

Cambridge University Press

978-1-107-03877-6 - Light Localisation and Lasing: Random and Quasi-Random Photonic Structures

Edited by M. Ghulinyan and L. Pavesi

Frontmatter

[More information](#)

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.

MHER GHULINYAN is a Scientist at the Center for Materials and Microsystems, Fondazione Bruno Kessler, Italy. His main research interests are in the field of complex dielectric systems and resonator optics.

LORENZO PAVESI is Professor of Experimental Physics, Chairman of the Department of Physics, and Head of the Nanoscience Laboratory at the University of Trento, Italy. His research activity is concerned with the optical properties of semiconductors and with silicon photonics.

Cambridge University Press
978-1-107-03877-6 - Light Localisation and Lasing: Random and Quasi-Random Photonic Structures
Edited by M. Ghulinyan and L. Pavesi
Frontmatter
[More information](#)

Cambridge University Press
978-1-107-03877-6 - Light Localisation and Lasing: Random and Quasi-Random Photonic Structures
Edited by M. Ghulinyan and L. Pavesi
Frontmatter
[More information](#)

LIGHT LOCALISATION AND LASING
Random and Quasi-Random Photonic Structures

Edited by

M. GHULINYAN
Fondazione Bruno Kessler, Italy

and

L. PAVESI
University of Trento, Italy



Cambridge University Press
978-1-107-03877-6 - Light Localisation and Lasing: Random and Quasi-Random Photonic Structures
Edited by M. Ghulinyan and L. Pavesi
Frontmatter
[More information](#)

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

Cambridge University Press is part of the University of Cambridge.

It furthers the University’s mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org

Information on this title: www.cambridge.org/9781107038776

© M. Ghulinyan and L. Pavesi 2015

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published 2015

Printed and bound in the United Kingdom by Clays, St Ives plc

A catalogue record for this publication is available from the British Library

Library of Congress Cataloging-in-Publication Data

Light localisation and lasing in random and quasi-random photonic structures / edited by Mher Ghulinyan and Lorenzo Pavesi.

pages cm

Includes bibliographical references and index.

ISBN 978-1-107-03877-6

1. Photonics – Materials. 2. Optoelectronic devices. I. Ghulinyan, Mher, editor of compilation. II. Pavesi, Lorenzo, editor of compilation.

TA1522.L53 2014

621.36’5–dc23

2014018695

ISBN 978-1-107-03877-6 Hardback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication, and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

Contents

<i>List of contributors</i>	<i>page</i> ix
<i>Preface</i>	xi
1 Light propagation and emission in complex photonic media	1
WILLEM L. VOS, AD LAGENDIJK, AND ALLARD P. MOSK	
1.1 General overview	1
1.2 Light in complex photonic media	3
1.2.1 Random media	3
1.2.2 Photonic band gap crystals	7
1.2.3 Waveguides and coupled cavities	7
1.2.4 Quasicrystals and aperiodic media	7
1.3 Shaping wavefronts in complex media	8
1.4 Unified view of complex media: photonic interaction strength	10
2 Transport of localized waves via modes and channels	13
ZHOU SHI AND AZRIEL GENACK	
2.1 Introduction	13
2.2 Analogies between transport of electrons and classical waves	15
2.3 Modes	22
2.4 Lasing in localized modes	34
2.5 Channels	41
2.6 Focusing	49
2.7 Conclusion	52
3 Modes structure and interaction in random lasers	54
MARCO LEONETTI AND CEFÉ LÓPEZ	
3.1 From lasers to random lasers	54
3.2 Random lasing regimes	56
3.2.1 Diffusive random lasers	56

vi	<i>Contents</i>	
	3.2.2 Mode structures in random lasers	59
	3.2.3 Anderson localization	59
	3.2.4 Lucky photons	60
	3.2.5 Localized modes	61
	3.3 Tuning emission from a macroscopic random laser	63
	3.4 Driving modes of a microscopic random laser	66
	3.4.1 Fluctuations	67
	3.4.2 Local mode selection	70
	3.5 Collective random lasing regimes	71
	3.6 Applications and perspectives	77
4	Ordered and disordered light transport in coupled microring resonators	80
	SHAYAN MOOKHERJEA	
	4.1 Introduction	80
	4.2 Optical microring chains	82
	4.2.1 Experimental details	84
	4.3 From ordered transport to disorder-induced bandwidth collapse	85
	4.4 Statistical measurements of light transport in the intermediate regime	89
	4.4.1 Intensity statistics	93
	4.4.2 Time statistics	95
	4.5 Summary	97
5	One-dimensional photonic quasicrystals	99
	MHER GHULINYAN	
	5.1 Introduction	99
	5.1.1 In between perfect periodicity and complete randomness	100
	5.2 1D quasiperiodicity: Fibonacci chain	101
	5.3 Photons in a 1D optical potential	103
	5.4 Photons in a 1D quasiperiodic potential	108
	5.4.1 Electronic energy spectrum of 1D Fibonacci quasicrystals	109
	5.4.2 Energy spectrum of 1D photonic Fibonacci quasicrystals	109
	5.4.3 Origin of band-edge states and pseudo band gaps	119
6	2D pseudo-random and deterministic aperiodic lasers	130
	HUI CAO, HEESO NOH, AND LUCA DAL NEGRO	
	6.1 Introduction	130
	6.2 Overview	131
	6.3 Pseudo-random laser	133

	<i>Contents</i>	vii
6.4	Optimization of structural aperiodicity for lasing	138
6.5	Conclusions and future prospects	143
7	Three-dimensional photonic quasicrystals and deterministic aperiodic structures	146
	ALEXANDRA LEDERMANN, MICHAEL RENNER, AND GEORG VON FREYMAN	
7.1	Classification	147
7.1.1	Quasi-periodic Fourier spectra	148
7.1.2	Non quasi-periodic Fourier spectra	151
7.1.3	Mode structure	152
7.1.4	Density of states and band structure	153
7.2	Generation of three-dimensional point-sets	154
7.2.1	Quasiperiodic pattern	154
7.2.2	3D aperiodic point-sets from mathematical sequences	162
7.3	Fabrication	163
7.3.1	One- and two-dimensional photonic structures	164
7.3.2	Three-dimensional photonic structures	164
7.3.3	Direct laser writing	166
7.4	Examples	167
7.4.1	High quality SU-8 icosahedral photonic quasicrystals	167
7.4.2	Rhombicuboctahedral quasicrystals	172
7.4.3	Deterministic aperiodic structures	177
8	Cavity quantum electrodynamics with three-dimensional photonic band gap crystals	180
	WILLEM L. VOS AND LÉON A. WOLDERING	
8.1	Introduction	180
8.2	Theory	183
8.2.1	Spontaneous emission control	183
8.2.2	The local density of optical states	184
8.2.3	Quantum efficiency of the emitters and degree of cQED control	185
8.2.4	Beyond weak coupling	188
8.3	Ultimate tools for 3D photonic band gap cavity QED	189
8.3.1	Requirements for 3D photonic band gap crystals	189
8.3.2	Optical signature of a 3D photonic band gap	191
8.3.3	Inverse opals	193
8.3.4	Diamond-like photonic crystals	196

viii	<i>Contents</i>	
	8.3.5 Woodpiles	196
	8.3.6 Inverse woodpiles	201
	8.3.7 Other diamond-like structures	203
8.4	Cavity quantum electrodynamics	204
	8.4.1 Inhibited spontaneous emission in a 3D photonic band gap	204
	8.4.2 Emission in a nanobox for light	207
	8.4.3 Laser action in 3D photonic crystal nanocavities	208
	8.4.4 Ultrafast all-optical switching of 3D photonic band gap crystals	209
8.5	Applications and prospects	211
8.6	Summary	213
	<i>References</i>	215
	<i>Index</i>	243

Contributors

- Hui Cao** *Department of Applied Physics, Yale University, 15 Prospect Street, New Haven, CT 06520, USA*
- Luca Dal Negro** *Division of Materials Science and Engineering, Department of Electrical and Computer Engineering & Photonics Center, Boston University, Brookline, MA 02446, USA*
- Azriel Genack** *Department of Physics, Queens College and Graduate Center of the City University of New York, 65–30 Kissena Blvd Flushing, NY 11367*
- Mher Ghulinyan** *Center for Materials & Microsystems, Fondazione Bruno Kessler, I-38123 Povo, Italy*
- Ad Lagendijk** *Complex Photonic Systems (COPS), MESA+ Institute for Nanotechnology, University of Twente, 7500 AE Enschede, the Netherlands*
- Alexandra Ledermann** *Optics Expert, Visteon Electronics Germany-GmbH, An der Raumfabrik 33b, D-76227 Karlsruhe, Germany*
- Marco Leonetti** *ISC-CNR, UOS Sapienza, P. A. Moro 2, 00185 - Rome, Italy and Instituto de Ciencia de Materiales de Madrid (CSIC) Cantoblanco 28049 Madrid, Spain*
- Cefe López** *Instituto de Ciencia de Materiales de Madrid (CSIC) Sor Juana Inés de la Cruz 3, 28049 Madrid, Spain*
- Shayan Mookherjea** *University of California, San Diego, Electrical and Computer Engineering, 9500 Gilman Dr. MC 0407, La Jolla, CA 92093, USA*
- Allard P. Mosk** *Complex Photonic Systems (COPS), MESA+ Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE Enschede, the Netherlands*
- Heeso Noh** *Department of Nano and Electronic Physics, Kookmin University, Seoul, Korea*

Michael Renner *Department of Physics and Research Center OPTIMAS, University of Kaiserslautern, Erwin-Schrödinger-Str. 56, 67663 Kaiserslautern, Germany*

Zhou Shi *Department of Physics, Queens College and Graduate Center of the City University of New York, 65–30 Kissena Blvd Flushing, NY 11367*

Georg von Freymann *Department of Physics and Research Center OPTIMAS, University of Kaiserslautern, Erwin-Schrödinger-Str. 56, 67663 Kaiserslautern, Germany; Fraunhofer – Institute for Physical Measurement Techniques (IPM), Erwin-Schrödinger – Str. 56, 67663 Kaiserslautern, Germany*

Willem L. Vos *Complex Photonic Systems (COPS), MESA+ Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE Enschede, the Netherlands*

Léon A. Woldering *Transducer Science and Technology (TST), MESA+ Institute for Nanotechnology, University of Twente, 7500 AE Enschede, the Netherlands*

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).

Cambridge University Press
978-1-107-03877-6 - Light Localisation and Lasing: Random and Quasi-Random Photonic Structures
Edited by M. Ghulinyan and L. Pavesi
Frontmatter
[More information](#)

xiv

Preface

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