CAMBRIDGE

Cambridge University Press & Assessment
978-0-521-51480-4 — Supercontinuum Generation in Optical Fibers
J. M. Dudley, J. R. Taylor
Frontmatter
More Information

SUPERCONTINUUM GENERATION IN OPTICAL FIBERS

The optical fiber based supercontinuum source has recently become a significant scientific and commercial success, with applications ranging from frequency comb production to advanced medical imaging. This unique book explains the theory of fiber supercontinuum broadening, describes the diverse operational regimes and indicates principal areas of applications, making it an indispensable guide for researchers and graduate students.

With contributions from major figures and groups who have pioneered research in this field, the book describes the historical development of the subject, provides a background to the associated nonlinear optical processes, treats the generation mechanisms from continuous wave to femtosecond pulse pump regimes and highlights several important applications. A full discussion of numerical methods and comprehensive computer code are also provided, enabling readers to confidently predict and model supercontinuum generation characteristics under realistic conditions.

J. M. DUDLEY is a Professor in the Département d'Optique P. M. Duffieux at the Université de Franche-Comté and CNRS research institute FEMTO-ST in Besançon, France. His research has spanned both experimental and theoretical nonlinear optics and photonics.

J. R. TAYLOR is a Professor in the Physics Department at Imperial College London. He has made contributions in various aspects of laser research, photonics, ultrafast processes, optical fibers and nonlinear optics.

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-0-521-51480-4 — Supercontinuum Generation in Optical Fibers
J. M. Dudley, J. R. Taylor
Frontmatter
More Information

SUPERCONTINUUM GENERATION IN OPTICAL FIBERS

Edited by

J. M. DUDLEY
Université de Franche-Comté

J. R. TAYLOR
Imperial College of Science, Technology and Medicine, London

CAMBRIDGE
UNIVERSITY PRESS

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE

Cambridge University Press & Assessment
978-0-521-51480-4 — Supercontinuum Generation in Optical Fibers
J. M. Dudley, J. R. Taylor
Frontmatter
More Information

Shaftesbury Road, Cambridge CB2 8EA, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India

103 Penang Road, #05–06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of Cambridge University Press & Assessment, a department of the University of Cambridge.

We share the University's mission to contribute to society through the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9780521514804

© Cambridge University Press & Assessment 2010

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 & Assessment.

First published 2010

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

ISBN 978-0-521-51480-4 Hardback

Cambridge University Press & Assessment 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.

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE

Cambridge University Press & Assessment
978-0-521-51480-4 — Supercontinuum Generation in Optical Fibers
J. M. Dudley, J. R. Taylor
Frontmatter
More Information

Contents

List of contributors *page* vii
Preface xi
1 Introduction and history 1
J. R. Taylor
2 Supercontinuum generation in microstructure fibers – a historical note 30
J. K. Ranka
3 Nonlinear fibre optics overview 32
J. C. Travers, M. H. Frosz and J. M. Dudley
4 Fibre supercontinuum generation overview 52
J. M. Dudley, G. Genty and S. Coen
5 Silica fibres for supercontinuum generation 62
J. C. Knight and W. J. Wadsworth
6 Supercontinuum generation and nonlinearity in soft glass fibres 82
Jonathan H. V. Price and David J. Richardson
7 Increasing the blue-shift of a picosecond pumped supercontinuum 119
M. H. Frosz, P. M. Moselund, P. D. Rasmussen, C. L. Thomsen and O. Bang
8 Continuous wave supercontinuum generation 142
J. C. Travers
9 Theory of supercontinuum and interaction of solitons with dispersive waves 178
D. V. Skryabin and A. V. Gorbach
10 Interaction of four-wave mixing and stimulated Raman scattering in optical fibers 199
S. Coen, S. G. Murdoch and F. Vanholsbeeck

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-0-521-51480-4 — Supercontinuum Generation in Optical Fibers
J. M. Dudley, J. R. Taylor
Frontmatter
More Information

11 Nonlinear optics in emerging waveguides: revised fundamentals and implications 226
S. Afshar V., M. Turner and T. M. Monro
12 Supercontinuum generation in dispersion-varying fibers 285
G. Genty
13 Supercontinuum generation in chalcogenide glass waveguides 306
Dong-Il Yeom, M. R. E. Lamont, B. Luther Davies and B. J. Eggleton
14 Supercontinuum generation for carrier-envelope phase stabilization of mode-locked lasers 334
S. T. Cundiff
15 Biophotonics applications of supercontinuum generation 349
C. Dunsby and P. M. W. French
16 Fiber sources of tailored supercontinuum in nonlinear microspectroscopy and imaging 373
A. M. Zheltikov
Index 399

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-0-521-51480-4 — Supercontinuum Generation in Optical Fibers
J. M. Dudley, J. R. Taylor
Frontmatter
More Information

Contributors

S. Afshar V.
Centre of Expertise in Photonics
School of Chemistry & Physics
University of Adelaide
Adelaide SA 5005
Australia

O. Bang
DTU Fotonik
Department of Photonics Engineering
Technical University of Denmark,
Ørsteds Plads 343
DK-2800 Kgs. Lyngby
Denmark

S. Coen
Department of Physics
University of Auckland
Private Bag 92019
Auckland
New Zealand

S. T. Cundiff
JILA
National Institute of Standards and Technology and University of Colorado
440 UCB
Boulder, CO 80309-0440
USA

J. M. Dudley
Laboratoire d'Optique P.M. Duffieux
Université de Franche-Comté
Institut FEMTO CNRS UMR 6174
Besançon
France

C. Dunsby
Physics Department and
Department of Histopathology,
Division of Investigative Science
Imperial College London
South Kensington Campus
London SW7 2AZ
United Kingdom

B. J. Eggleton
Centre for Ultrahigh-bandwidth Devices for Optical Systems (CUDOS)
School of Physics
University of Sydney
NSW 2006
Australia

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-0-521-51480-4 — Supercontinuum Generation in Optical Fibers
J. M. Dudley, J. R. Taylor
Frontmatter
More Information

P. M. W. French
Photonics Group
Physics Department
Imperial College London
South Kensington Campus
London SW7 2AZ
United Kingdom

M. H. Frosz
DTU Fotonik
Department of Photonics Engineering
Technical University of Denmark,
Ørsteds Plads 343
DK-2800 Kgs. Lyngby
Denmark

G. Genty
Optics Laboratory
Department of Physics
Tampere University of Technology
P.O. Box 692
FIN-33101 Tampere
Finland

A. V. Gorbach
Centre for Photonics and Photonic Materials
Department of Physics
University of Bath
Claverton Down
Bath BA2 7AY
United Kingdom

J. C. Knight
Centre for Photonics and
Photonic Materials
Department of Physics
University of Bath
Claverton Down
Bath BA2 7AY
United Kingdom

M. Lamont
Centre for Ultrahigh-bandwidth
Devices for Optical Systems
(CUDOS)
School of Physics
University of Sydney
NSW 2006
Australia

B. Luther Davies
Centre for Ultrahigh-bandwidth
Devices for Optical Systems
(CUDOS)
Laser Physics Centre
Australian National University
Canberra
ACT 0200
Australia

T. M. Monro
Centre of Expertise in Photonics
School of Chemistry & Physics
University of Adelaide
Adelaide SA 5005
Australia

P. M. Moselund
DTU Fotonik
Department of Photonics Engineering
Technical University of Denmark,
Ørsteds Plads 343
DK-2800 Kgs. Lyngby
Denmark

S. G. Murdoch
Department of Physics
University of Auckland
Private Bag 92019
Auckland
New Zealand

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-0-521-51480-4 — Supercontinuum Generation in Optical Fibers
J. M. Dudley, J. R. Taylor
Frontmatter
More Information

J. H. V. Price
Optoelectronics Research Centre
University of Southampton
Southampton SO17 1BJ
United Kingdom

J. K. Ranka
Lincoln Laboratory
Massachusetts Institute of Technology
244 Wood Street
Lexington, MA 02420
USA

P. D. Rasmussen
DTU Fotonik
Department of Photonics Engineering
Technical University of Denmark,
Ørsteds Plads 343
DK-2800 Kgs. Lyngby
Denmark

D. J. Richardson
Optoelectronics Research Centre
University of Southampton
Southampton SO17 1BJ
United Kingdom

D. V. Skryabin
Centre for Photonics and
Photonic Materials
Department of Physics
University of Bath
Claverton Down
Bath BA2 7AY
United Kingdom

J. R. Taylor
Femtosecond Optics Group
Photonics, Blackett Laboratory
Imperial College London
Prince Consort Road
London SW7 2BW
United Kingdom

C. L. Thomsen
NKT Photonics A/S
Blokken 84
DK-3460 Birkerød
Denmark

J. C. Travers
Femtosecond Optics Group
Photonics, Blackett Laboratory
Imperial College London
Prince Consort Road
London SW7 2BW
United Kingdom

M. D. Turner
Centre of Expertise in Photonics
School of Chemistry & Physics
University of Adelaide
Adelaide SA 5005
Australia

F. Vanholsbeeck
Department of Physics
University of Auckland
Private Bag 92019
Auckland
New Zealand

W. J. Wadsworth
Centre for Photonics and
Photonic Materials
Department of Physics
University of Bath
Claverton Down
Bath BA2 7AY
United Kingdom

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-0-521-51480-4 — Supercontinuum Generation in Optical Fibers
J. M. Dudley, J. R. Taylor
Frontmatter
More Information

D. I. Yeom
Division of Energy Systems Research
Ajou University
San5 Wonchun-dong, Yeongtong-gu
Suwon, 443-749
Korea

A. M. Zheltikov
Physics Department
International Laser Center
M. V. Lomonosov Moscow State University
Vorob'evy gory, 119992 Moscow
Russian Federation

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-0-521-51480-4 — Supercontinuum Generation in Optical Fibers
J. M. Dudley, J. R. Taylor
Frontmatter
More Information

Preface

Spectral broadening and the generation of new frequency components is an inherent feature of nonlinear optics, and has been studied in both bulk media and optical fiber waveguides since the 1960s. However, it was not until the early 1970s that the mechanism was widely applied to provide an extended "white-light" source for time resolved spectroscopy, which was later coined "a supercontinuum" by the Alfano group. Subsequent developments in the late 1970s in low-loss optical fibers with conventional structures for telecommunications led to the introduction of fiber as an ideal platform for supercontinuum generation. At the same time, the development of optical soliton physics throughout the late 1980s and early 1990s laid the theoretical foundation and established all the experimental mechanisms required for the production of this versatile source. Despite this progress, however, extensive laboratory deployment remained inhibited by unwieldy pump sources and unreliable system integration.

The advent of photonic crystal fiber in the late 1990s, together with developments in efficient high power and short pulse fiber lasers, fuelled a revolution in the generation of ultrabroadband high brightness optical spectra through the process of supercontinuum generation. Experiments using photonic crystal fiber in 1999–2000 attracted widespread interest and excitement because of the combination of high power, high coherence and the possibility to generate spectra spanning more than an octave. Moreover, the design freedom of photonic crystal fiber allowed supercontinuum generation to be optimized to the wider range of available pump sources, and experiments reported broadband spectra covering the complete window of transmission of silica based fiber using input pulses with durations ranging from several nanoseconds to several tens of femtoseconds, as well as high power continuous wave sources. Supercontinuum generation in PCF was rapidly applied to a range of fields including optical coherence tomography, spectroscopy, and optical frequency metrology and, indeed, this latter result was explicitly cited in the award of the 2005 Nobel Prize in physics.

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-0-521-51480-4 — Supercontinuum Generation in Optical Fibers
J. M. Dudley, J. R. Taylor
Frontmatter
More Information

These results have since led to a huge research effort studying nonlinear spectral broadening in PCF, and have also renewed interest in similar nonlinear phenomena in standard optical fiber. Recent results have provided new insight into the spectral broadening mechanisms, tailored supercontinuum properties to specific applications, and extended supercontinuum generation into new fibers and waveguides using engineered dispersion profiles and/or non-silica materials. Improvements in numerical modeling techniques have also led to remarkable agreement between theoretical prediction and experimental realization.

This progress has of course been well documented in the archival literature, but researchers are now facing the problem that there is no single resource that explains the physics of fiber supercontinuum generation, describes the important properties of new fibers and waveguides, and outlines the features of supercontinuum generation relevant to specific applications. Our aim with this book is to address this problem explicitly through a series of invited papers written by experts familiar with all aspects of this field: the fundamentals and recent developments in supercontinuum generation physics, the different possibilities raised by the availability of new fibers and materials; and the diverse applications where supercontinuum sources can be used.

The book begins with two chapters describing the historical development of the field preceding a concise introduction to nonlinear fiber optics and the numerical modeling of supercontinuum generation. This is followed by a chapter providing an overview of the fiber supercontinuum generation processes under a wide range of conditions. These first four introductory chapters are aimed to ensure that the book is self-contained and accessible to advanced undergraduates and beginning doctoral students requiring a broad introduction to the field. The most significant technical content of the book appears in the subsequent chapters where various aspects of fiber waveguide properties and fiber supercontinuum processes are described in detail by researchers who have been responsible for seminal contributions to the field.

At this point it is perhaps appropriate to add a short word about citing the work in this book. Books and monographs sometimes develop the tendency to become general references that are cited in lieu of the original literature. Whilst this can sometimes be useful, it can also sometimes be detrimental in hiding the contributions of primary journal papers and the original authors. As a solution to this problem, we wish to suggest that readers please take due care that they do not forget to cite the primary literature where appropriate. When material is described both in the primary literature and in this book, there is of course the possibility to cite both.

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-0-521-51480-4 — Supercontinuum Generation in Optical Fibers
J. M. Dudley, J. R. Taylor
Frontmatter
More Information

In closing, we wish to say that we have been very fortunate in being able to include chapters from pioneering and leading research groups from across the world, and we are very grateful to all contributors for their agreement, their effort and their patience. We hope that this book and the excellent contributions that we have been lucky enough to solicit from our colleagues will allow professionals to develop their research even further, and students to enter this field more effectively.

© in this web service Cambridge University Press & Assessment www.cambridge.org