Theoretical and Numerical Investigation of the Physics of Microstructured Optical Fibres

A thesis submitted for the degree of
Doctor of Philosophy

by

Boris T. KUHLMEY

Department of Theoretical Physics
School of Physics
The University of Sydney
Australia

and through the cotutelle scheme

Université de Droit, d'Économie et des Sciences d'Aix-Marseille
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Theoretical and Numerical Investigation of the Physics of Microstructured Optical Fibres

Étude Théorique et Numérique de la Physique des Fibres Optiques Microstructurées

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Boris KUHLMEY
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Les Directeurs de thèse: Daniel MAYSTRE et Ross McPHEDRAN

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Dr. D. MAYSTRE	Directeur de Recherche, Insitut Fresnel / CNRS	Directeur de thèse

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Abstract

Theoretical and Numerical Investigation of the Physics of Microstructured Optical Fibres

We describe the theory and implementation of a multipole method for calculating the modes of microstructured optical fibers (MOFs). We develop tools for exploiting results obtained through the multipole method, including a discrete Bloch transform. Using the multipole method, we study in detail the physical nature of solid core MOF modes, and establish a distinction between localized defect modes and extended modes. Defect modes, including the fundamental mode, can undergo a localization transition we identify with the mode's cutoff. We study numerically and theoretically the cutoff of the fundamental and the second mode extensively, and establish a cutoff diagram enabling us to predict with accuracy MOF properties, even for exotic MOF geometries. We study MOF dispersion and loss properties and develop unconventional MOF designs with low losses and ultra-flattened near-zero dispersion on a wide wavelength range. Using the cutoff-diagram we explain properties of these MOF designs.

Étude Théorique et Numérique de la Physique des Fibres Optiques Microstructurées

Nous détaillons la théorie et l'implémentation d'une méthode multipolaire pour le calcul de modes de fibres optiques microstructurées (FOM). Nous développons des outils pour l'exploitation de résultats obtenus par la méthode multipolaire, dont une transformée de Bloch discrète. À l'aide de la méthode multipolaire, nous étudions en détail la nature physique de modes de FOMs à cœur plein. Nous distinguons entre modes de défaut localisés et modes étendus. Les modes de défaut, y compris le mode fondamental, peuvent subir une transition de localisation que nous identifions à la coupure du mode. Nous étudions numériquement et théoriquement la coupure du mode fondamental et du second mode, puis établissons un diagramme de régime opératoire nous permettant de prédire avec précision les propriétés de FOMs même aux géométries complexes. Nous étudions la dispersion et les pertes des FOMs et proposons un nouveau type de FOM à faible pertes et à courbe de dispersion ultra plate, proche de zéro sur une vaste plage de longueur d'ondes. En s'appuyant sur le diagramme de régime opératoire, nous expliquons les propriétés de ce nouveau type de FOMs.

Acknowledgments

I have enough friends who have gone through, or are still doing, a PhD, and heard enough anonymous horror stories about PhDs to realize how lucky I have been throughout my own PhD. It appears that for many students, a PhD is a long and obscure time at the blurry frontier of student and working life, more often than not punctuated by times of doubts, vicious cycles of depressive unproductivity, meta-physical questioning on the significance of science in an immoral world ruled by the intricately interdependent super-powers of money, media, tradition and politics, and disillusion with academia and science itself. Not that I haven't gone through some of these tribulations myself, but they were kept to a strict minimum – in fact a welcome diversion from work necessary to avoid the ivory tower syndrome – thanks to the extraordinarily motivating environment I had the pleasure to work in, the constant and friendly attention of my supervisors, and many other factors I will attempt to recall and enumerate below.

While trying to remember and analyse the factors which contributed to the relative smoothness of my PhD, the contrast between the quite theoretical physics I dealt with during my postgraduate studies and the intricate complexity of the world we actually live in became strikingly obvious: whereas for the mostly linear phenomena I studied every effect has a straightforwardly and uniquely identifiable cause, in nature in general and for human interaction and personal development in particular, causality takes unfathomable detours and ramifications. The overly famous allegory of the butterfly in Brazil causing (or more accurately contributing to cause) a hurricane over the Caribbean came to my mind, and it seemed an impossible task to track back all the little butterflies at the tip of the branches of the fractal causal structure leading not to a hurricane but rather to the predominantly quite – yet exciting – stream of my PhD. Nevertheless, using the same imagery it appears that butterfly effects mostly influence *weather*, whereas *climate* is predominantly determined by larger, more identifiable effects, such as steady, planet-scaled oceanic and atmospheric streams. Identifying the people and events that played the role of the latter seemed much more feasible. (I will, however, certainly not resist the temptation of throwing in a few butterflies as they come to my mind.)

At the source of all lie of course my parents, without whom I wouldn't exist in the first place, and that essential gift of life shall not be unacknowledged. Although being born is a necessary condition for the completion of a PhD, it is certainly not sufficient: my parents wouldn't deserve their position at the top of the present acknowledgments had they contented themselves with dropping yet another being on this planet. Instead, they raised my brother and myself with care and attention, the right balance between parental authority and personal freedom, in a climate of tolerance and justice, giving us access to high quality education, helping us out whenever needed without rendering us dependent, in short they achieved the balance most parents endeavour but few achieve. Although I don't believe they intended for

me to become a scientist, they certainly didn't try to discourage me once I had caught the passion of science (to the point of indulging my whim of wanting a Helium-Neon laser for my thirteenth birthday). My brother also played an important role in my personal development – among many other things by being a perfect example I admired and tried to follow. In terms of academic achievement he set very high standards, and without the untold challenge of attempting to do as well as he did (whether this challenge came out of jealousy, sibling rivalry or something else I am not sure), I would certainly have been more slack about my studies.

Next in the list come the teachers and lecturers I had the privilege and pleasure of being taught by, especially, but not solely, my science teachers in high-school. More specifically, I'd like to thank my biology teachers (M. and Mme Margerie and especially Mlle Castel), who initiated me into the *méthode scientifique* more than any other teachers or lecturers later on; they believed I would continue my studies in biology – it is probably most ungrateful to their more than praiseworthy efforts that I didn't. M. Monnet, my maths teacher during the final year at high-school is without any doubt the one who gave me the first glimpse of the beauty of mathematics; M. Goldsztejn and M. Mantin in first and second year University deepened my appreciation of that beauty. Among my physics lecturers Dr. Barbet-Massin is certainly the one who left the most lasting and awe-inspiring impression, and is probably the one who made the difference, making me chose physics rather than biology or computer sciences for my further studies.

Now regarding the PhD itself, first I'd like to thank the referees for accepting the tedious task of reading the entire thesis and coming all the way to Marseille for the defence. I thank them also for their insightful comments and questions, my only regret is that some of them couldn't stay for the post-defence barbecue which I hoped to be a modest compensation for their work.

My deepest gratitude goes of course to my three supervisors – Dr. Gilles Renversez, Dr. Daniel Maystre and Prof. Ross McPhedran. The three of them have contributed towards the achievement of my thesis in different, complementary, essential ways. Gilles, a hard and hence demanding worker, has been a constant support throughout the PhD, of course as far as research is concerned, but also for practical and administrative matters. He didn't shy away from doing all derivations himself to check my results or from staying at the lab until undue hours when I needed his help, but at the same time he managed to leave me a total freedom in my research. He is an exceptionally reliable person whom I am proud to be able to call a friend. I should add that I was his first PhD student, which I have heard has made him a little nervous at the beginning, but he has proved that he is an excellent supervisor, and his future PhD students – and I hope he will have plenty of them – should deem themselves extremely lucky.

I knew Ross from a research project done under his supervision two years prior to the beginning of my PhD; it is during that research project that I discovered that theoretical and numerical physics are at least as beautiful, interesting, rewarding and fascinating as experimental physics. That research project having been an extremely positive experience, I contacted Ross a year and a half later regarding a possible PhD. He put forward the possibility of a *cotutelle* PhD between Marseille and Sydney, and soon we agreed on the topic of the PhD, which I was very enthusiastic about. I am most grateful to Ross for offering me that opportunity to work on a current topic of research at the edge of theory and applications, in an international environment and under shared supervision through the cotutelle scheme. Over the years, Ross has become much more than just an excellent, as motivating as demanding,

supervisor; I consider him a friend and mentor, his wisdom will remain an inspiration, his wit and anecdotes a delight. I'm looking forward to collaborate with him for many more years.

I had a more distant relationship with Daniel Maystre, since it was Gilles' assigned task and vocation to supervise me on a day to day basis in Marseille. Dr. Maystre gave Gilles and myself the initial impulse for the work, and kept on giving us much appreciated guidance throughout the PhD. I like to compare him to an oracle whom we went to seek answers from when we ran out of inspiration; his wisdom and breadth of knowledge certainly support the likening, but thankfully his answers didn't come in riddles – at least most of the time.

I consider Prof. Martijn de Sterke to have been my second supervisor in Sydney, although officially he wasn't. Martijn's dynamism, frankness and pragmatism are exemplary and appreciated by everyone I know who had the privilege to work with him, including myself. Without his comments and advice my work would probably have been much more of a random walk and hence much less productive.

It was also a great pleasure to work with Prof. Lindsay Botten, also known as the wizard of matrices, who – as wizards do – has an inclination for manipulating the most cryptic runes with the most powerful meaning, but – unlike wizards – doesn't shy away from explaining them in terms understandable to common mortals.

One of the things I appreciated most in the Department of Theoretical Physics at the University of Sydney was the fact that it was multidisciplinary, covering most aspects of modern theoretical physics. This made my collaboration with Prof. Peter Robinson possible, who brought his knowledge on phase transitions and critical systems without which our study on modal cutoffs would probably have been much less fruitful. Other people at the University of Sydney I'd like to thank for interesting discussions include the whole Department of Theoretical Physics (especially Dr. Ara Asatryan, for insightful comments on localization theory, Dr. Nicolae Nicorovici, for bug reports and comments, and of course Tom White for many things, but I'll come back to that), and colleagues from the Optical Fibre Technology Centre (especially Dr. Maryanne Large and Dr. Leon Poladian).

I also had the pleasure of frequent e-mail contact with A. Prof. Niels Asger Mortensen, who was working with Crystal Fibre at that time. He raised many very interesting questions, and our e-mail conversations were scientifically very fertile.

The highlight of my stay in Marseille were certainly the mostly political (but sometimes also scientific) debates occurring during the daily lunch and coffee breaks, bringing together almost all my colleagues from the CLARTE and TEM teams at the Institut Fresnel. Among them Dr. Frédéric Zolla and Dr. Anne Sentenac were probably the loudest and most entertaining. Besides politics, I also had many interesting scientific discussion with Frédéric Zolla, although he often assumed my knowledge of spectral theory was much broader than it actually was or should be, Prof. Gérard Tayeb, Prof. André Nicolet and Dr. Stefan Enoch. Also in Marseille, I'd like to thank Gabriel Soriano and Niña Gralak for many things but especially for food and accommodation, Charles Antoine Guérin, Boris Gralak and Nicolas Guérin. A big thank you to Mireille Frizzi and Françoise Maillet for helping out with all the administrative matters. Finally for Marseille, I'm very much indebted to Anthony Dubois, Joelle and Frédéric Forestier (as well as, again, to Tom White) for helping out (*le mot est bien faible...*) with the post-defence barbecue. Without them it just wouldn't have happened at all. Merci infiniment !!!!

Mentioning Frédéric Forestier, who is the system administrator of the CLARTE and TEM teams at the Insitut Fresnel, I'd like to acknowledge his work, along with the work of the sysadmins in Sydney, Sebastian Juraszek, Tony Monger and George Shan. We (*we* including everyone who uses a computer) wouldn't get much work done without the sysadmins' help

and constant efforts at maintaining the hardware and software infrastructure.

None of the work in the present PhD would have been possible without the support of the French educational system. By *support* I don't only mean the financial support, from which I have benefited since my third year of studies, but also the qualitative support, from the simple fact that a high quality education does exist in France, to the fact that education and studies (*still...*) are basically free of charge. I hope that the current changes in the French education system will not negatively affect this relative guarantee of equal opportunities.

More specifically, I'd like to congratulate whoever has initiated the *cotutelle* scheme for PhDs. It is a great invention, and I can only encourage all starting PhD students to consider doing their PhD in cotutelle. Working in two different laboratories, in two different countries, and with two different supervisors is highly beneficial in many ways. It enables one to be confronted with different approaches of science, different point of views, different work atmospheres. I mentioned at the beginning of the present acknowledgments that I know quite a few cases of PhD students giving up in the midst of their thesis. I am convinced that most of these students wouldn't have given up had they been given the chance of seeing science from another perspective in another lab, another country.

In that context I'd also like to thank the *Ministère de l'Éducation Nationale, de l'Enseignement Supérieur et de la Recherche*, the French Embassy in Australia, and the University of Sydney for financial support specific to the cotutelle. At the French Embassy in Australia, I'd like to express my gratitude to Alain Moulet, the *Attaché pour la Science et la Technologie*, who is universally recognized for having done a magnificent job in terms of initiating, coordinating and promoting the cotutelle arrangements and associated funding.

Tom White, whom I have already mentioned several times above, deserves a separate paragraph in the present acknowledgments. He has indeed helped me out in many ways throughout the past three years. As a colleague, he has helped me significantly in the early stages of implementing the multipole method. As a friend, he arranged for accommodation when I first arrived in Sydney, organized bushwalks in the Barrington Tops and in Tasmania and invited me to stay at his family's place in Tasmania. As a housemate, not only has he endured my most excessive cooking crises, he has actively participated in them, taking up the most ungrateful peeling, slicing, seeding or cleaning tasks I could imagine, and was even able to show enthusiasm when asked to carve half-millimetre apple slices or spiral segments in grapefruits. He is the best food-carver I know, and more generally the best cooking assistant I ever had the pleasure to work with. His patience has no limits, and his friendliness and helpfulness are incommensurable.

I'm also grateful to my other flatmates over the years of my PhD, Stéphane Ravier in Marseille, Fiona Reardon, Mert Akin and later Kathryn Topp and Ross McKerracher in Sydney, among so many other things especially for supporting my culinary experiments and washing up the literally thousands of things I can dirty within hours while cooking. My flatmates in Sydney shall also be thanked for pushing me to take up sport, and more generally for making me want to come back to Sydney.

My flatmates weren't the only ones who suffered from my cooking, and all the others who at some point or other have innocently declared themselves willing to help me in my cooking, accepting such tedious and unrewarding tasks as peeling and seeding grapes, carving roses in potatoes or filling 150 profiteroles shall not be forgotten.

Nor should be forgotten all those who have initiated me into the art of cooking: my mother and grandmothers, Noémie Favier, Jean-Marc Hénique, who all directly taught me, but also

Jean Brouilly, for making me discover *haute cuisine* good enough to bring tears to my eyes and for lifting my psychological barrier to cheese, Michel and Pierre Troisgros, Alain Ducasse and Franck Cerutti for making me understand the full meaning of the word perfection, and Tetsuya Wakuda for proving that Australia's chefs can be at least as good as the best French chefs.

And last but most importantly, I'd like to thank all my friends for being what they are. Tommy Wommy, Zoe, Stephen, Karen, Félicien, Antoine, Delph, Babeth, Pluc, Ben, Seb, Greg, Carron, Rachel, Cathrine, Kathryn, Tom, Thomas, Severine, Gilles, Isa, Emilie, Jérem, Marco, Solène, Marion, Marie, Steph, Mert, Fi, Coops, Drew, Rémi, Claude, Florent, Stan, Cécile, Vincent, Nathalie, Maraboule, Isaboule, Noémie, Sam, Didier... you all are the answer to the question of the meaning of life.

Preface

The work presented in this thesis was carried out at the Institut Fresnel, Université d'Aix-Marseille III, France and at the School of Physics, University of Sydney, Australia. Most of the work was done in close collaboration with researchers from these institutions, and has been published in several journals under the name of all participating researchers (see Appendix I). It is hence necessary to detail which part of the work presented in this thesis is due to the author. Chapters 1 and 2 are merely an introduction and don't present any new results. Chapter 3 presents the theory of the multipole method used for the study of microstructured optical fibres. Both the Institut Fresnel and the School of Physics, University of Sydney, have used multipole methods for studies of gratings and photonic crystals well before the work presented in this thesis started. The extension of this method to the study of microstructured optical fibres presented in Chapter 3 was done independently and simultaneously in slightly different ways at the School of Physics, University of Sydney by T. White, R. C. McPhedran, C. M. de Sterke and L. C. Botten, and at the Institut Fresnel by D. Maystre, G. Renversez and the author of this thesis. After a few months, R. C. McPhedran, L. C. Botten and the author sorted out the slight differences between both formalisms and agreed on the unified formalism presented in Ref. [1] and in Chapter 3. Chapter 4 presents the implementation of the multipole method, collecting experience gained by T. White and the author when implementing the method. In particular, T. White provided Figures 4.7 and 4.8 in Chapter 4. Chapters 5-7 result mainly from the author's work at the School of Physics, University of Sydney. However, through very frequent discussions, the work has benefited from the knowledge and guidance of many people from the School of Physics, especially Ross McPhedran, Martijn de Sterke, Thomas White and Peter Robinson. The idea of using a Fourier transform to analyse modes came from M. de Sterke, and the idea of the Bloch transform emerged during a discussion between R. McPhedran and the author. P. Robinson brought his knowledge of phase transitions and extrapolations from finite to infinite systems essential to the studies of scaling laws in Chapter 7. Chapter 8 results mainly from the work of G. Renversez, who directed and run all dispersion simulations. The author's contribution to the work on dispersion merely consisted in providing the software and suggesting a few interpretations. The derivation of the Wijngaard identity in Appendix B is the work of D. Maystre. The correct choice of the square root described in Appendix A results from many discussions between the Australian and the French team, but the correct square root cutoff for n_{i} was established by G. Renversez who generalized earlier work by M. Nevière. Finally, regarding the culinary part of the present thesis, the recipes for two side dishes are directly taken from Ref. [2], while all other recipes are the fruit of the author's culinary experiments undertaken during his PhD.

Author's signature:

Contents

This thesis includes a CD-ROM containing a colour version of the manuscript and a document detailing some of the numerical experiments undertaken to validate our code (in French).