

Microstructured Polymer Optical Fibres

Maryanne C. J. Large • Leon Poladian
Geoff W. Barton • Martijn A. van Eijkelenborg

Microstructured Polymer Optical Fibres

 Springer

Maryanne C. J. Large
University of Sydney
School of Physics
Sydney NSW 2006
Australia

Leon Poladian
University of Sydney
School of Mathematics and Statistics
Sydney NSW 2006
Australia

Geoff W. Barton
University of Sydney
Department of Chemical
and Biomolecular Engineering
Sydney NSW 2006
Australia

Martijn A. van Eijkelenborg
University of Sydney
Optical Fibre Technology Centre
206 National Innovation Centre
Eveleigh NSW 1430
Australia

Library of Congress Control Number: 2007930766

ISBN 978-0-387-31273-6

e-ISBN 978-0-387-68617-2

© 2008 Springer Science+ Business Media, LLC

All rights reserved. This work may not be translated or copied in whole or in part without the written permission of the publisher (Springer Science+ Business Media, LLC, 233 Spring Street, New York, NY 10013, USA), except for brief excerpts in connection with reviews or scholarly analysis. Use in connection with any form of information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed is forbidden.

The use in this publication of trade names, trademarks, service marks, and similar terms, even if they are not identified as such, is not to be taken as an expression of opinion as to whether or not they are subject to proprietary rights.

9 8 7 6 5 4 3 2 1

springer.com

The work presented in this book is the culmination of six years work at the Optical Fibre Technology Centre, where all of the authors have been based at one time or another. While most of us have ended up in other departments, we would like to acknowledge the role the OFTC played in making this work possible. It has been an extraordinary place to work.

Preface

This book is intended to provide a concise and accessible introduction to microstructured polymer optical fibres (mPOF). Authors of books in any technical field need to make decisions about just how technical the explanations should be, and we have taken the view that this book should be accessible not only to academics but also, for example, to engineers who may wonder if mPOF have anything to offer for their applications, or interested undergraduate students. We have therefore aimed at conveying a correct conceptual understanding of the ideas in the clearest possible way. Even within the theoretical sections of the book we have tried to avoid using equations as the explanation of first resort. Indeed, often the same idea is explained in multiple ways, first at a very conceptual level and then later in the book in more detail. However, correctness is never sacrificed to achieve simplicity. Fuller and more technical explanations can be found in the referenced scientific literature, and or in one of the several other books available in the general area of microstructured fibres.

Much of the material in this book applies to microstructured fibres made from any material, such as the explanations of how the fibres work, much of the fabrication, the modelling techniques and some of the characterisation techniques and applications. However the book is primarily about mPOF. The community working in silica microstructured fibres (more commonly known as “Photonic crystal fibres” or PCF) is much more extensive than that working in polymers, and many of the applications they have explored have not been attempted in mPOF, and in some cases are unsuitable for them. But while mPOF is a younger technology, it also extends the scope of microstructured fibres in important ways. The large suite of fabrication techniques available in polymers mean not only that the fibres can be mass produced, but also make it much easier to produce different hole structures. In silica, most microstructured fibres use the “stack and draw” technique, where a preform is constructed by stacking capillaries and rods, which is then drawn to fibre. This technique, while versatile in many ways, restricts the types of structures that can be made. By contrast, mPOFs can and have been made with a

wide variety of hole arrangements. In addition, many of the applications that are targeted in polymers require thick multimode fibres, often with extremely large cores, while PCFs are usually single or few-moded and are no longer flexible at large diameters. Finally, the material properties of polymer are very different to those of silica, and they can be modified in many more ways, not only by doping, but also by, for example, co-polymerisation or the attachment of other active groups. The area of material modification (the topic of Chapter 11) has not been treated extensively in the book primarily because little work has been done in this area. One of our intentions in writing this book is to stimulate interest in the field, and a greater involvement of chemists and material scientists would be very welcome, though we add as a caveat that any new materials used should remain drawable and preferably also highly transparent.

The book is conceptually, though not formally divided into two parts. We have tried to make each chapter relatively self contained, to make it easier to extract the information quickly without extensive cross-referencing.

In the first part of the book we introduce the ideas behind microstructured fibres. A history and description of both polymer fibres (POFs) and microstructured optical fibres (MOFs) is given in Chapter 1. Chapter 2 focusses on the basic concepts of waveguide theory, while Chapter 3, shows how the properties of microstructured fibres differ from those of conventional fibres. One of the challenges posed by the wealth of new and potentially complex designs enabled by microstructured fibres has been to be able to understand the effect of the fibre geometry on the optical properties. The modelling of microstructured fibres in Chapter 4 compares the mathematical approaches that have been used to model microstructured fibres, and extends them to include approaches to design. The range of fabrication methods available to mPOF fabrication is presented in Chapter 5 along with a discussion of the control of hole deformation in Chapter 6. The first part of the book concludes with a chapter on how to prepare mPOF for experiments and an outline of the most common characterisation techniques in Chapter 7.

In the second part of the book we describe a number of applications that use mPOF. The applications we have chosen are not comprehensive. We have restricted ourselves to those where the results are more than preliminary, or where the applications illustrate important new capabilities of the fibres. In particular, we aim to show how the physical principles explained in the first part of the book can be made technologically useful. Where possible we have also tried to bench-mark the performance against conventional polymer fibres where appropriate. The first two applications use microstructures by themselves to achieve their effects, while the last two applications describe modifications to the fibre by post-processing or doping.

Chapter 8 presents work on Hollow-Core mPOF (HC-mPOF), which is particularly significant as it allows guidance of wavelengths where the polymer is not considered transparent and in addition it provides a new route to beating the lowest-loss record for conventional polymer fibre. Chapter 9,

which presents a Graded Index Microstructured Polymer Optical Fibre for large-core high-bandwidth FTTH applications. In Chapter 10 the fabrication and characterisation of Bragg and Long Period Gratings in mPOF is described. Chapter 11 outlines various doping methods that specifically use the hole structure to introduce organic dyes and nanoparticles into mPOFs.

The area of microstructured polymer optical fibres is developing very rapidly, and many of the results presented here will date quickly. While the authors optimistically anticipate many further editions of this book, the delay implicit in any publication can be considerable. To address this, we have established a website where the latest results will be posted, together with additional material such as animations, publications for downloading and relevant news items. The web address is: www.mpof.net.au.

Acknowledgments

The work presented in this book originates from many different mPOF research projects over the last six years and material is included that was the result of working with research students and collaborators, both Australian and international.

Firstly, and most importantly, we would like to express our sincere thanks to Joseph Zagari, Alex Argyros, Steve Manos and Nader Issa for their work as part of their postgraduate research at the Optical Fibre Technology Centre (OFTC) of the University of Sydney. They contributed a large fraction of the results presented throughout this book and without their contributions and enthusiasm this book would have been very much thinner. We also thank our current postgraduate students: Felicity Cox, Richard Lwin and Helmut Yu who are so critical to the ongoing work of our group. Mark Hiscocks, Matt Fellow, Trungta Keawfanapadol and Hong Nguyen also made contributions during the course of projects at the OFTC.

Particular thanks are due to Barry Reed, who has made almost all of our fibre preforms over the last six years, as well as many custom-designed pieces of equipment. His attention to detail, and his pride in his work are very much appreciated.

Steve Manos prepared the vast majority of the figures for the book, a task that involved running numerous simulations as well as doing the graphics. A number of other figures were adapted from publications by Nader Issa, Alex Argyros and Richard Lwin. We also thank Richard Lwin, Helmut Yu, and the Australian Key Centre for Microscopy and Microanalysis at the University of Sydney for the electron microscope images and technical assistance.

More generally, we would like to thank our colleagues at the OFTC. Ian Bassett, Geoff Henry, Sue Law and Wayne Padden contributed directly to work presented here, both as colleagues and as friends. Simon Fleming, Ron Bailey and Peter Henry provided advice and support at critical times. Shicheng Xue and Roger Tanner from the the School of Aerospace, Mechanical and Mechatronic Engineering at the University of Sydney have been long-term colleagues, and their insights into the rheology of the draw process have been extremely important. We have also benefited from the expertise

of Ross McPhedran, Martijn de Sterke and Nicolae Nicorovici, at the School of Physics, particularly during the early stages of our work.

We would like to thank Christophe Barbé and Kim Finnie of the Materials Division at the Australian Nuclear Science and Technology Organisation (ANSTO) for advice, discussions and instructions on the fabrication of nanoparticles.

We also thank Francois Ladouceur at the University of New South Wales for his contributions to the work on nanoparticles and in establishing the mPOF draw tower facility. He has been a stimulating collaborator in various roles since the beginning of the mPOF development.

Tanya Monro and Heike Ebendorff-Heidepriem at the University of Adelaide were responsible for developing billet extrusion for mPOF preforms, and their expertise in this area was extremely helpful.

Karl-Friedrich Klein of the University of Applied Sciences of Friedberg, and Alexander Bachmann and Hans Poisel of the Polymer Optical Fiber Application Centre, both in Germany, have characterised many of our fibres. They could not have been more helpful in trying to unravel the behaviour of the high bandwidth fibres.

Tim Birks, Jonathan Knight and Philip Russell at the University of Bath in England are thanked for collaborations, enlightening arguments, and their willingness to share their expertise and data.

We thank David Webb, Helen Dobb and Karen Carroll at Aston University in the UK for their help with writing gratings in our fibres.

John Harvey, David Hirst and Laura Harvey at the University of Auckland in New Zealand have assisted us in many ways, particularly in the development of cleaving and measurement techniques.

Lili Wang and her colleagues at the Xi'an Institute of Optics and Precision Mechanics in China are thanked for providing us with preforms made by a variety of techniques.

Many people read and helped with the preparation of this manuscript. We would like to particularly thank the several long-suffering people who innocently expressed an interest in our work, only to be landed with a manuscript of this book for comment. The thoughtful suggestions and careful proof-reading of John Love, Roger Tanner, Rod Vance, Haida Liang, Cristiano Cordeiro and Boris Kuhlmeier were very much appreciated. Further thanks are due also due to our colleagues for their patience in reading various drafts, especially Alex Argyros.

We would also like to thank Maksim Skorobogatiy from the *École Polytechnique de Montréal* for material on the all-polymer Bragg fibres.

Financial support for the research described in this book was provided by a number of sources. We gratefully acknowledge the Australian Research Council, the New Zealand Foundation for Research Science and Technology, the Australian Photonics Cooperative Research Centre, The Australian Academy of Technological Sciences and Engineering and the Bandwidth Foundry Pty Ltd - the latter being a Major National Research Facility supported by the Australian and New South Wales Governments.

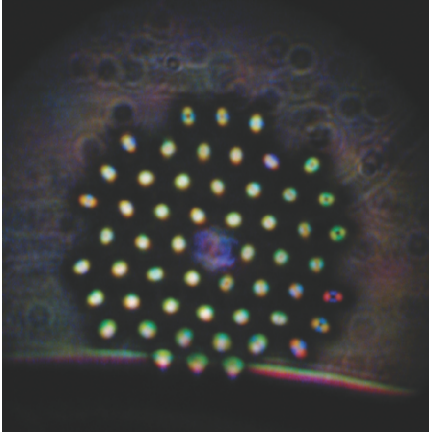


Figure 3.4: A low contrast photonic bandgap fibre shows the interaction of rod and core modes. The wavelengths of light in the core correspond to bandgaps in the cladding structure.

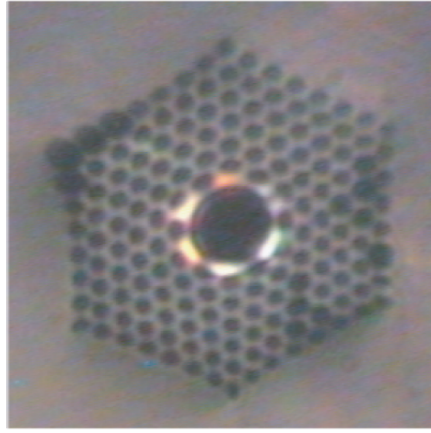


Figure 8.7: The solid region surrounding the core of a hollow core fibre can support modes, as shown here, which can couple light out of the core.

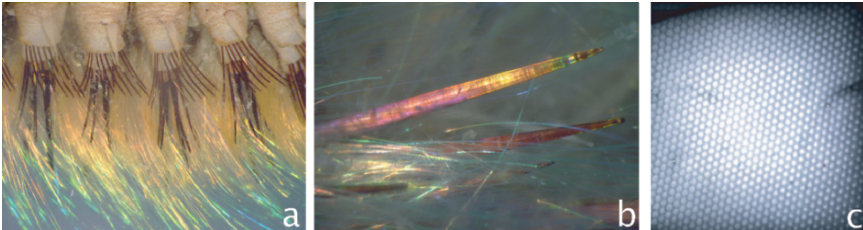


Figure 3.5: Photonic bandgap effects seen in the spines of a seamouse (a) and (b) and a cross-section through a spine showing the microstructure (c).

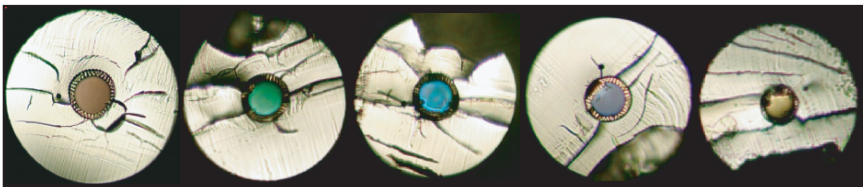


Figure 8.5: Different colours guided in the hollow core of a bandgap fibre drawn to different diameters, changing through red, green, blue, blue-violet and yellow (= red + green) as the structure size decreases.

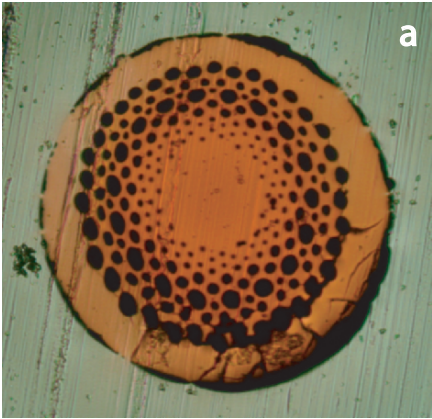


Figure 11.2: (a) Cross-section of a doped mPOF. Orange coloured parts are Rhodamine doped.

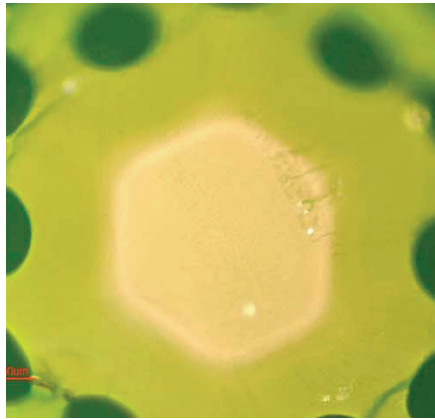


Figure 11.3: Cross-section of a pre-form prior to the dopant diffusion fronts meeting at the core. The green is the fluorescence of the dye.

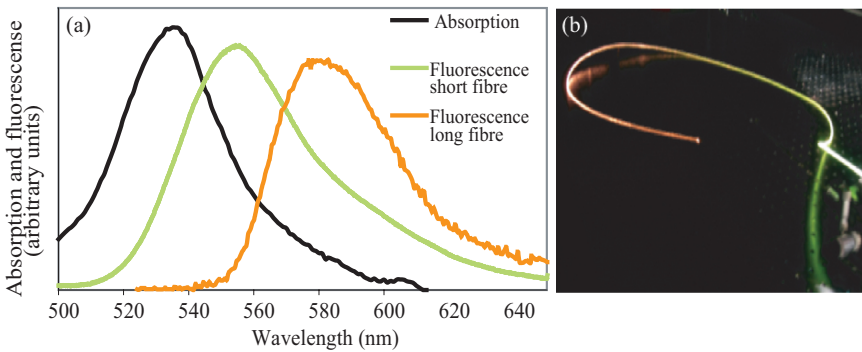


Figure 11.5: (a) The absorption spectrum of the Rhodamine 6G dye and two fluorescence spectra corresponding to short (a few mm) and long (2 m) fibres. (b) Photograph illustrating the re-absorption process.

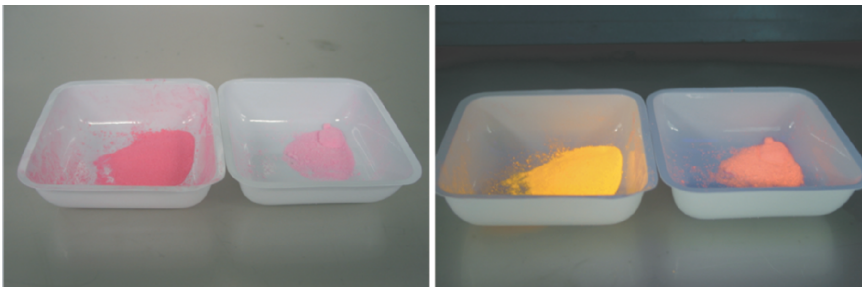


Figure 11.7: Silica nanoparticles containing R6G and Rhodamine B and their appearance under normal light and UV light.

Contents

Preface	vii
Colour Plates	xiii
List of Figures	xix
List of Tables	xxiii
List of Symbols and Acronyms	xxv
1 History and Applications of Polymer Fibres and Microstructured Fibres	1
1.1 Early Stages Of Polymer Fibre Development	1
1.2 Fabrication Considerations For Optical Fibres	3
1.3 Index Contrast Between Core And Cladding	6
1.4 Physical Properties Of Polymers	7
1.5 Current Applications Of Conventional Polymer Fibres	8
1.5.1 Illumination	8
1.5.2 Sensing	8
1.5.3 High Speed Data Transmission	8
1.6 History And Overview Of Microstructured Fibres	10
References	16
2 Concepts in Waveguide Theory	21
2.1 Modes	21
2.1.1 Degeneracy, Polarisation And Birefringence	22
2.1.2 Weak Guidance	24
2.1.3 Counting Modes	24
2.1.4 Effective Indices And Cutoff	26
2.2 Coupling Light In And Out	27
2.2.1 Numerical Aperture	28
2.2.2 Mode Field Diameter Or Spot Size	29

2.3	Bandwidth And Dispersion	30
2.3.1	Intra- And Inter-Modal Dispersion	31
2.3.2	Group Velocity And Chromatic Dispersion	32
2.4	Power Mixing In Multimode Fibres	32
2.4.1	Equilibrium	33
2.4.2	Over- And Under-Filled Launch Conditions	34
2.5	Conventional Guidance Mechanisms	35
	References	37
3	Guiding Concepts in Microstructured Fibres	39
3.1	Photonic Bandgap Guidance	39
3.2	Confinement Loss	45
3.2.1	Counting Modes In Microstructured Fibres	46
3.2.2	Endlessly Single-Mode Fibre	48
3.3	Manipulating Dispersion	49
	References	50
4	The Modelling and Design of mPOFs	53
4.1	Nomenclature	54
4.2	Algorithms	57
4.2.1	Conventional Approaches	57
4.2.2	Nonconventional Approaches	59
4.2.3	Available Software	63
4.3	Power Mixing Theory	63
4.3.1	Deterministic and Stochastic Coupling	64
4.3.2	Comparing Two Common Perturbations	66
4.3.3	Equilibrium Length And Power Distribution	67
4.4	Example Designs For Various Fibre Attributes	68
4.4.1	Mode Number And Spacing	68
4.4.2	Capture And Coupling Efficiency	69
4.4.3	Mode Profile	69
4.4.4	Dispersion	71
4.4.5	Polarisation	72
4.5	Automated Design	73
	References	77
5	Fabrication of mPOFs	83
5.1	Preform Production	84
5.1.1	Bragg Preforms	84
5.1.2	Capillary Stacking	84
5.1.3	Drilling Monolithic Preforms	86
5.1.4	Extrusion	89
5.1.5	Injection Moulding	91
5.1.6	Casting	92
5.2	Fibre Drawing And Furnace Design	94
5.2.1	Convective Heat Transfer	95

5.2.2	Radiative Heat Transfer	99
5.2.3	Monitoring And Control	102
5.3	Quality Of Fabricated MPOF	103
5.3.1	Material	103
5.3.2	Structure	104
	References	106
6	Effects of Drawing on the Microstructure	111
6.1	Scaling Analysis For Fibre Drawing	111
6.2	Isothermal Analysis Of Hole Deformation	115
6.2.1	Hole-Size Changes	115
6.2.2	Hole-Shape Changes	117
6.2.3	Approximate Analysis Of Hole Behaviour	120
6.3	Nonisothermal Analysis Of Hole Deformation	121
6.3.1	Convective Heat Transfer	122
6.3.2	Radiative Heat Transfer	125
6.3.3	Pressure Modified Hole Deformation	126
	References	128
7	The Handling and Characterisation of mPOFs	131
7.1	Cutting And Handling	131
7.1.1	Melt Cutting	131
7.1.2	Laser Cutting	132
7.1.3	Hot-Knife Cutting	133
7.2	Fibre Characterisation	136
7.2.1	Structural Characterisation	136
7.2.2	Single- And Multimode Guiding	137
7.2.3	Near- And Far-Fields	138
7.2.4	Numerical Aperture	140
7.2.5	Transmission Loss	141
7.2.6	Bandwidth	148
7.2.7	Birefringence	152
	References	158
8	Hollow-Core mPOF	165
8.1	Introduction	165
8.2	Fabrication	166
8.3	Transmission Properties	168
8.4	Issues Affecting The Performance Of Bandgap Fibres	171
8.4.1	Importance of structural dimensions	171
8.4.2	Role Of Surface Modes	171
8.4.3	Ultimate Loss Limits For Hollow-Core MPOF	172
8.5	Applications Of Photonic Bandgap Fibres	176
8.6	Challenges And Future Directions	176
	References	177

9	Graded-Index mPOFs	181
9.1	Material Dispersion	181
9.2	Intermodal Dispersion	183
9.3	The Effect of the Graded-Index Microstructure	183
9.4	Experimental Characterisation Of GImPOFs	188
9.5	Challenges And Future Directions	189
	References	190
10	Bragg and Long Period Gratings in mPOF	193
10.1	Introduction	193
10.2	Fibre Bragg Gratings	197
10.2.1	FBGs In Microstructured Fibres	197
10.2.2	FBGs In Polymer Fibres	197
10.2.3	FBGs In Microstructured Polymer Fibres	198
10.3	Long Period Gratings	202
10.3.1	LPG In Microstructured Fibres	202
10.3.2	LPGs In Polymer Fibres	203
10.4	Challenges And Future Directions	207
	References	208
11	Material Additives for mPOF	213
11.1	Introduction	213
11.2	Doping Methods	216
11.2.1	Solution Doping	216
11.2.2	Nanoparticle Doping	220
11.3	Fluorescence Measurements	221
11.4	An MPOF Amplifier And Laser	222
11.5	Challenges And Future Directions	225
	References	225
	Index	229

List of Figures

1.1	Material loss in silica, CYTOP and PMMA	3
1.2	Transmission in PMMA-based POF	4
1.3	Historical development of PMMA-based POF	5
1.4	Endlessly single-mode fibre	11
1.5	Spectra of Bragg fibres	13
1.6	Bragg, ring-structured and photonic bandgap fibres	13
1.7	Air-guiding fibre	14
1.8	A graded-index mPOF	15
2.1	Transverse modes for bound, radiation and leaky modes	23
2.2	V parameter for graded-index fibres	25
2.3	Effective indices and mode cutoff	28
2.4	Geometric optics and numerical aperture	29
2.5	Equilibrium, under-filled and over-filled power distributions	33
2.6	Pulse distortion due to intermodal dispersion	35
2.7	Guidance by total internal reflection	36
3.1	Bragg reflection in multilayer stacks	40
3.2	Photonic bandgap fibre cladding	40
3.3	Formation of bandgaps	42
3.4	Low contrast photonic bandgap fibre	43
3.5	Photonic bandgaps in seamouse spines	44
3.6	Reflectance mechanisms in Bragg fibres	44
3.7	Confinement of fundamental mode in a MOF	46
3.8	Confinement loss of a single-mode microstructured fibre	47
3.9	Wavelength dependence of effective cladding index	48
3.10	Material dispersion of PMMA and silica	50
4.1	Transverse polarisation for some common mode types	55
4.2	Equilibrium length and power distribution	67
4.3	Geometric birefringence	73

5.1	Examples of all-polymer Bragg preforms and fibres.	84
5.2	Stacked-capillary silica preforms.	85
5.3	Scaffold-structure silica preform.	86
5.4	Stacked-capillary polymer preform.	87
5.5	Drilled polymer preforms.	87
5.6	Graded-index mPOF preform and fibre.	88
5.7	Extruded polymer preforms.	90
5.8	Moulds for casting polymer preforms.	93
5.9	An mPOF preform neck-down region.	95
5.10	Options for drawing an mPOF preform to fibre.	96
5.11	Schematic diagram of an mPOF draw tower.	97
5.12	Temperature profile of a long furnace.	98
5.13	Diagram of a convective heating furnace.	99
5.14	Temperature profile of a short furnace.	100
5.15	Polymer draw tower with a radiative furnace.	101
5.16	Draw tension, speed and fibre diameter during a draw.	105
6.1	Collapse ratio versus capillary number at $\chi = 0.2$	116
6.2	Collapse ratio versus capillary number at $\chi = 0.5$	117
6.3	Hole deformation in drawing cane and fibre	118
6.4	Cross-sections of two PMMA mPOFs	119
6.5	Capillary number versus temperature for PMMA and silica	121
6.6	Radial temperature profiles across PMMA preforms	123
6.7	Preform temperature profiles versus Biot number	125
6.8	Shape of the neck-down for different thermal conditions	126
6.9	MPOF drawn from convective and radiative furnaces	126
6.10	Impact of internal pressurisation on hole structure	127
7.1	Melt-cut surface tomography	132
7.2	Automated mPOF cutter	133
7.3	SEM image of a ‘good’ cut	134
7.4	Optical vs. SEM images of GI mPOF	137
7.5	SEM images of a rectangular core mPOF	139
7.6	Measured near- and far-field intensity distributions	139
7.7	Measuring numerical apertures	141
7.8	SEM of circular-core mPOF	141
7.9	Measured NA versus wavelength	142
7.10	Transmission loss for GI mPOF	145
7.11	Loss versus outer diameter	146
7.12	Loss spectrum of a low-loss mPOF	147
7.13	History of mPOF loss	147
7.14	Output fields of Mitsubishi GK40 POF	149
7.15	Multi-mode fibre bandwidth characterisation	150
7.16	Variable and fixed aperture launch units	151
7.17	Transmission pulses of a DMD measurement	152

7.18	Hole pattern in a birefringent PMMA preform and fibre	154
7.19	SEM image of inner rings of elliptical holes	155
7.20	Spectrum for birefringence measurements	156
7.21	Measured and numerically calculated birefringence	157
8.1	Material absorption spectrum of PMMA	166
8.2	Drilled Bragg preform and extender for pressurisation	167
8.3	Bragg structured Bandgap mPOFs	167
8.4	Cane and fibre drawn from capillary-stacked preforms	168
8.5	Bandgap mPOF transmission spectra	169
8.6	Bandgap mPOF loss spectrum	170
8.7	A surface mode in a bandgap mPOF	172
8.8	Schematic diagram of surface modes	173
8.9	Interpenetrating fingers at core-cladding interface	173
8.10	Effect of core size of loss of HC-MOF	174
8.11	Loss projections for bandgap mPOF	175
9.1	Source linewidth and maximum bandwidth	182
9.2	Microstructured and azimuthally-averaged GI profiles	184
9.3	Cutoff behaviour of 135 micron core GI mPOF	185
9.4	Phase and group index for GI profiles	186
9.5	Mode profiles of the four modes identified in Fig. 9.3.	187
9.6	Four manufactured GI mPOFs	188
10.1	Schematic of a fibre grating	194
10.2	Grating features	195
10.3	Set-up for Bragg grating writing	199
10.4	Grating growth	200
10.5	Grating reflection spectra	200
10.6	Confinement loss and spectral peaks	201
10.7	Effect of strain on gratings	202
10.8	Setup for the imprinting of LPGs in mPOF	204
10.9	Spectra of mechanically induced gratings	204
10.10	Spectrum of heat imprinted LPG	205
10.11	Grating aging tests	206
10.12	Grating resonances	207
11.1	Diffusion of dye and solvent fronts through PMMA	215
11.2	Cross section of R6G doped GI mPOF	217
11.3	The effects of heating on dopant diffusion	217
11.4	Loss comparison between doped and undoped mPOF	218
11.5	Fluorescence spectra of R6G doped mPOF	219
11.6	The effects of heating on dopant diffusion using acetone	220
11.7	SEM images of silica nanoparticles	221
11.8	Fluorescence spectra of nanoparticle-doped mPOF	222

11.9 Images of a large-core mPOF for amplification	223
11.10 Schematic of the setup for gain measurements	223
11.11 Gain versus wavelength and pump energy	224
11.12 Spectra of fluorescence, ASE and lasing in mPOF	224

List of Tables

1.1	A comparison of material properties for PMMA and silica.....	7
1.2	New IEC SC86A standard for graded-index POF.	10
4.1	<i>HE</i> and <i>EH</i> modes	56
4.2	Correspondences between scalar and vector modes	56
4.3	Algorithms for leaky boundary conditions	60
4.4	Software for modelling MOF	64
5.1	Fibre diameters for two different draw systems	97
5.2	Measured bulk material loss for three types of PMMA rod. Loss is quoted at a wavelength of 633 nm.	104
5.3	Hole dimensions during hole collapse	105
6.1	Representative microstructured fibre drawing conditions	113
6.2	Representative material properties.	113
6.3	Impact of furnace type on performance of suspended-core fibre.	127
7.1	Processing options for graded-index mPOF	144
9.1	Comparison of microstructured and non-microstructured GI fibres.	186
9.2	Bandwidth of three GI _m POFs	189
9.3	Recent high-speed transmission experiments	190

List of Symbols and Acronyms

β	propagation constant
ε	aspect ratio
κ	thermal conductivity
Λ	period
μ	viscosity
ρ	spot size
ρ	density
σ	surface tension
χ	relative hole size
Bi	Biot number
Br	Brinkman number
Ca	capillary number
C_o	collapse ratio
Dr	draw ratio
Fr	Froude number
n_g	group index
n_{eff}	effective index
Pe	Peclet number
Re	Reynolds number
T_g	glass transition temperature
T_{draw}	drawing temperature
v_g	group velocity
v_{ph}	phase velocity
V	V parameter, dimensionless frequency
ARROW	anti-resonant reflective optical waveguide
DMA	differential mode attenuation
DMD	differential mode delay
FBG	fibre Bragg grating
EH	hybrid mode

FTTH	Fibre-to-the-Home
GI POF	graded-index POF
GImPOF	graded-index mPOF
HC-mPOF	hollow-core mPOF
HE	hybrid mode
LAN	local area network
LD	laser diode
LED	light emitting diode
LPG	long period grating
MFD	mode field diameter
MOF	microstructured optical fibre
mPOF	microstructured polymer optical fibre
NA	numerical aperture
PMMA	polymethylmethacrylate
POF	polymer optical fibre
PCF	photonic crystal fibre
RZ	Return-to-Zero
NRZ	Non-Return-to-Zero
TE	transverse electric mode
TM	transverse magnetic mode
VCSEL	vertical cavity surface emitting laser

History and Applications of Polymer Fibres and Microstructured Fibres

What's past is prologue.

William Shakespeare, *The Tempest*

This chapter places the rest of the book in context. It describes the history and state-of-the-art of both polymer fibres (POFs) and microstructured optical fibres (MOFs). The physical properties of these fibre types differ considerably in terms of the materials used and the possible waveguide geometries, and these form the basis for the difference in their applications. This chapter outlines both the physical differences and the major applications of each. The applications of POFs are described in more detail because most of the applications of microstructured fibres reappear in later chapters.

1.1 Considerations In The Early Stages Of Polymer Fibre Development

Historically the important drawback of polymer fibres has been their relatively low transmission compared to silica. This has, more than any other issue, dominated the development of POF. It has spurred materials development to reduce attenuation, and led to a gradual appreciation of the alternative virtues of POF, such as their ability to remain flexible even with large cores, the variety of fabrication techniques available for such fibres, and the fact that they can incorporate many forms of dopant material.

The struggle to reduce transmission losses has been a dominating theme during the development of all optical fibres. In the very earliest days, while the major loss mechanisms were still unclear, there was a great deal of experimentation with the materials used. In the early 1950s, some of the very first optical fibres were made of polymer, with claddings made with liquid beeswax [Hecht 1999]. The coating was later changed to a liquid polymer which was cured and painted black to prevent light leaking out. The requirement for painting is itself highly suggestive of the poor quality of the optical guidance.

In parallel to this polymer work, optical fibres were also being made of silica, sometimes with polymer claddings. For more than a decade after these early studies, the transmission of optical fibres of all types remained surprisingly bad. When, in 1965 Charles Kao concluded that a loss of 20 dB/km was needed for them to be practical for data transmission, that seemingly modest figure was still $50\times$ lower than what was possible using the best fibres at the time [Hecht 1999]. Fortunately, Kao also supplied the insights into how to achieve these lower losses. By greatly improving the purity of silica, he and others were able to dramatically reduce the loss of silica fibres. The best silica fibres now have a loss of some 0.15 dB/km at 1550 nm and form the backbone of modern telecommunications systems.

This extraordinary success was deeply problematic for polymer optical fibres, because the absorption loss of polymers is intrinsically much higher than that of silica. Losses in all optical fibres are dominated at short wavelengths by Rayleigh scattering, but in polymers, absorption due to the harmonics of the C-H vibration becomes very significant at wavelengths longer than about 600 nm. One approach to reducing this has been to shift the harmonics to longer wavelengths by replacing hydrogen with something heavier, such as deuterium or fluorine. The use of fluorination has substantially improved the transmission of polymer fibres, not just by reducing the loss, but also by extending their transmission window into the infrared. This is particularly attractive because it allows the use of low-cost components such as sources and detectors previously developed for use with silica fibres. This advantage is offset by the additional cost of fluorination, always a difficult and expensive process, which produces hydrofluoric acid as a by-product.

Theoretically, the best fluorinated material should have a loss approaching that of silica [Koike 1998], though the best experimental results are about only 10 dB/km. For a variety of reasons, the most commonly used polymer for POF remains polymethylmethacrylate (PMMA) which has a theoretical loss limit of 106 dB/km at the most useful transmission window (650 nm). Other polymers that have been used for POF include Polycarbonate and Polystyrene, the former being used in applications that require higher thermal stability. Figure 1.1 compares the transmission of fibres made from silica, fluorinated polymer (the proprietary material CYTOP), and PMMA. Figure 1.2 shows the transmission spectrum of PMMA in its transparency region.

Despite their high attenuation, POF have continued to be developed commercially because they have some major advantages over silica. Figure 1.3 shows the transmission characteristics of PMMA based POF from the first commercially available fibre, produced by DuPont in 1963. Processing improvements lowered the loss for PMMA step index fibres to around 150 dB/km at 650 nm in the 1980s. Graded-index POF was first made in 1982 which by 1990 had achieved similar transmission characteristics to step index POF.

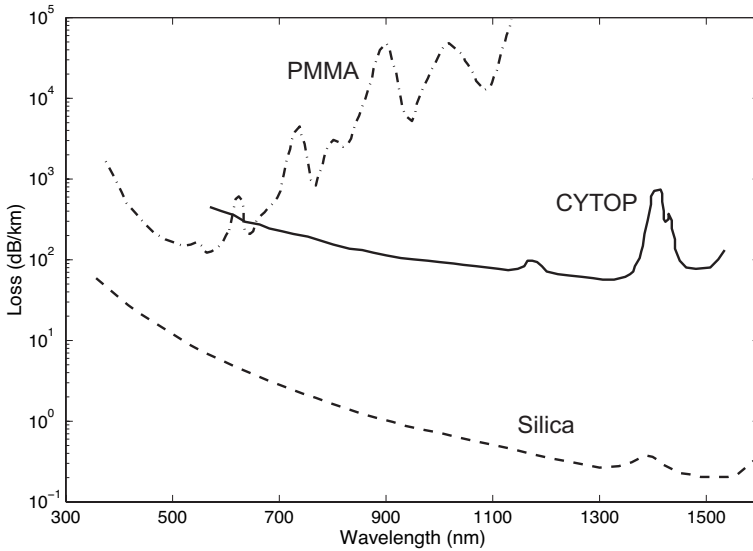


Fig. 1.1. The transmission of fibres made from silica, fluorinated polymer (the proprietary material CYTOP), and PMMA. After Murofushi [1996].

1.2 Fabrication Considerations For Polymer And Glass Optical Fibres

Fabrication methods may not initially seem an important point of comparison between polymer and glasses, but in fact there are significant differences between them which impact strongly on their applications. These are more than simply cost related as the fabrication methods also define what kind of fibres can be made using the two platforms. Understanding these constraints is particularly significant for microstructured fibres, as in some cases these allow the production of fibre types that would be very hard to produce by any other means.

There are two general approaches to making optical fibres. In most cases, particularly in silica, fibres are drawn from a “preform” – a short, fat version of the fibre which contains the desired radial structure (see Chapter 5). In other cases, the fibre is drawn directly from liquid material. In glasses, this liquid is simply molten glass [Palais 1992], but for polymer fibres it may either be molten polymer, or unpolymerised material [Daum et al. 2002].

Glass fibres are normally produced using preforms. The desired refractive index profile is usually produced by doping with small amounts of materials such as germanium or boron. The most important doping methods are based around vapour deposition, in which layers of the desired material are successively deposited and oxidised by a flame. This can be done in a very controlled manner to produce a wide range of index profiles with very high