THE UNIVERSITY of ADELAIDE

Nanodiamond in Optical Fibre

by

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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 Prawer. 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.

To Kris Rowland, thank you for the unannounced drop-ins whenever I had a question and for the chats that usually followed.

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.

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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

NV^0 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	$=$	$2.997\,924\,58 \times 10^{8}\,\mathrm{m\,s^{-1}}$ (defined)
Permittivity of free space	ϵ_0	$=$	$8.854 \times 10^{-12}\,\mathrm{F\,m^{-1}}$
Permeability of free space	μ_0	$=$	$4\,\pi \times 10^{-7}\ \mathrm{V\,s\,A^{-1}\,m^{-1}}$

Symbols

a	coupling coefficient
k_0	free space wavenumber
n	refractive index
N_j	$= \frac{1}{2} \int_{A_\infty} \mathbf{e}_j \times \mathbf{h}_j^* \cdot \hat{z} \ \mathrm{d}A$
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.