Microstructured Polymer Optical Fibres

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

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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

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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 Fellew, 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 Whayne 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.

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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.

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

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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 Kuhlmey were very much appreciated. Further thanks are due also due to our colleagues for their patience in reading various drafts, especially Alex Argyros.

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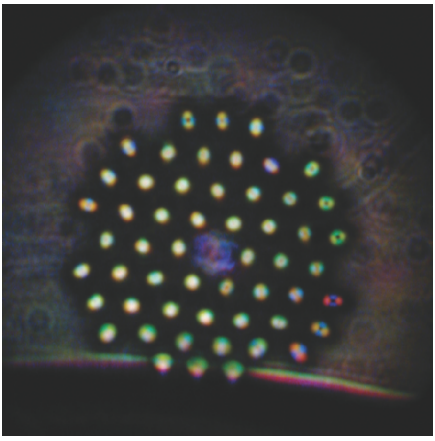

Figure 3.4: A low contrast photonic bandgap fibre shows the interaction of rod and core modes. The wavelengths of light in the core correspond to bandgaps in the cladding structure.

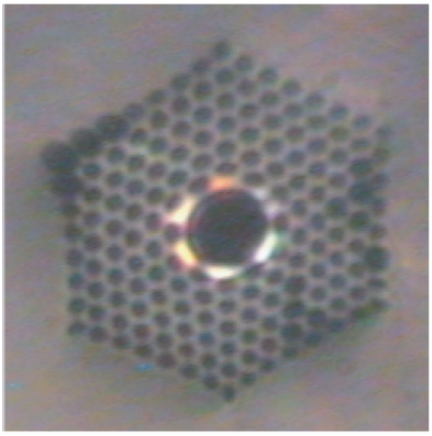

Figure 8.7: The solid region surrounding the core of a hollow core fibre can support modes, as shown here, which can couple light out of the core.

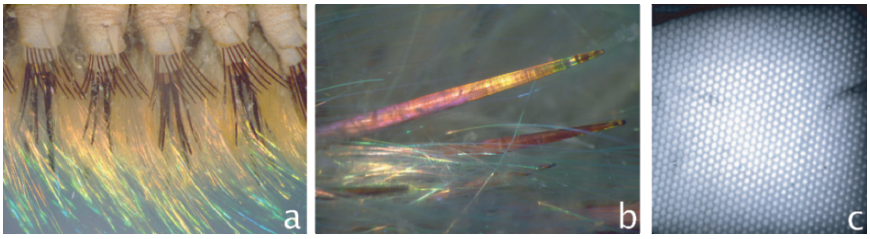

Figure 3.5: Photonic bandgap effects seen in the spines of a seamouse (a) and (b) and a cross-section through a spine showing the microstructure (c).

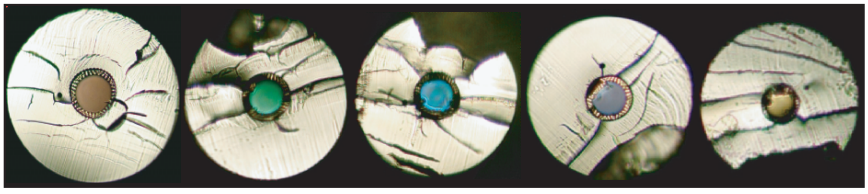

Figure 8.5: Different colours guided in the hollow core of a bandgap fibre drawn to different diameters, changing through red, green, blue, blue-violet and yellow (= red + green) as the structure size decreases.

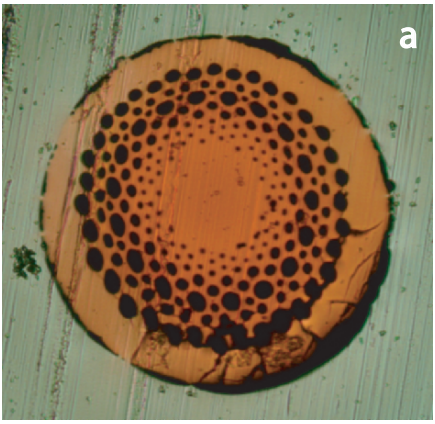

Figure 11.2: (a) Cross-section of a doped mPOF. Orange coloured parts are Rhodamine doped.

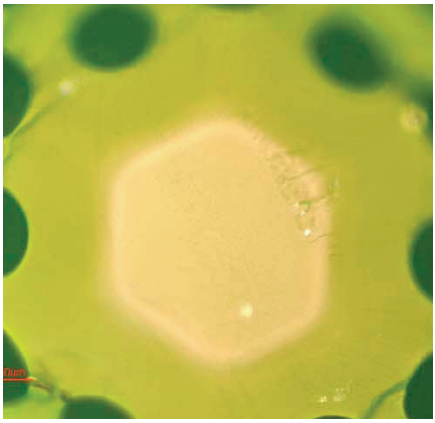

Figure 11.3: Cross-section of a preform prior to the dopant diffusion fronts meeting at the core. The green is the fluorescence of the dye.

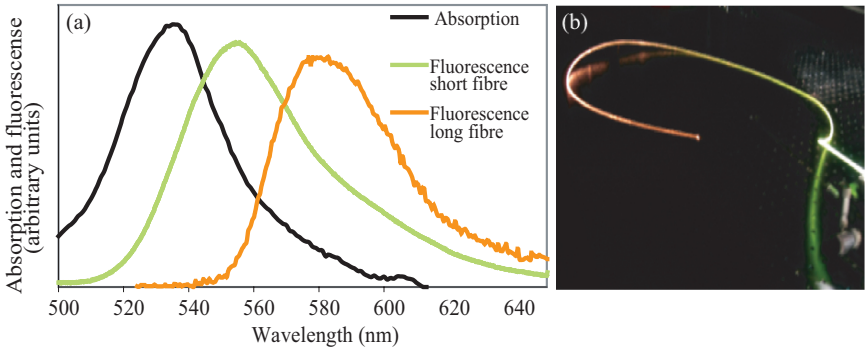

Figure 11.5: (a) The absorption spectrum of the Rhodamine 6G dye and two fluorescence spectra corresponding to short (a few mm) and long (2 m) fibres. (b) Photograph illustrating the re-absorption process.

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

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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	microsturctured 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

1

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× 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 Raleigh 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.

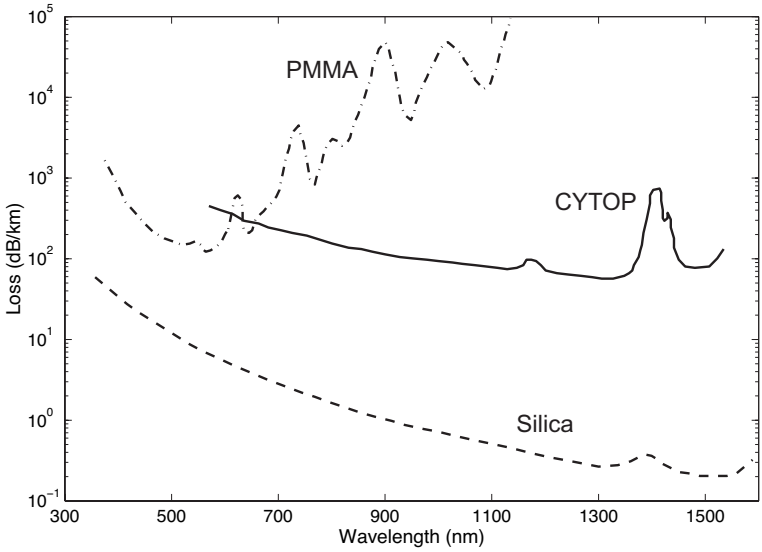

Fig. 1.1. The transmission of fibres made from silica, fluorinated polymer (the proprietary material CYTOP), and PMMA. After Murofushi [1996].

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