



Wiley Series in Pure and Applied Optics • Glenn Boreman, Series Editor

NEMATICONS

Spatial Optical Solitons in Nematic Liquid Crystals

Edited by

GAETANO ASSANTO

 **WILEY**

Nematicons

Spatial Optical Solitons in Nematic Liquid Crystals

Edited by

GAETANO ASSANTO



 **WILEY**

A JOHN WILEY & SONS, INC., PUBLICATION

Copyright © 2013 by John Wiley & Sons, Inc. All rights reserved.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at <http://www.wiley.com/go/permission>.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at www.wiley.com.

Library of Congress Cataloging-in-Publication Data:

Nematicons : spatial optical solitons in nematic liquid crystals / [edited by]
Gaetano Assanto.

pages cm. – (Wiley series in pure and applied optics ; 74)

Includes bibliographical references.

ISBN 978-0-470-90724-5

1. Solitons. 2. Nematic liquid crystals. 3. Liquid crystals—Spectra. I.

Assanto, Gaetano, 1958-

QC174.26.W28N46 2012

530.12'4—dc23

2012010716

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Nematicons

WILEY SERIES IN PURE AND APPLIED OPTICS

Founded by Stanley S. Ballard, University of Florida

EDITOR: Glenn Boreman, University of Central Florida, CREOL & FPCE

A complete list of the titles in this series appears at the end of this volume.

To my parents

Preface

Solitons in physics and solitons in optics are well-established contemporary topics, addressed in a large number of scientific papers and several books. Spatial optical solitons form a specific class, as optics in space is characterized by diffraction rather than dispersion, beam size rather than pulse duration, one or two transverse dimensions rather than one in the temporal domain. For a long time, the available experimental observations of optical solitons in space were limited by the magnitude of the material nonlinearities, until molecular and photorefractive media allowed investigating them at low power and with continuous-wave sources, including incoherent ones. Among the well-known molecular dielectrics exhibiting a large optically nonlinear response were liquid crystals, typically employed in thin samples. It was realized in the early days of both nonlinear optics and liquid crystals that the reorientational response of nematic liquid crystals could lead to quite impressive effects, both in the electro-optic and all-optical domains. Later on, beam propagation over extended distances in nematic liquid crystals was exploited to demonstrate self-focusing and related phenomena, until it became clear that optical spatial solitons could be supported by such a response at the molecular level. I came across light self-localization in nematic liquid crystals during international meetings, where I attended the inspiring presentations by Prof. M. Karpierz (Poland) and Prof. M. Warenghem (France) on light self-confinement in nematic liquid crystals, and decided to get involved in research on nematons. The discussions with Prof. I. C. Khoo were enlightening and the collaboration with Prof. C. Umeton allowed the program to get started on the right foot. The term “nematicon” was actually coined during a car trip in Poland as I was having a conversation on the topic with M. Karpierz and G. I. Stegeman. The Greek root *νεματικός* means “filament-like” or “spaghetti-like,” appropriate to both the topic and the culinary culture of someone like me, of Italian birth and upbringing.

This is the first book specifically dealing with spatial optical solitons in nematic liquid crystals. It is a multiauthor contribution to the field and contains review as well as original (previously unpublished) material, from theoretical models to advanced numerical simulations and from experimental observations to applications. The various contributors and chapters have been selected and invited in order to cover most of the relevant activities in this field over the past 12 years.

G. ASSANTO

Italy
February 2012

Acknowledgments

Prof. Glenn Boreman and his wife, Maggie, friends since my PhD studies at the University of Arizona in Tucson, Arizona, encouraged me to consider preparing a Wiley book on nematicons. George Telecki soon joined them in keeping up the necessary pressure. Thanks a lot. I hope you were right and that readers will enjoy this book.

I thank all the authors who kindly accepted my invitation to contribute one or more chapters, and to subject themselves to a number of requests concerning contents, style, mode of presentation, and deadlines. I express my gratitude to all the students and colleagues who do not appear as book contributors but are coauthors of papers and precious actors inspiring various portions of the scientific activities. They include R. Asquini, R. Barboza, I. Burgess, O. Buchnev, G. Coschignano, D. Christodoulides, A. d'Alessandro, A. de Luca, R. Dabrowski, A. Dyadyusha, A. Fratalocchi, M. Kaczmarek, I. C. Khoo, M. Kwasny, L. Lucchetti, R. Morandotti, E. Nowinowski-Kruszelnicki, A. Pasquazi, K. A. Rutkowska, S. V. Serak, F. Simoni, G. I. Stegeman, N. Tabiryan, M. Trotta, and C. Umeton.

Finally, I pay a special tribute to Alessandro Alberucci and Armando Piccardi for greatly supporting me in the no less important task of arranging, organizing, managing, and editing the manuscript.

GA

Contributors

Alessandro Alberucci, Nonlinear Optics and OptoElectronics Lab, University ROMA TRE, Rome, Italy

Gaetano Assanto, Nonlinear Optics and OptoElectronics Lab, University ROMA TRE, Rome, Italy

Jeroen Beeckman, Department of Electronics and Information Systems, Ghent University, Ghent, Belgium

Milivoj R. Belić, Science Program, Texas A&M University at Qatar, Doha, Qatar

Jean-Francois Blach, Unité de Catalyse et de Chimie du Solide, Faculté des Sciences, Université d'Artois, Lens, France

Umberto Bortolozzo, INLN, Université de Nice-Sophia Antipolis, CNRS, Valbonne, France

Dongmei Deng, Laboratory of Nanophotonic Functional Materials and Devices, School of Information and Photoelectronic Science and Engineering, South China Normal University, Guangzhou, China

Anton S. Desyatnikov, Nonlinear Physics Centre, Research School of Physics and Engineering, The Australian National University, Canberra, ACT, Australia

Catherine García-Reimbert, Department of Mathematics and Mechanics, IIMAS, Fenomenos Nonlineales y Mecánica, Universidad Nacional Autónoma de México, Mexico D.F., Mexico

Qi Guo, Laboratory of Nanophotonic Functional Materials and Devices, School of Information and Photoelectronic Science and Engineering, South China Normal University, Guangzhou, China

Jean-Francois Henninot, Unité de Catalyse et de Chimie du Solide, Faculté des Sciences, Université d'Artois, Lens, France

Wei Hu, Laboratory of Nanophotonic Functional Materials and Devices, School of Information and Photoelectronic Science and Engineering, South China Normal University, Guangzhou, China

Yana V. Izdebskaya, Nonlinear Physics Centre, Research School of Physics and Engineering, The Australian National University, Canberra, ACT, Australia

Mirosław A. Karpierz, Warsaw University of Technology, Warsaw, Poland

Yuri S. Kivshar, Nonlinear Physics Centre, Research School of Physics and Engineering, The Australian National University, Canberra, ACT, Australia

Urszula A. Laudyn, Warsaw University of Technology, Warsaw, Poland

Daquan Lu, Laboratory of Nanophotonic Functional Materials and Devices, School of Information and Photoelectronic Science and Engineering, South China Normal University, Guangzhou, China

Tim R. Marchant, School of Mathematics and Applied Statistics, University of Wollongong, Wollongong, New South Wales, Australia

Antonmaria A. Minzoni, Department of Mathematics and Mechanics, IIMAS, Fenómenos No lineales y Mecánica, Universidad Nacional Autónoma de México, Mexico D.F., Mexico

Kristiaan Neyts, Department of Electronics and Information Systems, Ghent University, Ghent, Belgium

Shigen Ouyang, Laboratory of Nanophotonic Functional Materials and Devices, School of Information and Photoelectronic Science and Engineering, South China Normal University, Guangzhou, China

Marco Peccianti, Institute for Complex Systems, ISC-CNR, Rome, Italy

Armando Piccardi, Nonlinear Optics and OptoElectronics Lab, University ROMA TRE and CNISM, Rome, Italy

Stefania Residori, INLN, Université de Nice-Sophia Antipolis, CNRS, Valbonne, France

Katarzyna A. Rutkowska, Warsaw University of Technology, Warsaw, Poland

Luke W. Sciberras, School of Mathematics and Applied Statistics, University of Wollongong, Wollongong, New South Wales, Australia

Noel F. Smyth, School of Mathematics and Maxwell Institute for Mathematical Sciences, University of Edinburgh, Edinburgh, Scotland, United Kingdom

Marc Warenghem, Unité de Catalyse et de Chimie du Solide, Faculté des Sciences, Université d'Artois, Lens, France

Annette L. Worthy, School of Mathematics and Applied Statistics, University of Wollongong, Wollongong, New South Wales, Australia

Wei-Ping Zhong, Department of Electronic and Information Engineering, Shunde Polytechnic, Guangdong Province, Shunde, China

Contents

Preface	xv
Acknowledgments	xvii
Contributors	xix
Chapter 1. Nematicons	1
<i>Gaetano Assanto, Alessandro Alberucci, and Armando Piccardi</i>	
1.1 Introduction	1
1.1.1 Nematic Liquid Crystals	1
1.1.2 Nonlinear Optics and Solitons	3
1.1.3 Initial Results on Light Self-Focusing in Liquid Crystals	3
1.2 Models	4
1.2.1 Scalar Perturbative Model	5
1.2.2 Anisotropic Perturbative Model	9
1.3 Numerical Simulations	13
1.3.1 Nematicon Profile	13
1.3.2 Gaussian Input	14
1.4 Experimental Observations	17
1.4.1 Nematicon–Nematicon Interactions	22
1.4.2 Modulational Instability	26
1.5 Conclusions	31
References	33
Chapter 2. Features of Strongly Nonlocal Spatial Solitons	37
<i>Qi Guo, Wei Hu, Dongmei Deng, Daquan Lu, and Shigen Ouyang</i>	
2.1 Introduction	37
2.2 Phenomenological Theory of Strongly Nonlocal Spatial Solitons	38
2.2.1 The Nonlinearly Induced Refractive Index Change of Materials	38
2.2.2 From the Nonlocal Nonlinear Schrödinger Equation to the Snyder–Mitchell Model	39
2.2.3 An Accessible Soliton of the Snyder–Mitchell Model	42
2.2.4 Breather and Soliton Clusters of the Snyder–Mitchell Model	45
2.2.5 Complex-Variable-Function Gaussian Breathers and Solitons	46

2.2.6	Self-Induced Fractional Fourier Transform	47
2.3	Nonlocal Spatial Solitons in Nematic Liquid Crystals	49
2.3.1	Voltage-Controllable Characteristic Length of NLC	50
2.3.2	Nematicons as Strongly Nonlocal Spatial Solitons	52
2.3.3	Nematicon–Nematicon Interactions	54
2.4	Conclusion	61
	Appendix 2.A: Proof of the Equivalence of the Snyder–Mitchell Model (Eq. 2.16) and the Strongly Nonlocal Model (Eq. 2.11)	61
	Appendix 2.B: Perturbative Solution for a Single Soliton of the NNLSE (Eq. 2.4) in NLC	62
	References	66
Chapter 3.	Theoretical Approaches to Nonlinear Wave Evolution in Higher Dimensions	71
	<i>Antonmaria A. Minzoni and Noel F. Smyth</i>	
3.1	Simple Example of Multiple Scales Analysis	71
3.2	Survey of Perturbation Methods for Solitary Waves	77
3.3	Linearized Perturbation Theory for Nonlinear Schrödinger Equation	81
3.4	Modulation Theory: Nonlinear Schrödinger Equation	83
3.5	Radiation Loss	88
3.6	Solitary Waves in Nematic Liquid Crystals: Nematicons	91
3.7	Radiation Loss for The Nematicon Equations	96
3.8	Choice of Trial Function	101
3.9	Conclusions	105
	Appendix 3.A: Integrals	106
	Appendix 3.B: Shelf Radius	107
	References	108
Chapter 4.	Soliton Families in Strongly Nonlocal Media	111
	<i>Wei-Ping Zhong and Milivoj R. Belić</i>	
4.1	Introduction	111
4.2	Mathematical Models	112
4.2.1	General	112
4.2.2	Nonlocality Through Response Function	113
4.3	Soliton Families in Strongly Nonlocal Nonlinear Media	115
4.3.1	One-Dimensional Hermite–Gaussian Spatial Solitons	115
4.3.2	Two-Dimensional Laguerre–Gaussian Soliton Families	116
4.3.3	Accessible Solitons in the General Model of Beam Propagation in NLC	118
4.3.4	Two-Dimensional Self-Similar Hermite–Gaussian Spatial Solitons	125
4.3.5	Two-Dimensional Whittaker Solitons	126

4.4	Conclusions	133
	References	135
Chapter 5.	External Control of Nematicon Paths	139
	<i>Armando Piccardi, Alessandro Alberucci, and Gaetano Assanto</i>	
5.1	Introduction	139
5.2	Basic Equations	140
5.3	Nematicon Control with External Light Beams	142
5.3.1	Interaction with Circular Spots	143
5.3.2	Dielectric Interfaces	145
5.3.3	Comments	146
5.4	Voltage Control of Nematicon Walk-Off	147
5.4.1	Out-of-Plane Steering of Nematicons	147
5.4.2	In-Plane Steering of Nematicon	149
5.5	Voltage-Defined Interfaces	152
5.6	Conclusions	156
	References	156
Chapter 6.	Dynamics of Optical Solitons in Bias-Free Nematic Liquid Crystals	159
	<i>Yana V. Izdebskaya, Anton S. Desyatnikov, and Yuri S. Kivshar</i>	
6.1	Summary	159
6.2	Introduction	159
6.3	From One to Two Nematicons	160
6.4	Counter-Propagating Nematicons	162
6.5	Interaction of Nematicons with Curved Surfaces	165
6.6	Multimode Nematicon-Induced Waveguides	167
6.7	Dipole Azimuthons and Charge-Flipping	170
6.8	Conclusions	172
	References	173
Chapter 7.	Interaction of Nematicons and Nematicon Clusters	177
	<i>Catherine García-Reimbert, Antonmaria A. Minzoni, and Noel F. Smyth</i>	
7.1	Introduction	177
7.2	Gravitation of Nematicons	179
7.3	In-Plane Interaction of Two-Color Nematicons	184
7.4	Multidimensional Clusters	190
7.5	Vortex Cluster Interactions	199
7.6	Conclusions	205
	Appendix: Integrals	206
	References	206

Chapter 8. Nematicons in Light Valves	209
<i>Stefania Residori, Umberto Bortolozzo, Armando Piccardi, Alessandro Alberucci, and Gaetano Assanto</i>	
8.1 Introduction	209
8.2 Reorientational Kerr Effect and Soliton Formation in Nematic Liquid Crystals	210
8.2.1 Optically Induced Reorientational Nonlinearity	211
8.2.2 Spatial Solitons in Nematic Liquid Crystals	211
8.3 Liquid Crystal Light Valves	212
8.3.1 Cell Structure and Working Principle	213
8.3.2 Optical Addressing in Transverse Configurations	215
8.4 Spatial Solitons in Light Valves	216
8.4.1 Stable Nematicons: Self-Guided Propagation in the Longitudinal Direction	216
8.4.2 Tuning the Soliton Walk-Off	218
8.5 Soliton Propagation in 3D Anisotropic Media: Model and Experiment	220
8.5.1 Optical Control of Nematicon Trajectories	224
8.6 Soliton Gating and Switching by External Beams	224
8.7 Conclusions and Perspectives	227
References	229
 Chapter 9. Propagation of Light Confined via Thermo-Optical Effect in Nematic Liquid Crystals	 233
<i>Marc Warenghem, Jean-Francois Blach, and Jean-Francois Henninot</i>	
9.1 Introduction	233
9.2 First Observation in NLC	235
9.3 Characterization and Nonlocality Measurement	240
9.4 Thermal Versus Orientational Self-Waveguides	246
9.5 Applications	248
9.5.1 Bent Waveguide	248
9.5.2 Fluorescence Recovery	249
9.6 Conclusions	250
References	252
 Chapter 10. Discrete Light Propagation in Arrays of Liquid Crystalline Waveguides	 255
<i>Katarzyna A. Rutkowska, Gaetano Assanto, and Mirosław A. Karpierz</i>	
10.1 Introduction	255
10.2 Discrete Systems	256
10.3 Waveguide Arrays in Nematic Liquid Crystals	258

10.4	Discrete Diffraction and Discrete Solitons	263
10.5	Optical Multiband Vector Breathers	265
10.6	Nonlinear Angular Steering	267
10.7	Landau–Zener Tunneling	268
10.8	Bloch Oscillations	270
10.9	Conclusions	272
	References	273

Chapter 11. Power-Dependent Nematicon Self-Routing **279**

Alessandro Alberucci, Armando Piccardi, and Gaetano Assanto

11.1	Introduction	279
11.2	Nematicons: Governing Equations	280
11.2.1	Perturbative Regime	282
11.2.2	Highly Nonlinear Regime	284
11.2.3	Simplified (1 + 1)D Model in a Planar Cell	285
11.3	Single-Hump Nematicon Profiles	287
11.3.1	(2 + 1)D Complete Model	288
11.3.2	(1 + 1)D Simplified Model	289
11.4	Actual Experiments: Role of Losses	290
11.4.1	BPM (1 + 1)D Simulations	291
11.4.2	Experiments	292
11.5	Nematicon Self-Steering in Dye-Doped NLC	293
11.6	Boundary Effects	298
11.7	Nematicon Self-Steering Through Interaction with Linear Inhomogeneities	302
11.7.1	Interfaces: Goos-Hänchen Shift	303
11.7.2	Finite-Size Defects: Nematicon Self-Escape	304
11.8	Conclusions	305
	References	306

Chapter 12. Twisted and Chiral Nematicons **309**

Urszula A. Laudyn and Mirosław A. Karpierz

12.1	Introduction	309
12.2	Chiral and Twisted Nematics	310
12.3	Theoretical Model	312
12.4	Experimental Results	314
12.4.1	Nematicons in a Single Layer	314
12.4.2	Asymmetric Configuration	315
12.4.3	Multilayer Propagation	317
12.4.4	Influence of an External Electric Field	317
12.4.5	Guiding Light by Light	319
12.4.6	Nematicon Interaction	319

12.5	Discrete Diffraction	321
12.6	Conclusions	323
	References	323
Chapter 13.	Time Dependence of Spatial Solitons in Nematic Liquid Crystals	327
	<i>Jeroen Beeckman and Kristiaan Neyts</i>	
13.1	Introduction	327
13.2	Temporal Behavior of Different Nonlinearities and Governing Equations	328
13.2.1	Reorientational Nonlinearity	328
13.2.2	Thermal Nonlinearity	331
13.2.3	Other Nonlinearities	333
13.3	Formation of Reorientational Solitons	333
13.3.1	Bias Voltage Switching Time	334
13.3.2	Soliton Formation Time	336
13.3.3	Experimental Observation of Soliton Formation	337
13.3.4	Influence of Flow Effects	341
13.4	Conclusions	344
	References	344
Chapter 14.	Spatiotemporal Dynamics and Light Bullets in Nematic Liquid Crystals	347
	<i>Marco Peccianti</i>	
14.1	Introduction	347
14.1.1	$(2 + 1 + 1)$ D Nonlinear Wave Propagation in Kerr Media	348
14.2	Optical Propagation Under Multiple Nonlinear Contributions	349
14.2.1	Multiple Nonlinearities and Space–Time Decoupling of the Nonlinear Dynamics	349
14.2.2	Suitable Excitation Conditions	350
14.3	Accessible Light Bullets	351
14.3.1	From Nematicons to Spatiotemporal Solitons	351
14.3.2	Experimental Conditions for Accessible Bullets Observation	353
14.4	Temporal Modulation Instability in Nematicons	355
14.5	Soliton-Enhanced Frequency Conversion	355
14.6	Conclusions	357
	References	358
Chapter 15.	Vortices in Nematic Liquid Crystals	361
	<i>Antonmaria A. Minzoni, Luke W. Sciberras, Noel F. Smyth, and Annette L. Worthy</i>	
15.1	Introduction	361

15.2	Stabilization of Vortices in Nonlocal, Nonlinear Media	364
15.3	Vortex in a Bounded Cell	373
15.4	Stabilization of Vortices by Vortex–Beam Interaction	378
15.5	Azimuthally Dependent Vortices	382
15.6	Conclusions	387
	References	389
 Chapter 16. Dispersive Shock Waves in Reorientational and Other Optical Media		391
	<i>Tim R. Marchant</i>	
16.1	Introduction	391
16.2	Governing Equations and Modulational Instability	392
16.3	Existing Experimental and Numerical Results	394
16.4	Analytical Solutions for Defocusing Equations	396
16.5	Analytical Solutions for Focusing Equations	398
	16.5.1 The 1 + 1 Dimensional Semianalytical Soliton	400
	16.5.2 Uniform Soliton Theory	402
	16.5.3 Comparisons with Numerical Solutions	403
16.6	Conclusions	406
	References	407
 Index		411