



THE UNIVERSITY
of ADELAIDE

Nanodiamond in Optical Fibre

by

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in the

Faculty of Sciences

School of Chemistry & Physics

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Declaration of Authorship

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“Don’t panic.”

Douglas Adams, *The Hitchhiker’s Guide to the Galaxy*

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Abstract

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Diamond, prized as both a gemstone and a cutting and polishing material, has recently been recognised for another remarkable property, a host of optically active colour centre defects. With the rise of interest in these colour centres, due to the unique optical properties, comes a need for interfacing with other optical platforms. Recent advances have attempted to fabricate optical structures from the diamond itself, or to combine these colour centres with the well-known fabrication techniques of other materials by placing nanodiamond crystals on the surface of other structures, such as microdisks, microspheres, and optical fibres.

This thesis presents a new approach to this integration by demonstrating the fabrication of a hybrid nanodiamond-glass material. This technique embeds the nanodiamond within the optical structure, offering interaction with the bound optical fields, protection, and ease of fabrication. A range of optical structures has previously been fabricated from the chosen glass, tellurite, and fabrication of an optical fibre is demonstrated here.

Also presented is the derivation of a model describing coupling of an emitter to an optical fibre. While used here to investigate coupling of diamond colour centres to the optical fibre modes, it is more generally applicable to any emitter.

These results show the first steps of a new approach to diamond integrated photonics.

Acknowledgements

Firstly, a special thank you to my supervisors, Shahraam Afshar, Heike Ebendorff-Heidepriem, Andrew Greentree and Tanya Monro. This thesis would not have been possible without their discussions, assistance and support — and their efforts above and beyond the call of duty in the face of a looming deadline for submission.

Thank you to Brant Gibson for your guidance during my time at the University of Melbourne — from discussions of measurements, to discussions of football and the best Teriyaki beef lunch I've ever had. Also from the University of Melbourne; David Simpson, Snjezana Tomljenovic-Hanic, Igor Aharonovich, Julius Orwa, and Stephen Praver. Without the sharing of their expertise in diamond there would only be tellurite in the diamond-tellurite fibre.

I appreciate the help of Alastair Dowler, Roger Moore, Kevin Kuan, Kenton Knight and Rachel Moore. Without their vast technical knowledge this project would not have proceeded.

Thank you to my office buddies, Erik Schartner, Stephen Warren-Smith, Michael Oermann, Sean Manning and Sebastian Ng, for the chats (both work-related and, more commonly, not so work-related), lunches, and occasional after-hours gaming sessions.

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I enjoyed working with everyone at IPAS, thank you all for the discussions and corridor meetings.

Finally, another special thanks — this time to my family for their support over the years. To my new family, my wife Katie for always being there for me, and my daughter Ruby for being so cute and making me happy every time I look at her.

Contributions

All aspects of the project were discussed at regular meetings with my supervisors — Shahraam Afshar, Heike Ebendorff-Heidepriem, Andrew Greentree and Tanya Monro — and, later in the project, Brant Gibson (University of Melbourne).

Chapter 2

I derived the equations for the coupling coefficients, using Snyder and Love's *Optical Waveguide Theory*. I researched the appropriate power function needed to normalise the guided power capture, beginning with a dipole radiating in a bulk material. When we realised that this did not include the effects of the fibre structure (and specifically the core-cladding interface), I deduced that the correct expression was to use the radiation modes, in addition to the guided mode power, to calculate total power.

I wrote the Matlab code to calculate these coupling coefficients and the radiation modes and power, and the Meep control files of the finite-difference time domain method calculations. Step-index mode solving code was written in collaboration with Kris Rowland.

The whispering gallery mode calculations were performed in collaboration with Shahraam Afshar. The planning of the investigation into this effect, and obtaining and discussion of the results, was a joint exercise, and included some discussions with Kris Rowland and Alexandre Francois. I wrote the Matlab code to calculate the guided and radiated power, the corresponding electric and magnetic fields, and the code to find contributions from different β ranges. Shahraam Afshar derived the expression for, and wrote the code to calculate, the positions of the pure whispering gallery mode modal solutions.

Chapter 3 and 4

Glass fabrication was performed by Kevin Kuan and Kenton Knight, with some assistance from me. Planning of the glass melts was a joint discussion between me, Heike Ebendorff-Heidepriem, and either Kevin Kuan or Kenton Knight. I performed the preform extrusions. The fibre drawing was performed by Roger Moore and Alastair Dowler, with some assistance and guidance from me. Lidded wagon-wheel fabrication included discussions with Heike Ebendorff-Heidepriem and Roger Moore.

I performed the scanning electron microscope imaging, with assistance from Heike Ebendorff-Heidepriem and Rachel Moore. Raman spectroscopy of glass sample G1 was performed by Elizabeth Carter (Vibrational/Electronic Spectroscopy, School of Chemistry, The University of Sydney). Raman and photoluminescence spectroscopy, and NV^0/NV^- ratio measurements on preform sample P2 were performed by Igor

Aharonovich and Julius Orwa (University of Melbourne). I performed the optical microscope imaging.

I performed the confocal imaging and anti-bunching measurements, with training and assistance from Brant Gibson. Confocal measurements were planned in collaboration with Brant Gibson. The confocal system used was previously set up at the University of Melbourne.

Contents

Declaration of Authorship	iii
Abstract	v
Acknowledgements	vi
Contributions	vii
List of Figures	xiii
List of Tables	xvii
List of Abbreviations	xix
Physical Constants	xx
Symbols	xxiii
1 Introduction	1
1.1 Nitrogen-vacancy colour centres	2
1.2 Other candidate single photon sources	4
1.3 Combining diamond and photonic structures	5
1.4 Microstructured optical fibres	6
1.5 Outline	8
2 Modelling	9
2.1 Modelling of dipole-fibre coupling	11
2.1.1 Extension to multiple emitters	14
2.2 Analytical model results	16
2.2.1 Total power change	16
2.2.2 Capture fraction	19
2.2.3 Whispering Gallery Modes	23
2.2.3.1 Identification through field patterns and peak positions	26
2.2.3.2 Coupling changes: radiation pattern narrowing	28
2.2.3.3 Sensitivity to refractive index change	30
2.2.3.4 Fabry-Perot type mode peaks in total power	32
2.3 Finite-difference time domain method: validating the analytical model .	33
2.3.1 Selective mode coupling	35
2.3.2 Total emitted power	36
2.3.3 Capture fraction	39
2.3.4 Whispering gallery modes	43
2.4 Conclusion	45

3	Glass Fabrication and Optical Characterisation	47
3.1	Summary of samples	48
3.2	General fabrication information	50
3.2.1	Diamond nanocrystals	50
3.2.2	Tellurite glass	50
3.2.3	Glass fabrication	52
3.2.4	Unstructured fibre fabrication	53
3.3	Characterisation methods	55
3.3.1	Confocal microscopy	55
3.3.2	Photon statistics measurement	56
3.3.3	Raman properties of nanodiamond	57
3.3.4	Scanning electron microscopy	58
3.4	Initial glass trials	58
3.4.1	G1 diamond polishing powder-doped block	58
3.4.1.1	G1: Loss measurement	59
3.4.1.2	G1: Raman spectroscopy	59
3.4.1.3	G1: Confocal microscopy	59
3.4.2	G2 non-irradiated nanodiamond-doped	62
3.4.2.1	P2: Photoluminescence	63
3.4.2.2	P2: Increase in negative nitrogen-vacancy to neutral nitrogen-vacancy ratio	65
3.4.2.3	P2: Preferential graphite oxidation in glass melt conditions	66
3.4.2.4	F2: Confocal microscopy	66
3.4.2.5	F2: Scanning electron microscopy	67
3.4.3	G3 reduced nanodiamond concentration	69
3.4.3.1	P3: Loss measurements	70
3.4.3.2	F3: Confocal microscopy	71
3.5	Further reducing nanodiamond concentration	74
3.5.1	G4 nanodiamond dilution	75
3.6	Irradiated nanodiamond	76
3.6.1	G5 irradiated nanodiamond-doped	78
3.7	Conclusion	79
4	Microstructured Fibres	81
4.1	Wagon-wheel fabrication	82
4.1.1	Using pressurisation and vacuum	84
4.2	Wagon-wheel fibre samples	84
4.2.1	G6 non-irradiated nanodiamond-doped 50mm billet	84
4.2.2	P6 wagon-wheel preform	85
4.2.3	F6a wagon-wheel fibre	85
4.3	Lidded wagon-wheel fibre	89
4.3.1	T6b tube with extruded slot	90
4.3.2	F6b lidded wagon-wheel fibre	90
4.3.3	T6c tube with cut slot	91
4.3.4	F6c lidded wagon-wheel fibre	91
4.3.5	Confocal imaging of lidded wagon-wheel	92
4.4	Conclusion	95

5	Conclusion	99
A	Derivations	103
A.1	Step-index guided mode fields	103
A.1.1	Hybrid (HE) modes	103
A.1.2	Transverse electric (TE) modes	104
A.1.3	Transverse magnetic (TM) modes	104
A.2	Step-index radiation mode fields	105
A.3	Single emitter coupling to step-index fibre modes	108
A.4	Extension to multiple emitters	112
A.5	Mode power from coupling coefficients	113
B	Published papers	115
B.1	Diamond in Tellurite Glass: a New Medium for Quantum Information	115
B.2	Dipole emitters in fiber: interface effects, collection efficiency and optimization	121
C	Glass fabrication details	135
C.1	Sample number conversion to in-house codes	135
C.2	Tellurite annealing process	135
C.3	Subtracting Fresnel reflection from UV-Vis spectra	136
C.4	Calculating loss	136
	Bibliography	137

List of Figures

1.1	Diagram of an NV colour centre	2
1.2	Energy level diagram for the NV^- charge state of NV	3
1.3	SEM image of a wagon-wheel suspended core fibre	8
2.1	Diagram of the step-index model with a single dipole	11
2.2	Total dipole power versus core diameter for $n_{\text{core}} = 1.6, 2, 2.5$. Step-index fibre in air cladding. Dipole is z -oriented and emitting at 700 nm	18
2.3	Total power versus dipole radial position for different core diameters. Step-index fibre with core refractive index of 2 in air cladding. Dipole is z -oriented and emitting at 700 nm	19
2.4	Comparison of capture fraction results using modal expansion and bulk material expressions for total power	20
2.5	Capture fraction vs. core diameter and dipole position	21
	(a) Radial dipole	21
	(b) Azimuthal dipole	21
	(c) Longitudinal dipole	21
2.6	Slice at $\rho = 0.5$ of azimuthal capture fraction data	22
2.7	Maximum capture fraction as a function of cladding index	24
2.8	Total power vs. core diameter, showing WGM resonances	24
2.9	Schematic showing a WGM in a fibre geometry	25
2.10	S_z showing WGM resonance for z -oriented dipole	26
2.11	Comparison of peaks to WGM TE modal solutions	27
2.12	Contributions of beta components to WGM peaks	29
2.13	Schematic showing a representation of β for radiation modes	30
2.14	WGM resonance shifts due to cladding refractive index change	31
2.15	Total power versus core diameter and dipole position, showing Fabry-Perot interference conditions	34
2.16	FDTD flux along the fibre length	36
2.17	FDTD calculated E_y field for a z -oriented dipole at the centre of the fibre	37
2.18	Comparison of fields and intensity obtained using the FDTD method and step-index fibre analytical field expressions	38
2.19	Schematics of the FDTD domain for calculating power.	39
	(a) Dipole at fibre centre	39
	(b) Dipole at fibre interface	39
	(c) Dipole in bulk glass for normalisation	39
2.20	Comparison of total power emitted by the dipole obtained by FDTD and step-index model	40
2.21	Convergence for FDTD total power calculation	40
2.22	FDTD flux integration surfaces for power calculations	41
2.23	Comparison of capture fraction results for FDTD and analytical method	42
2.24	Convergence for FDTD capture fraction calculation	43
2.25	Comparison of WGM peaks calculated by FDTD and analytical method	44
2.26	Comparison of WGM fields using FDTD and analytical method	44
	(a) E_z field showing WGM in fibre obtained via FDTD	44
	(b) S_z field showing WGM in fibre obtained via analytical method	44
3.1	Image of extrusion die	54

3.2	Bare fibre fabrication schematic	54
3.3	Confocal schematic	56
3.4	Raman spectrum of non-irradiated ND	57
3.5	Image of glass G1	58
3.6	UV-Vis loss measurements for sample G1	60
	(a) Loss vs. wavelength	60
	(b) Loss vs. wavelength ⁻⁴	60
3.7	Raman spectrum for sample G1 at 488 nm	61
	(a) Full	61
	(b) Zoom	61
3.8	Confocal image of glass sample G1	62
3.9	Anti-bunching data for glass sample G1	63
3.10	Spectrum of single centre in glass sample G1	64
	(a) NV centre and background	64
	(b) Background subtracted	64
3.11	Image of glass G2	65
3.12	PL spectrum of preform P2	65
3.13	NV ⁻ to NV ⁰ ratio improvement in preform P2	66
3.14	Raman spectrum of preform P2	67
3.15	Confocal scan and anti-bunching data for fibre F2	68
3.16	SEM images of fibre F2	69
	(a) Bare fibre cross-section	69
	(b) Zoom of a hole	69
3.17	Microscope images comparing hole defects in bare fibre samples	70
	(a) Fibre F2	70
	(b) Fibre F3	70
	(c) Fibre F4	70
3.18	Image of glass G3	71
3.19	UV-Vis loss measurements for sample P3	72
	(a) Loss vs. wavelength	72
	(b) Loss vs. wavelength ⁻⁴	72
3.20	Comparison of NV density	73
	(a) F3: 9.4 ppm wt. ND	73
	(b) F2: 280 ppm wt. ND	73
3.21	Anti-bunching data for fibre F3	74
3.22	Image of glass G4	75
3.23	Confocal scan of fibre F4	76
3.24	Comparison of emission from confocal scan	77
	(a) Non-irradiated (F3)	77
	(b) Irradiated (F5)	77
3.25	Image of glass G5	78
	(a) Side view	78
	(b) Bottom view	78
4.1	Structured fibre fabrication schematic	83
4.2	Die design for wagon-wheel preform	84
4.3	Diagram of pressurisation schemes	85

4.4	Images of glass G6	85
	(a) Side view	85
	(b) Bottom view	85
4.5	Images of wagon-wheel preform P6	86
	(a) Cross-section	86
	(b) Side	86
4.6	SEM image of wagon-wheel fibre F6a	86
	(a) Cross-section	86
	(b) Core region	86
4.7	Confocal image of fibre F6a	87
4.8	Schematic showing the lidded wagon-wheel fibre fabrication	89
4.9	Extrusion die used for slotted tube preform T6b	90
4.10	Images of slotted tube preform T6b	90
4.11	Microscope image of lidded wagon-wheel fibre F6b	91
4.12	Schematic of cut cladding slot for lidded wagon-wheel	92
4.13	Images of tube preform T6c after cutting slot	92
	(a) Side, showing limited slot	92
	(b) Cross-section	92
4.14	Evolution of fibre draw for lidded wagon-wheel fibre F6c	93
4.15	SEM images of lidded and standard wagon-wheel fibre	94
4.16	Schematic of confocal scan direction	95
4.17	Confocal cross-sections comparing lidded to standard wagon-wheel fibre	96
	(a) Standard wagon-wheel	96
	(b) F6c lidded wagon-wheel	96
	(c) F6c lidded wagon-wheel	96

List of Tables

2.1	Maximum capture fractions	22
2.2	Comparison of resonance Q -factor to WGM modal solutions	30
3.1	Summary of fabricated glasses	49
3.2	Summary of fabricated fibres in Chapter 3	50
3.3	Summary of fabricated fibres in Chapter 4	50
A.1	Radiation mode coefficients	107
C.1	Glass and preform samples	135
C.2	Fibre samples	135

List of Abbreviations

AFM	atomic force microscope
APD	avalanche photodiode
CVD	chemical-vapour deposition
FDTD	finite-difference time domain
HBT	Hanbury Brown-Twiss
IPAS	Institute for Photonics & Advanced Sensing
MOF	microstructured optical fibre
NA	numerical aperture
ND	nanodiamond
NV	nitrogen-vacancy
NV⁰	neutral nitrogen-vacancy
NV⁻	negative nitrogen-vacancy
ODMR	optically detected magnetic resonance
PL	photoluminescence
PML	perfectly-matched layer
RAM	random access memory
RF	radio frequency
RT	room temperature
SEM	scanning electron microscopy
SNOM	scanning near-field optical microscope
UV-Vis	ultraviolet-visible spectroscopy
WGM	whispering gallery mode
ZPL	zero phonon line

Physical Constants

Speed of Light	c	$=$	$2.997\,924\,58 \times 10^8 \text{ m s}^{-1}$	(defined)
Permittivity of free space	ϵ_0	$=$	$8.854 \times 10^{-12} \text{ F m}^{-1}$	
Permeability of free space	μ_0	$=$	$4 \pi \times 10^{-7} \text{ V s A}^{-1} \text{ m}^{-1}$	

Symbols

a	coupling coefficient
k_0	free space wavenumber
n	refractive index
N_j	$= \frac{1}{2} \int_{A_\infty} \mathbf{e}_j \times \mathbf{h}_j^* \cdot \hat{\mathbf{z}} \, dA$
P	power
r_{core}	fibre core radius
β	propagation constant
λ	wavelength
ω	angular frequency
ρ	normalised dipole radial position (r/r_{core})

*To my lovely wife Katie,
and our daughter Ruby (the cutest baby in the world),
this is for you kiddo.*