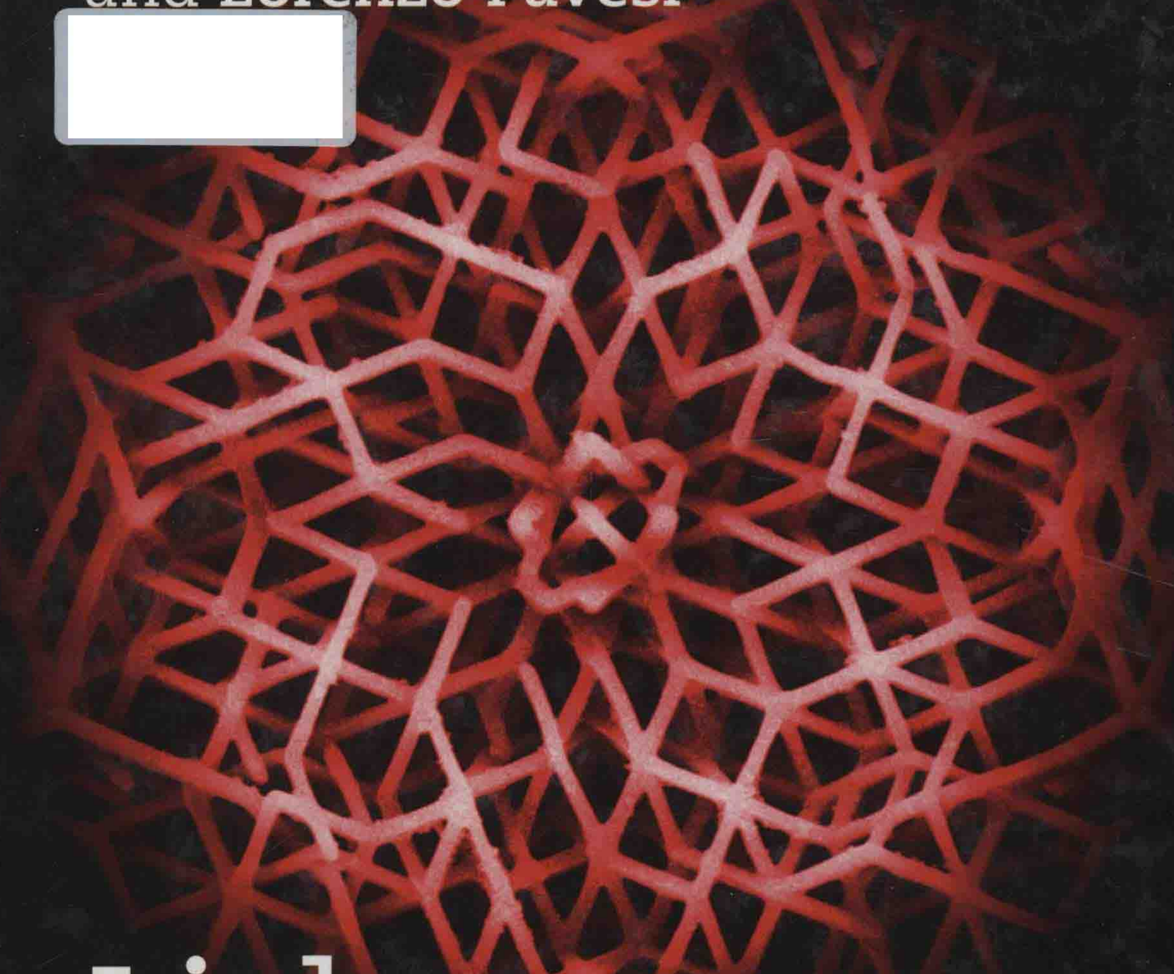
and **Lorenzo Pavesi**



Light Localisation and Lasing

Random and Quasi-random Photonic Structures

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LIGHT LOCALISATION AND LASING

The properties of quasi-random and random photonic systems have been extensively studied over the last two decades, but recent technological advances have opened new horizons in the field, providing better samples and devices. New optical characterization techniques have enhanced understanding of the novel and fundamental properties of these systems.

This book examines the full hierarchy of these systems, from 1D to 2D and 3D, from photonic crystals and random microresonator chains to quasicrystals. It treats photon transport as well as photon generation and random lasing, and deals with semiconductors, organics, and glass materials.

Presenting basic and state-of-the-art research on this fascinating field, this collection of self-contained chapters is an ideal introductory text for graduate students entering this field, as well as a useful reference for researchers in optics, photonics, and optical engineering.

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Preface

This book is the result of our interest in understanding, mastering, and engineering randomness in photonic systems. It is a natural consequence of what we did in the past. In the late 1980s, while Lorenzo Pavesi was working on semiconductor superlattices he noticed that for some energies the vertical transport through the superlattice minibands was inhibited due to disorder (L. Pavesi *et al.* 1989. *Phys. Rev. B*, **39**, 7788). Then, working on the recombination dynamics of excitons in porous silicon, he further noticed that the random arrangement of silicon quantum dots has a strong influence on the recombination dynamics of excitons (L. Pavesi *et al.* 1993. *Phys. Rev. B*, **48**, 17625). After Mher Ghulinyan came to Trento in 2002, we developed the techniques to fabricate free-standing porous silicon dielectric multilayers of any stacking sequence (M. Ghulinyan *et al.* 2003. *J. Appl. Phys.*, **93**, 9724). This was the first time that we had the chance to design at will one-dimensional periodic, aperiodic, or random photonic systems. A fascinating new physics opened up for us: that of the analogy of photon propagation in complex dielectric systems with carrier transport in random electronic systems. Our latest results in the field are associated with sequences of ring resonators where randomness causes the formation of resonant coupling between different rings with the possibility of yielding the optical analog of the electromagnetic induced transparency (M. Mancinelli *et al.* 2011. *Opt. Express*, **19**, 13664), or chaotic photon propagation.

Over all these years, we have had the chance to interact with many researchers active in the field of periodic, quasiperiodic, and random photonic systems. From these interactions the idea of this book was born. We have therefore collected together a series of self-contained chapters to cover the whole field with the specific aim of introducing the different aspects, showing the current status of the research, and envisaging future directions. All invited authors have responded to this challenge with great enthusiasm and professionalism.

The book opens with Chapter 1 by W. L. Vos, A. Lagendijk, and A. P. Mosk, which introduces the field and covers the timeline between the early studies on these systems and the very latest achievements in the field. An extended historical overview details the early stages of research, its progress throughout past decades, and finally focuses the reader's attention on recent advances, which are detailed in the subsequent chapters.

This is followed by Chapter 2 by A. Genack and Z. Shi, where the transport of light (classical photons) through a random medium is described. In particular, it is shown that the modes in a random medium are in complex correlation with each other and the overall transmission of the system critically depends on how much the different modes overlap. The role of mode statistics is crucial for both linear and nonlinear optical phenomena and this statistics determines, for example, the threshold of random lasing in an amplifying medium.

Chapter 3 by M. Leonetti and C. López deals with the phenomenon of random lasing in disordered highly scattering materials. Like conventional resonators, random lasers can display spectrally narrow emission lines and a threshold-like onset. However, these devices possess several interesting properties which make them different from conventional lasers: such as the fact that they provide a poly-directional output. Specifically, a random laser can be continuously driven from a configuration exhibiting weakly interacting electromagnetic resonances to a regime of collectively oscillating, strongly interacting modes.

Quasi-one-dimensional sequences of coupled resonators are the subject of Chapter 4 by S. Mookherjea. In this chapter, the focus is on the fundamental aspects of light propagation, including a study of non-idealities (e.g. disorder-induced deviations from ballistic transport) in chains of silicon microring resonators. The slowing down of light propagation is achieved through the phenomenon of light interference in a sequence of coupled resonators. Meanwhile, in disordered structures, the same light interference is also responsible for the localization of electromagnetic waves.

Chapter 5 by M. Ghulinyan enters into the topic of quasi-random optical systems (quasicrystals). Quasicrystals are aperiodic structures that are constructed following simple deterministic generation rules, and if made from dielectric material, can show fascinating properties which govern light transport through them. Quasicrystals exhibit an energy spectrum that consists of a self-similar set of eigenstates and their transmission spectrum contains forbidden frequency regions called "pseudo band gaps," similar to the band gaps of a photonic crystal. This chapter details the peculiarities of ultrashort light pulse propagation through pseudo band-edge states of Fibonacci-type photonic quasicrystals, showing interesting optical phenomena such as mode beating, strong pulse stretching and suppressed group velocities originating from the excitation of "critically localized" band-edge states.

Two-dimensional aperiodic systems, past, present, and future, are discussed in Chapter 6 by H. Cao, H. Noh, and L. Dal Negro. The recent developments in advanced nanolithographic techniques have allowed the realization of bi-dimensional arrays of metal nanoparticles, arranged in an aperiodic order in both dimensions in a plane. These plasmonic nanostructures can alter out-of-plane white light scattering, following the strict rules of underlying quasiperiodic order. New and fascinating features, such as colored photonic–plasmonic scattering, plasmon-enhanced structural coloration of metal films, mode patterns, dipole radiation, and lasing from optimized aperiodic structures are discussed.

Chapter 7 by A. Ledermann, M. Renner, and G. von Freymann focuses on three-dimensional (3D) quasicrystals and deterministic aperiodic structures. Both fabrication and characterization are presented. The quality of quasicrystalline order is investigated through the comparison of obtained diffraction patterns of structures with a local five-fold real-space symmetry axis, revealing a ten-fold symmetry, as required by theory for 3D structures. Importantly, this chapter reports on the realization of a high-quality silicon inverse quasicrystal operating at near-infrared frequencies.

The book closes with Chapter 8 by W. L. Vos and L. A. Woldering on 3D photonic band gap crystals. Three-dimensional photonic crystals with a 3D photonic band gap play a fundamental role in cavity quantum electrodynamics (QED), especially in phenomena where the local density of optical states is essential: spontaneous emission inhibition or enhancement of emitters embedded in a 3D band gap crystal, thresholdless laser action in a miniature photonic crystal cavity, and breaking of the weak-coupling limit of cavity QED. Finally, several exciting applications of 3D photonic band gap crystals are discussed, namely the shielding of decoherence for quantum information science, the manipulation of multiple coupled emitters including resonant energy transfer, lighting, and a possible spin-off to 3D nanofabrication for future high-end computing.

We are grateful to our past and present colleagues, students, and friends at the Nanoscience Laboratory of the Department of Physics of the University of Trento and at the Center for Materials and Microsystems of the Bruno Kessler Foundation in Trento, for maintaining an environment of scientific excellence and friendship over the years. We owe special thanks to the authors of the various chapters for their excellent work. In addition to thanking the authors, we would like to thank L. Barnes and N. Gibbons, the editorial assistants, for their help, assistance and patience.

LP. I dedicate this book to my children – Maria Chiara, Matteo, Michele, and Tommaso – who have taught me how the disorder of things does not necessarily lead to the clutter of minds, but rather that from chaos can arise creativity (any allusion to their bedrooms is intentional).

MG. I dedicate this book to my sons Davit and Michael, and to my wife Lilit, with whom I have taught our sons for years that order is good and disorder is bad (but I have it clear in my mind that certain disorder on certain length-scales is so rich and fascinating).

Mher Ghulinyan and Lorenzo Pavesi

Contents

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Light propagation and emission in complex photonic media

WILLEM L. VOS, AD LAGENDIJK, AND ALLARD P. MOSK

1.1 General overview

In many areas in the physical sciences, the propagation of waves in complex media plays a central role. Acoustics, applied mathematics, elastics, environmental sciences, mechanics, marine sciences, medical sciences, microwaves, and seismology are just a few examples, and of course nanophotonics [6, 429, 448, 449]. Here, complex media are understood to exhibit a strongly inhomogeneous spatial structure, which determines to a large extent their linear and nonlinear properties. Examples of complex media are random, heterogeneous, porous, and fractal media. The challenges that researchers in these areas must surmount to describe, understand, and ultimately predict wave propagation are formidable. Right from the start of this field – in the early 1900s – it was clear that new concepts and major approximations had to be introduced. Famous examples of such concepts are the effective medium theory [55, 60, 321] and the radiative transport theory [81, 491]. These concepts are very much alive, even today. The fundamental challenge with these approximate concepts is that often the length scales of the inhomogeneities in the complex medium are comparable with the wavelength, whereas the range of validity of these approximations is restricted to situations where these length scales are much larger than the wavelength. Consequently, many relevant situations arise where either the effective medium theory, or radiative transport theory, or both, fail dramatically. Examples of such situations are given in this introduction and throughout this book.

The complexity of the medium that supports wave propagation can be classified in a number of ways. Many different types of spatial inhomogeneities in a host matrix can be envisioned, varying from completely random, via aperiodic and

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waveguide structures, to quasi-crystalline and even structures with long-range periodic order. The inhomogeneities could be of a self-organized form, or the fruit of precise engineering. An additional classification is whether or not the complexity is confined to the surface (in two dimensions (2D)) or is present throughout the volume of the medium (in three dimensions (3D)), as in porous media. A useful criterion for the classication of inhomogeneous media is whether the inhomogeneity is of a continuous nature, or stems from discrete scatterers. One can thus classify the topology of the inhomogeneities relevant to classical waves: if the inhomogeneities are connected from one side to the other, the medium has a network topology; if the inhomogeneities are completely surrounded by host material, the complex medium is said to have a Cermet topology. It appears that topology plays an important role in the scattering of various types of waves – such as scalar, elastic, electromagnetic – in complex media [120].

Ever since the breakthrough achievement of renormalization group theory [539] the dimensionality of a complex system has been known to be vital [80, 429]. Hence, the dimensionality of the problem is crucial to the study of waves in complex media. 1D and 2D systems have the intriguing property that waves are always localized, that is, a wave that starts at a certain spatial position always returns. As stated by the Mermin–Wagner–Hohenberg theorem, 2D systems have the lower critical dimension for most field theories [195, 330], allowing for the study and use of a wealth of scaling phenomena that are highly challenging to uncover. In a 3D world there is a striking phase transition between localized and extended states. Famous examples are Anderson localization, or the photonic band gap in 3D.

From scaling theory [2, 429], it is known that the extent of the complex system is crucial. The finite size determines the transport of the waves – specifically, the conductance. For extended states, it appears that the conductance scales with dimensionality minus two, times the logarithm of the system size. For localized states, the conductance decreases exponentially with system size. Therefore, the study of system size dependence of complex media provides an important key in distinguishing extended from localized states, and in characterizing the formation of gaps.

Advances made in the understanding of waves in complex media have led to a number of practical applications, and are generating new ones at an ever increasing pace [530]. Examples are found in remote optical sensing ("looking through a cloud"), inverse optical scattering, noninvasive medical imaging ("find the tumour in tissue"), applied optics (quality control of optical systems by controlling surface roughness), optical devices and (random) lasers, furthermore, in oil and mineral prospecting by seismic methods, in ultrasonic imaging and non-destructive testing ("find hairline cracks in an airplane wing"), material characterization, all the way to microwave propagation and detection in antennas, mobile phones, and radar.