THE UNIVERSITY
of ADELAIDE

Development of air-clad holmium-doped silica fibre lasers

by

Sebastian Ng

A thesis submitted for the degree of
Doctor of Philosophy

in the
Faculty of Sciences
School of Physical Sciences

December 2016

Abstract

This thesis describes the development of microstructured rare-earth-doped silica fibres for high power lasers. Motivated by the demand for increasingly higher power fibre lasers, this research aims to overcome the power scaling limits from non-linear effects in optical fibres. The project focussed on the demonstration of the first air-clad holmium-doped silica fibre laser. Novel fabrication techniques were employed to directly drill air-claddings in preforms produced with modified chemical vapour deposition.

Key limitations for increasing single-mode laser output powers are the onset of non-linear effects, the coupling of pump power from high-power low-brightness sources, and poor lasing efficiency. Holmium doped fibre lasers were identified as a promising pathway for overcoming these power scaling limits due to their potential for high efficiencies and long wavelength emission in silica. Low loss high numerical aperture air-clad fibres were used to address the limited pump coupling, which is a primary restriction for power scaling of holmium-doped fibre lasers.

Low dopant concentration fibres were fabricated to prevent clustering of holmium ions, which can limit the efficiency of holmium lasers. To compensate for the reduced pump absorption, small cladding to core area ratios were used. Coupling ability of the reduced pump cladding area was achieved with the low-loss high numerical aperture air-claddings.

Multiple cladding geometries were fabricated and characterised to show their suitability for fibre laser operation. The highest reported numerical aperture for holmium-doped double-clad silica fibre was achieved. Air-clad holmium-doped fibre lasers, pumped with in-house developed thulium lasers, were demonstrated. Over 10 W of output power at 2.1 μm was achieved with high beam quality. Mechanical, thermal and laser transition modelling was performed to analyse the lasing results. This revealed that the reduction of fibre length through changes in cladding geometry or increased dopant concentration are critical for efficient high-power double-clad holmium doped fibre lasers.

Air-clad holmium-doped fibre lasers are an attractive pathway for increasing high-power fibre laser output powers. These findings show potential for compact infra-red laser sources, short fibre length laser applications, and are a key step in the development of efficient high-power directly-diode pumped holmium-doped fibre lasers.

Acknowledgements

I acknowledge the hard work and support of my primary supervisor David Ottaway in providing extraordinary amounts of advice, encouragement and discussion. Without your help this project would not have been possible, thank you. I would also like to thank my supervisor Tanya Monro for her unerring patience and her guidance throughout this project. I greatly appreciate the support of Peter Henry, for all of his advice and dedication in teaching me the ins and outs of silica fabrication. I would like to thank David Lancaster for the time and effort he spent on the early stages of this project and his contribution to my research.

I would like to acknowledge my friends and colleagues at the University of Adelaide for their friendship and support including Erik Schartner, Matthew Henderson, Elizaveta Klantsataya, Myles Clark, Christopher Kalnins, Ori Henderson-Sapir, Miftar Ganija, Ka Wu, Andre Luiten, Andrew McKinnon, Peter Veitch, Nigel Spooner, Herbert Foo, Heike Ebendorff-Heidepriem, Murry Hamilton, Alexandre Francois, Megan Schartner, Tristan Davies and Jesper Munch.

This project was made easier and more pleasant with the help of the professional staff of the School of Chemistry and Physics, especially Adrian Giffen, Adrian Selby, Alastair Dowler, Blair Middlemiss, Carol Maelzer, Jeanette Roulston, Katie Burton, Mary Odlum, Olivia Towers, Ramona Adjoran, Sharon Leech and Wayne England.

On a personal note, I would like to thank my partner Liz who has provided a never ending supply of support both, emotionally and in my formation of words. I would also like to thank my family Mum, Dad, Lorraine, Georgia, Smokey, Kibble, and Martin.

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968.

I also give permission for the digital version of my thesis to be made available on the web, via the Universitys digital research repository, the Library Search and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

Contents

Acronyms

Al^{3+} aluminium

AOI angle of Incidence

AOTF acousto-optical tunable filter

AR anti-reflection

ASE amplified spontaneous emission

BOP beginning-of-pull

CAD computer aided design

CCD charge-coupled device

CW continuous-wave

CGS colloidal graphite solution

dB decibel

Dy^{3+} dysprosium

EOP end-of-pull

Er^{3+} erbium

Eu^{3+} europium

ESA excited state absorption

EST excited state transfer

FBG fibre Bragg grating

FEA finite element analysis

FWHM full-width at half-maximum

GDF germanium-doped fibre

Ge germanium

GSA ground state absorption

HeNe helium-neon

Ho^{3+} holmium

HOM higher-order modes

HR highly reflective

HT highly transmissive

InGaAs indium-gallium-arsenic

InGaAsP indium-gallium-arsenic-phosphorus

IR infrared

LIDAR light detection and ranging

LIMO Lissotschenko Mikrooptik GmbH

LMA large mode area

LWP long-wave pass

MCVD modified chemical vapour deposition

Mid-IR mid-infrared

MO microscope objective

MOF microstructured optical fibre

NA numerical aperture

ND neutral density

Nd^{3+} neodymium

NIR near-infrared

OD optical density

OH hydroxyl

OPO optical parametric oscillator

OSA optical spectrum analyser

PPM parts per million

PR partially reflective

RE rare-earth

RI refractive Index

RIU eefractive index units

RIP refractive index profile

SBS stimulated Brillouin scattering

RBW resolution bandwidth

SEM scanning electron microscope

SiO_2 silica

SMA second moment of area

SRS stimulated Raman scattering

SW-IR short-wave infrared

TIR total internal reflection

Tm^{3+} thulium

UTS ultimate tensile strength

UV ultra-violet

WLS white light source

Yb^{3+} ytterbium