CONTROL OF COMPLEX STRUCTURAL GEOMETRY IN OPTICAL FIBRE DRAWING

A thesis submitted for the degree of
Doctor of Philosophy

by

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2004
Preface

This thesis contains no material which has been presented for a degree at this or any other university and, to the best of my knowledge and belief, contains no copy or paraphrase of work published by another person, except where duly acknowledged.

Katja Lyytikäinen

Sydney, 28th March 2004
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ACKNOWLEDGEMENTS

I would like to thank my supervisors Pam McNamara, Simon Fleming and Adrian Carter for all the help they have provided during the course of this study. Special thanks are due to John Canning for his support and time in helping to solve the numerous challenges in the silica PCF project. I would also like to acknowledge the OFTC fibre fabrication team for their help. The preforms were made by Justin Digweed, Ron Bailey, Peter Henry, Tom Ryan and Barry Reed. Special thanks are due to Justin Digweed for setting up the pressurisation system, help in fibre drawing, measurements and stacking of the PCF preforms.

I also wish to acknowledge Shane Huntington of the University of Melbourne for making the etching and AFM measurements and Peter Pace for providing data on fibre etching. I thank the staff of the Australian Key Centre for Microscopy and Microanalysis, University of Sydney: Adam Sikorski for preparing the TEM samples, Shaun Bulcock for operating the STEM and Ian Kaplin for his help with the SEM. I would also like to acknowledge Yucheng Zhao of the OFTC who developed the tomographic software and Jarek Abramczyk of Nufern Ltd for fibre refractive index profile measurements.

Appreciation must also go to the following members of OFTC for their help: Elizabeth Buckley for measurements on PCFs, Joseph Zagoni for stacking PCF preforms and Leon Poladian for doing the dispersion simulations. I also thank the following people: Geoff Barton (University of Sydney), Karl-Friedrich Klein (FH Giessen-Friedberg) and Gerhard Schütz (Heraeus-Tenevo) for useful discussions and Heraeus-Tenevo for preform samples; Juha Ruokolainen and Peter Råback from CSC-Scientific Computing for developing the ELMER-program; Bernard Pailthorpe and Ben Simmons of Vislab at the University of Sydney for computing help. I would also like to acknowledge Australian Government, DEST, the University of Sydney and the Australian Photonics Cooperative Research Centre for funding.

Finally I would like to express my deepest gratitude and love for my fiancé Justin for his dedication in helping me in every way possible during my candidature.
ABSTRACT

Drawing of standard telecommunication-type optical fibres has been optimised in terms of optical and physical properties. Specialty fibres, however, typically have more complex dopant profiles. Designs with high dopant concentrations and multidoping are common, making control of the fabrication process particularly important. In photonic crystal fibres (PCF) the inclusion of air-structures imposes a new challenge for the drawing process.

The aim of this study is to gain profound insight into the behaviour of complex optical fibre structures during the final fabrication step, fibre drawing. Two types of optical fibre, namely conventional silica fibres and PCFs, were studied. Germanium and fluorine diffusion during drawing was studied experimentally and a numerical analysis was performed of the effects of drawing parameters on diffusion. An experimental study of geometry control of PCFs during drawing was conducted with emphasis given to the control of hole size. The effects of the various drawing parameters and their suitability for controlling the air-structure was studied. The effect of air-structures on heat transfer in PCFs was studied using computational fluid dynamics techniques.

Both germanium and fluorine were found to diffuse at high temperature and low draw speed. A diffusion coefficient for germanium was determined and simulations showed that most diffusion occurred in the neck-down region. Draw temperature and preform feed rate had a comparable effect on diffusion. The hole size in PCFs was shown to depend on the draw temperature, preform feed rate and the preform internal pressure. Pressure was shown to be the most promising parameter for on-line control of the hole size. Heat transfer simulations showed that the air-structure had a significant effect on the temperature profile of the structure. It was also shown that the preform heating time was either increased or reduced compared to a solid structure and depended on the air-fraction.
The majority of the work presented in this thesis has been published in the following publications [A1-A9]. During the course of the study a large number of papers were published which resulted indirectly from the findings in this thesis and where the research done in this thesis was essential to the published studies. These co-authored papers are listed below in [A10-A41] and include studies in the area of FBG in PCFs [A20, A22, A29, A39], Fresnel fibres [A18, A19, A23, A26, A27, A38], cleaving of PCFs [A16, A30, A31], tapering of PCFs [A21], microfluidics [A11, A34-A37] and preform and fibre measurement techniques [A10, A13, A14, A28, A32, A33].

First author journal papers


First author conference papers


A7. Lyytikäinen, K. and Huntington, S. T., "Characterising submicron changes in optical fibres due to the drawing process using atomic force microscopy,"


Co-authored journal papers


Co-authored conference papers


<table>
<thead>
<tr>
<th>ACRONYMS</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFM</td>
<td>atomic force microscopy</td>
</tr>
<tr>
<td>ASOF</td>
<td>application specific optical fibres</td>
</tr>
<tr>
<td>BHF</td>
<td>buffered HF</td>
</tr>
<tr>
<td>BSE</td>
<td>back-scattered electron</td>
</tr>
<tr>
<td>CRN</td>
<td>continuous random network</td>
</tr>
<tr>
<td>CT</td>
<td>computer tomography</td>
</tr>
<tr>
<td>DCF</td>
<td>dispersion-compensating fibre</td>
</tr>
<tr>
<td>EDFA</td>
<td>erbium-doped fibre amplifier</td>
</tr>
<tr>
<td>EDS</td>
<td>energy dispersive spectrometry</td>
</tr>
<tr>
<td>EELS</td>
<td>electron energy loss spectroscopy</td>
</tr>
<tr>
<td>EMU</td>
<td>Electron Microscope Unit</td>
</tr>
<tr>
<td>EPMA</td>
<td>electron probe microanalyser</td>
</tr>
<tr>
<td>ESI</td>
<td>equivalent step-index</td>
</tr>
<tr>
<td>FBG</td>
<td>fibre Bragg gratings</td>
</tr>
<tr>
<td>FEG</td>
<td>field emission guns</td>
</tr>
<tr>
<td>FFP</td>
<td>far-field profile</td>
</tr>
<tr>
<td>FIB</td>
<td>focused ion beam</td>
</tr>
<tr>
<td>FIC</td>
<td>flow indicator and controller</td>
</tr>
<tr>
<td>ID</td>
<td>inner diameter</td>
</tr>
<tr>
<td>MCVD</td>
<td>modified chemical vapour deposition</td>
</tr>
<tr>
<td>MFD</td>
<td>mode-field diameter</td>
</tr>
<tr>
<td>MM</td>
<td>multimode</td>
</tr>
<tr>
<td>MPOF</td>
<td>microstructured polymer optical fibre</td>
</tr>
<tr>
<td>NA</td>
<td>numerical aperture</td>
</tr>
<tr>
<td>NFP</td>
<td>near-field profile</td>
</tr>
<tr>
<td>NZ-DSF</td>
<td>nonzero-dispersion-shifted fibres</td>
</tr>
<tr>
<td>OD</td>
<td>outer diameter</td>
</tr>
<tr>
<td>OFTC</td>
<td>Optical Fibre Technology Centre, University of Sydney</td>
</tr>
<tr>
<td>OVD</td>
<td>outside vapour deposition</td>
</tr>
<tr>
<td>PBG</td>
<td>photonic band gap</td>
</tr>
<tr>
<td>PCF</td>
<td>photonic crystal fibre</td>
</tr>
<tr>
<td>PCS</td>
<td>plastic-clad silica</td>
</tr>
</tbody>
</table>
PCVD  plasma chemical vapour deposition
PIC  pressure indicator and controller
PID  proportional-integral and derivative
PIPS precision ion polishing system
PMD  polarisation mode dispersion
PMMA polymethylmethacrylate
POF  polymer optical fibre
RI  refractive index
RIP  refractive index profile
RNF  refracted near-field
SD  standard deviation
SE  secondary electron
SEM  scanning electron microscopy
SIMS  secondary ion mass spectrometry
SM  single-mode
STEM  scanning transmission electron microscope
TEC  thermally expanded core
TEM  transmission electron microscopy
TIR  total internal reflection
VAD  vapour-phase axial deposition
WDM  wavelength division multiplexing
WDS  wavelength dispersive spectrometer
ZDF  zero-dispersion-shifted fibres
# NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Area, m²</td>
</tr>
<tr>
<td>C</td>
<td>Concentration, mol%</td>
</tr>
<tr>
<td>C_i</td>
<td>Concentration of species i, mol%</td>
</tr>
<tr>
<td>D</td>
<td>Diameter, m or diffusion coefficient, m²/s</td>
</tr>
<tr>
<td>D_0</td>
<td>Pre-exponential diffusion term, m²/s</td>
</tr>
<tr>
<td>E</td>
<td>Activation energy, J/mol or emissivity matrix (AIII)</td>
</tr>
<tr>
<td>F</td>
<td>Force, N or view factor matrix (AIII)</td>
</tr>
<tr>
<td>G</td>
<td>Gebhardt factor</td>
</tr>
<tr>
<td>H</td>
<td>Internal heat generation, J/m³s or visibility function (AIII)</td>
</tr>
<tr>
<td>J</td>
<td>Diffusion flux, mol/m³s</td>
</tr>
<tr>
<td>K</td>
<td>Equilibrium constant</td>
</tr>
<tr>
<td>L</td>
<td>Length, m</td>
</tr>
<tr>
<td>N</td>
<td>Number of layers</td>
</tr>
<tr>
<td>M</td>
<td>Total amount of substance, mol</td>
</tr>
<tr>
<td>R</td>
<td>Gas constant, J/molK</td>
</tr>
<tr>
<td>S</td>
<td>Surface area, m² or sensitivity factor</td>
</tr>
<tr>
<td>T</td>
<td>Temperature, K or °C</td>
</tr>
<tr>
<td>V</td>
<td>Normalized frequency (Ch1) or velocity, m/s</td>
</tr>
<tr>
<td>a</td>
<td>Scaling factor</td>
</tr>
<tr>
<td>a_i</td>
<td>Constant (AIII), i=1-4</td>
</tr>
<tr>
<td>b</td>
<td>Constant (AIII)</td>
</tr>
<tr>
<td>c</td>
<td>Concentration, mol/m³ or constant (AIII)</td>
</tr>
<tr>
<td>c_p</td>
<td>Specific heat capacity, J/kgK</td>
</tr>
<tr>
<td>d</td>
<td>Diameter, m</td>
</tr>
<tr>
<td>f</td>
<td>Function</td>
</tr>
<tr>
<td>g</td>
<td>Acceleration of gravity, m/s²</td>
</tr>
<tr>
<td>h</td>
<td>Heat transfer coefficient W/m²K, or thickness (S4.1.2), m</td>
</tr>
<tr>
<td>k</td>
<td>Heat conductivity, W/mK</td>
</tr>
<tr>
<td>k_j</td>
<td>Reaction rate constant, j=reaction number</td>
</tr>
<tr>
<td>n</td>
<td>Normal to the surface or refractive index or reaction order</td>
</tr>
<tr>
<td>p</td>
<td>Pressure, Pa</td>
</tr>
</tbody>
</table>
\( p_0 \) Pressure difference between hole and atmosphere, Pa
\( q \) Heat flux, W/m\(^2\)
\( r \) Radial coordinate, radius, m
\( r_{	ext{etch}} \) Etching reaction rate, mol/m\(^2\)s
\( r_{	ext{ID}} \) Initial tube inner radius, m
\( t \) Time, s or thickness, m
\( v \) Velocity, m/s
\( x \) Spatial coordinate, m
\( y \) Spatial coordinate, m
\( z \) Axial coordinate, m or length, m

**Greek symbols**

\( \Delta \) Relative index difference
\( \Lambda \) Pitch, m
\( \alpha \) Absorption coefficient, m\(^{-1}\)
\( \beta \) Angle
\( \varepsilon \) Emissivity
\( \varepsilon' \) Constant involving emissivity (S5.1)
\( \phi_c \) Critical angle
\( \eta \) Kinematic viscosity, m\(^2\)/s
\( \lambda \) Wavelength, m
\( \mu \) Dynamic viscosity, Pas
\( \theta \) Angle
\( \rho \) Density, kg/m\(^3\)
\( \sigma \) Stefan-Boltzmann constant
\( \xi \) Surface tension, N/m

**Subscripts**

0 Initial
1 Inner (S.5.1)
2 Outer (S5.1)
a Ambient
c Conduction
e  External fluid
ext External
f  Fibre or fictive (S4.1.1)
g  Gravity or glass transition (S4.1.1)
I  Inertia
i  Surface participating in radiation
k  Surface participating in radiation
p  Preform
r  Radiation
T  Tension
ξ  Surface tension