

Modes and Propagation in Microstructured Optical Fibres

by

Nader A. Issa



Thesis

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Supervision

Professor Simon C. Fleming

Dr. Martijn A. van Eijkelenborg

Dr. Leon Poladian

Dr. Ian M. Bassett

**Optical Fibre Technology Centre
and School of Physics
University of Sydney**

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2005

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Declaration

I declare that this thesis is my own work and has not been submitted in any form for another degree or diploma at any university or other institute of tertiary education. Information derived from the published and unpublished work of others has been acknowledged in the text and a list of references is given.

Nader A. Issa
June 21, 2005

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Modes and Propagation in Microstructured Optical Fibres

Nader A. Issa
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Abstract

Microstructured optical fibres (MOFs), also commonly called photonic crystal fibres or holey fibres, describe a type of optical fibre in which continuous channels of (typically) air run their entire length. These ‘holes’ serve to both confine electromagnetic waves within the core of the fibre *and* to tailor its transmission properties. In order to understand and quantify both of these functions, a new computational algorithm was developed and implemented. It solves for the eigenvalues of Maxwell’s wave equations in the two-dimensional waveguide cross-section, with radiating boundary conditions imposed outside the microstructure. This yields the leaky modes supported by the fibre. The boundary conditions are achieved exactly using a novel refinement scheme called the Adjustable Boundary Condition (ABC) method. Two implementations are programmed and their computational efficiencies are compared. Both use an azimuthal Fourier decomposition, but radially, a finite difference scheme is shown to be more efficient than a basis function expansion. The properties of the ABC method are then predicted theoretically using an original approach. It shows that the method is highly efficient, robust, automated and generally applicable to any implementation or to other radiating problems. A theoretical framework for the properties of modes in MOFs is also presented. It includes the use of the Bloch-Floquet theorem to provide a simpler and more efficient way to exploit microstructure symmetry. A new, but brief study of the modal birefringence properties in straight and spun fibres is also included.

The theoretical and numerical tools are then applied to the study of polymer MOFs. Three types of fibres are numerically studied, fabricated and characterised. Each is of contemporary interest. Firstly, fabrication of the first MOFs with uniformly oriented elliptical holes is presented. A high degree of hole ellipticity is achieved using a simple technique relying on hole deformation during fibre draw. Both form and stress-optic birefringence are characterized over a broad scaled-wavelength range, which shows excellent agreement with numerical modelling. Secondly, an analysis of leaky modes in real air core MOFs,

fabricated specifically for photonic band gap guidance, is then used to identify alternative guiding mechanisms. The supported leaky modes exhibit properties closely matching a simple hollow waveguide, weakly influenced by the surrounding microstructure. The analysis gives a quantitative determination of the wavelength dependent confinement loss of these modes and illustrates a mechanism not photonic band gap in origin by which colouration can be observed in such fibres. Finally, highly multimode MOFs (also called ‘air-clad’ fibres) that have much wider light acceptance angles than conventional fibres are studied. An original and accurate method is presented for determining the numerical aperture of such fibres using leaky modes. The dependence on length, wavelength and various microstructure dimensions are evaluated for the first time for a class of fibres. These results show excellent agreement with published measurements on similar fibres and verify that bridge thicknesses much smaller than the wavelength are required for exceptionally high numerical apertures. The influence of multiple layers of holes on the numerical aperture and capture efficiency are then presented. It shows that a substantial increase in both these parameters can be achieved for some bridge thicknesses. Simple heuristic expressions for these quantities are given, which are based on the physical insight provided by the full numerical models. The work is then supported by the first fabrication attempts of large-core polymer MOFs with thin supporting bridges. These fibres exhibit relatively high numerical apertures and show good agreement with theoretical expectations over a very wide scaled-wavelength range.

Publications

The following publications were generated from research conducted during the period of candidature: March 2001 to September 2004.

Publications in which this author is listed first amongst those who have contributed, have been written by this author. Those publications represent research conducted at the Optical Fibre Technology Centre by the listed authors, who are ordered by greatest relative contribution as estimated by the first author through appropriate discussions. Additional acknowledgements are given in each publication.

This thesis has been based on these publications. The relationship between individual chapters and particular publications is discussed within the preface. The particular contributions of listed authors is also discussed within the preface.

First author publications

Journal publications

1. Nader A Issa and Wayne E Padden, “*Light acceptance properties of multimode microstructured optical fibers: Impact of multiple layers,*” *Optics Express*, Vol. 12, No. 14, pp. 3224-35 (2004)
2. Nader A Issa, “*High numerical aperture in multimode microstructured optical fibers,*” *Applied Optics*, Vol. 43, No. 33, pp. 6191-7 (2004)
3. Nader A Issa, Martijn A van Eijkelenborg, Matthew Fellow, Felicity Cox, Geoffrey Henry and Maryanne CJ Large, “*Fabrication and study of microstructured optical fibers with elliptical holes,*” *Optics Letters*, Vol. 29, No. 12, pp. 1336-8 (2004)
4. Nader A Issa, Alexander Argyros, Martijn A van Eijkelenborg and Joseph Zagari, “*Identifying hollow waveguide guidance in air-cored microstructured optical fibres,*” *Optics Express*, Vol. 11, No. 9, pp. 996-1001 (2003)
5. Nader A Issa and Leon Poladian, “*Vector wave expansion method for leaky modes of microstructured optical fibres,*” *Journal of Lightwave Technology*, Vol. 21, No. 4, pp. 1005-12 (2003)

Conference presentations

1. Nader A. Issa, Clemens von Korff Schmising, Whayne E. Padden and Martijn A. van Eijkelenborg, “*High numerical aperture in large-core microstructured polymer optical fibres,*” Proceedings of the international Plastic Optical Fiber (POF) conference, Nürnberg, Germany, pp. 436-43 (2004)
2. Nader A Issa, Martijn A van Eijkelenborg, Matthew Fellow, Felicity Cox, Geoffrey Henry and Maryanne CJ Large, “*Fabrication and characterization of microstructured optical fibres with elliptical holes,*” Proceedings of the Conference of Lasers and Electro-Optics/International Quantum Electronics Conference (CLEO/IQEC), San Francisco, USA, paper CThX3 (2004)
3. Nader A Issa, Martijn A van Eijkelenborg, “*Designing multicore optical fibres with minimal modal dispersion,*” Proceedings of the Conference of Lasers and Electro-Optics/International Quantum Electronics Conference (CLEO/IQEC), San Francisco, USA, paper CTuD2 (2004)
4. Nader A Issa, Alexander Argyros, Martijn A van Eijkelenborg and Joseph Zagari, “*Hollow waveguide guidance in air-cored microstructured optical fibres,*” Proceedings of the Australian Conference on Fibre Optic Technology (ACOFT), Melbourne, Australia, pp. 141-4 (2003)
5. Nader A Issa and Leon Poladian, “*Vector wave equation expansion method for leaky modes in microstructured optical fibres,*” Proceedings of the Australian Conference on Fibre Optic Technology (ACOFT) Sydney Convention Centre, Sydney, Australia, pp. 72-4 (2002)
6. Nader A Issa and Leon Poladian, “*Considerations for an expansion method used to calculate leaky modes in MOFS,*” Proceedings of Australian Optical Society (AOS) conference, Sydney, Australia (2002)

Special presentations

1. Nader A Issa, “*Modelling high numerical aperture MOFs,*” Bath University photonic crystal fibre workshop, Bath, UK (2004)
2. Nader A Issa, “*Numerical methods for holey fibres,*” Commercialisation of MPOF workshop, Polymer Optical Fibre Application Center, Nürnberg, Germany (2004)
3. Nader A Issa, Martijn A van Eijkelenborg, Alexander Argyros, Geoff W Barton, Ian M Bassett, Matthew Fellow, Geoff Henry, Maryanne CJ Large, Steven Manos,

Whayne E Padden, Leon Poladian, Joseph Zagari, “*Recent advances in microstructured polymer optical fibres,*” Poster at FiberComm 2003 trade exhibition, Munich, Germany (2003)

4. Nader A Issa, “*Elliptical hole microstructured polymer optical fibres,*” OFTC departmental seminar, Sydney, Australia (2004)
5. Nader A Issa, “*Multicore optical fibres with minimal modal dispersion,*” OFTC departmental seminar, Sydney, Australia (2003)
6. Nader A Issa, “*Device design for Quasi-Phase-Matched Second Harmonic Generation,*” OFTC departmental seminar, Sydney, Australia (2002)

Jointly authored publications

Journal publications

1. Martijn A van Eijkelenborg, Alexander Argyros, Alexander Bachmann, Geoff W Barton, Maryanne CJ Large, Geoffrey Henry, Nader A Issa, Karl-Freidrich Klein, Hans Poisel, Wilson Pok, Leon Poladian, Steven Manos, Joeseoph Zagari, “*Bandwidth and loss measurements of graded-index microstructured polymer optical fibre,*” Electronics Letters, Vol. 40, No. 10, pp. 592-3 (2004)
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3. Joseph Zagari, Alexander Argyros, Geoff W Barton, Geoffrey Henry, Maryanne Large, Nader A Issa, Leon Poladian and Martijn A van Eijkelenborg, “*Small-core single-mode microstructured polymer optical fibre with large external diameter,*” Optics Letters, Vol. 29, No. 8, pp. 818-20 (2004)
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5. D. Kácik, I. Turek, I. Martincek, John Canning, Nader A Issa and Katja Lyytikäinen, “*Intermodal interference in a photonic crystal fibre,*” Optics Express, Vol. 12, No. 15, pp. 3465-70 (2004)
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Whayne E Padden, Leon Poladian, Joseph Zagari, “*Recent progress in microstructured polymer optical fibre fabrication and characterization,*” *Optical Fiber Technology*, Vol. 9, No. 4 pp. 199-209 (2003)

7. Leon Poladian, Nader A Issa, and Tanya M Monro, “*Fourier decomposition algorithm for leaky modes of fibres with arbitrary geometry,*” *Optics Express*, Vol. 10, No. 10, pp. 449-54 (2002)
8. Martijn A van Eijkelenborg, Maryanne C J Large, Alexander Argyros, Joseph Zagari, Steven Manos, Nader A Issa, Ian Bassett, Simon Fleming, Ross C McPhedran, C Martijn de Sterke and Nicolae AP Nicorovici, “*Microstructured polymer optical fibre,*” *Optics Express*, Vol. 9, No. 7, pp. 319-27 (2001)

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1. John Canning, Whayne E Padden, Leon Poladian, Nader A Issa, “*Imaginary refractive index waveguides and applications,*” *Proceedings of the International Microwave and Optoelectronics Conference, Iguazu Falls, Brazil*, pp. 443-5(2003)
2. Martijn A van Eijkelenborg, Alexander Argyros, Geoff W Barton, Ian Bassett, Felicity Cox, Matthew Fellow, Simon Fleming, Geoffrey Henry, Nader A Issa, Maryanne CJ Large, Steven Manos, Leon Poladian, Joseph Zagari, “*New possibilities with microstructured polymer optical fibres,*” *Proceedings of the international Plastic Optical Fibers (POF) Conference, Tokyo, Japan*, pp. 18-20 (2002)
3. Maryanne CJ Large, Martijn A van Eijkelenborg, Alexander Argyros, Joseph Zagari, Steven Manos, Nader A Issa, Ian M Bassett, Simon C Fleming, Geoff W Barton, “*Novel Microstructured Optical Fibres fabricated in Polymer,*” *Proceedings of the Australian Conference on Fibre Optic Technology (ACOFT), Sydney, Australia*, pp. 78-80 (2002)
4. Maryanne CJ Large, Martijn A van Eijkelenborg, Alexander Argyros, Joseph Zagari, Steven Manos, Nader A Issa, Ian Bassett, Simon Fleming, Ross C McPhedran, C Martijn de Sterke and Nicolae AP Nicorovici, “*Single-mode microstructured polymer optical fibre,*” *Proceedings of the Optical Fibre Communication Conference (OFC), Anaheim, USA*, pp. 527-8 (2002)
5. Maryanne CJ Large, Martijn A van Eijkelenborg, Alexander Argyros, Joseph Zagari, Steven Manos, Nader A Issa, Ian Bassett, Simon C Fleming, Ross C McPhedran, C Martijn de Sterke and Nicolae AP Nicorovici, “*Microstructured polymer optical fibres: a new approach to POFs,*” *Post deadline paper of the Plastic Optical Fiber (POF) conference, Amsterdam, the Netherlands*, pp. 27-30 (2001)

Invited conference presentations

1. Martijn A van Eijkelenborg, Alexander Argyros, Alexander Bachmann, Geoff W Barton, Geoffrey Henry, Nader A Issa, Karl-Freidrich Klein, Maryanne CJ Large, Steven Manos, Wayne E Padden, Leon Poladian, Hans Poisel, Yucheng Zhao, “*Applications of microstructured polymer optical fibres,*” Proceedings of the Conference of Lasers and Electro-Optics/International Quantum Electronics Conference (CLEO/IQEC), San Francisco, USA, Paper CThX1 (2004)
2. Maryanne CJ Large, Alexander Argyros, Geoff W Barton, Felicity Cox, Geoffrey Henry, Nader A Issa, Steven Manos, Wayne E Padden, Leon Poladian, Martijn A van Eijkelenborg, Alexander Bachmann, Karl-Freidrich Klein, Hans Poisel, “*Future Directions for Microstructured Polymer Optical Fibres,*” Photonics West, San Jose, USA (2004)
3. Maryanne CJ Large, Alexander Argyros, Geoff W Barton, Ian Bassett, Felicity Cox, Matthew Fellow, Geoffrey Henry, Nader A Issa, Steven Manos, Wayne E Padden, Leon Poladian, Martijn A van Eijkelenborg, Joseph Zagari, “*Microstructured Optical Fibres: Why use polymers?*” Proceedings of the European Conference on Optical Communications (ECOC-IOOC), Vol. 4, paper Th2.7.1, Rimini, Italy, pp. 1014-7 (2003)
4. Geoff W Barton, Martijn A van Eijkelenborg, Geoffrey Henry, Nader A Issa, Karl-Friedrich Klein, Maryanne Large, Steve Manos, Wayne E Padden, Wilson Pok, Leon Poladian, “*Characteristics of Multimode Microstructured POF Performance,*” Proceedings of the international Plastic Optical Fibers (POF) conference, Seattle, USA, pp. 81-4 (2003)
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9. Maryanne CJ Large , Martijn A van Eijkelenborg, Alexander Argyros, Joseph Zagari, Nader A Issa, Ian Bassett, Ross C McPhedran, and Nicolae AP Nicorovici, “*Microstructured Polymer Optical Fibres: Progress and Promise,*” SPIE vol 4616, Photonics West, San Jose (2002)

Journal publications from research prior to candidature but completed during candidature

1. Joseph J Monaghan, Andrew Kos, Nader A Issa, “*Fluid motion generated by impact,*” Journal of waterway, port, coastal and ocean engineering, Vol. 129, No. 6, pp. 250-9 (2003)

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and exciting. I also thank her for nominating me for a number of opportunities that have shaped my PhD.

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Nader A. Issa

University of Sydney

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Preface

The intentions of this preface are: to outline the structure of this thesis, to identify original findings and to associate some individual chapters with the publications listed on the previous pages. Importantly, the specific contributions of others to this work are explicitly stated here.

Part I

During the period in which this thesis was produced, Microstructured Optical Fibre (MOF) technology had matured at a rapid pace. Research had gradually shifted focus from foundational investigations of the principles of behaviour to more application driven and device based development. This transition has been intimately related to the steady improvement in fabrication quality and reproducibility. A ‘speed-of-light’ introduction to the background history of this technology is provided in Chapter 1. However, more comprehensive tours can be found in other sources [Russell, 2003, Knight, 2003, Bjarklev et al., 2003]. This author has been fortunate to bear witness *and* assist in the early stages of MOF development at the Optical Fibre Technology Centre (OFTC). Personal contributions have been made on a number of fronts, including the fabrication of Microstructured Polymer Optical Fibre (mPOF), characterisation and a great deal of numerical modelling. Some of this work is summarised in Section 1.3 and by van Eijkelenborg et al. [2003], where many of the jointly authored publications (in which this author is not the first) are described in their context.

A great deal of theoretical/analytic work pertaining to electromagnetic waveguide problems is available in prior literature. However, their application to MOFs sometimes requires some creative adjustment or simply needs to be explicitly stated before they are widely appreciated. Some of these important tools are re-cast in the context of MOFs in Chapter 2. The study of mode-symmetry classes is perhaps more relevant to MOFs than conventional fibres, simply because of the greater geometric freedom they permit. This is introduced in Section 2.1. It begins with the most commonly used reference for this topic and an introduction to its suggested procedure for mode-symmetry classification. However, the classification used throughout this thesis is slightly different and it is presented in Section 2.1.2. The approach, based on the Bloch-Floquet theorem, is a relatively standard

one in many numerical problems. Its application specifically to MOF modelling was originally proposed by Leon Poladian [Poladian et al., 2002] and subsequently adopted here. Its implementation is simpler and allows a reduction in the minimum waveguide sector for some mode classes. The benefit for numerical analysis can be enormous, which had been known and used throughout this thesis. Its description in that chapter does include some original findings, such as the procedures for orthogonalisation and the resemblance to circular fibre modes. This full description is believed to be unpublished in an explicit form. Section 2.2 simply summarises the important points relating to the properties of leaky modes, as these modes are used throughout this thesis. With the exception of Eq. (2.8), all other contents can be found in the stated references.

Chapter 3 is composed of two major ingredients. Firstly, the issue of polarization and polarization birefringence in straight MOFs is discussed in sections 3.1 and 3.2. These sections were written in order to address an unanswered question at the time: Can the geometry of a straight MOF be used to induce circular-polarization birefringence? The answer, ‘Not without loss’, seems to be commonly accepted, but an explicit proof is believed not to exist in the literature. Thus the proof is completely original, but it does follow immediately from the fact that transverse field components of a lossless mode can always be made everywhere real. This is commonly stated as a postulate, without proof, in a number of standard texts. The second focus of this chapter is the derivation of the induced circular-polarization birefringence in a spun fibre, using a form of local mode coupling. The derivation is similar to that given in [Bassett, 1988]. However, this alternative approach, which is presented in section 3.3 and 3.4, is shorter but results in the same conclusions. Section 3.4 goes further than this reference by providing the full coupled vector terms in a spun fibre. The expressions are evaluated for the first time for a real MOF.

Part II

While part I of this thesis contains the theoretical aspects of modes in MOFs, part II concentrates on the development of numerical tools, which have been tailored specifically to model the unique properties of these fibres. In particular, the calculation of confinement loss necessitated the development of a new numerical method, which is placed in context of other numerical schemes at the introduction of the chapter. There are two unique and creative aspects to this numerical method: the procedure for determining confinement loss, referred to as the ABC method (section 4.3), and the implementations (sections 4.4 and 4.6). The ABC scheme, of iteratively refining the boundary conditions of the eigenvalue problem, was originally proposed by Leon Poladian and Tanya Monro. It was first implemented by Poladian et al. [2002] within the simpler scalar approximation. However, it is not suited to the accurate study of MOFs that have the refractive index contrasts of air to polymer or glass and is incapable of quantifying polarization effects such as birefringence. The set of basis functions used in this reference was suggested by this

author and the same basis functions were used in the first fully vectorial implementation. This implementation is described in Section 4.4, which correlates with the content of journal publication No. 5 ([Issa and Poladian, 2003a]). Having observed the performance of this implementation in the numerical tests given in section 4.5, an alternative, superior implementation was proposed by this author and adopted. It is presented in Section 4.6 and its comparative performance is given in Section 4.7. Both implementations are original, however, the second is unpublished.

It was only after the ABC method had been implemented and its favourable properties been observed, that attempts were made to understand and predict the behaviour of the method. A full theoretical description of its behaviour was completed by this author and shown to accurately predict the actual numerical performance. This analysis is presented in Chapter 5. The findings are completely original, generally applicable to any implementation and currently unpublished in full form. Portions of the derivation, were however, presented in conference presentation No. 6 ([Issa and Poladian, 2002]).

Part III

This part is exclusively devoted to application. In this theme, three separate chapters consider different types of fibres. Each are studied numerically, fabricated and characterised.

Chapter 6 is based on journal publication No. 3 ([Issa et al., 2004d]) and relates to the polarization birefringence induced by elliptical holes in the fibre. Although significant theoretical interest on this topic has appeared in the literature, this work represents the first ever reported fabrication and characterization of MOF with uniformly oriented elliptical holes. The demonstration is thus original, as is the comparison with numerical calculation to identify the relative contributions of stress and form birefringence. Contributors to this work are: Geoffrey Henry, who fabricated the fibres using a new sleeving technique that reduced the hole pitch enough to allow single mode operation. Felicity Cox, who initially discovered this type of hole deformation in similar fibres fabricated for poling purposes. Matthew Fellow who made numerous attempts at fabricating fibres with elliptical holes and carried out some preliminary measurements on other fibres with partial success. Finally, Martijn van Eijkelenborg and Maryanne Large, who supervised and coordinated the efforts of these contributors. New fibre requests, as well as all the characterization measurements, fibre treatments, numerical simulations and analysis presented in this chapter were carried out by this author alone.

The work contained in Chapter 7 was completed after much attention had been given to light guidance in hollow-core mPOFs within the research group at the OFTC. What was initially believed to be photonic band gap guidance in short sections of sample fibres (due to observed colouration at the output of the fibre), was later shown by this author to be the result of another optical effect. The work presented in this chapter is original and novel. It is based on journal publication No. 4 ([Issa et al., 2003b]). Fibre fabrication was

performed jointly by Joseph Zagari and Martijn van Eijkelenborg. The first experimental observations and some later experimental characterisation was conducted by Alex Argyros.

Chapter 8 relates to the numerical aperture and capture efficiency in highly multimoded MOFs. Numerical modelling of this problem is highly non-trivial, as standard formulae available for conventional fibres fail. This interesting problem was originally proposed to this author by Karl Klein. The approach presented in Section 8.2 is original and solely developed by this author. As are the results relating to single layer structures in Section 8.3. These two sections are based on journal publication No. 2 ([Issa, 2004a]). Section 8.4 relates to the impact of multiple layers on both numerical aperture and capture efficiency. It is based on journal publication No. 1 ([Issa and Padden, 2004b]). The study of multiple layers was also originally proposed to this author by Karl Klein as an obvious extension to the investigation. Naturally, the simulation method used for single layer structures was applied to the problem of multiple layers. Whayne Padden contributed intellectually to this work during the analysis and understanding of the generated numerical results. The findings in this section quantifying and explaining the increase in numerical aperture for such fibres are completely original. Fabrication of the first polymer MOF with high numerical aperture was carried out jointly by this author and Martijn van Eijkelenborg. Characterisation experiments were completed jointly by this author and Clemens von Korff Schmising. This work is presented in section 8.5, which is based on conference presentation No. 1 ([Issa et al., 2004c]).

Non-represented work

A substantial body of work, conducted during the period of candidature, is not represented in this thesis. The deliberate omission is aimed at preserving the continuity of this thesis and reducing its size. Some of that work has been presented in other forms, such as conference presentation No. 3, special presentation No. 6 and some of the jointly authored publications (journal and conference) listed on previous pages.