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**Development of air-clad holmium-doped
silica fibre lasers**

by
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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.

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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.

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Acronyms

Al³⁺	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
Dy³⁺	dysprosium
EOP	end-of-pull
Er³⁺	erbium
Eu³⁺	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

Ho³⁺ 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

Nd³⁺ 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** refractive index units
- RIP** refractive index profile
- SBS** stimulated Brillouin scattering
- RBW** resolution bandwidth
- SEM** scanning electron microscope
- SiO₂** silica
- SMA** second moment of area
- SRS** stimulated Raman scattering
- SW-IR** short-wave infrared
- TIR** total internal reflection
- Tm³⁺** thulium
- UTS** ultimate tensile strength
- UV** ultra-violet
- WLS** white light source
- Yb³⁺** ytterbium