THE UNIVERSITY of ADELAIDE

Development of dual-wavelength pumped mid-infrared fibre laser

by

Ori Henderson-Sapir

Supervisors:
Dr. David J. Ottaway
Prof. Jesper Munch

A thesis submitted in fulfilment of the degree of Doctor of Philosophy

in the
Faculty of Science
School of Physical Sciences

July 2015

Declaration of Authorship

I, Ori Henderson-Sapir, declare that this thesis titled 'Development of dual-wavelength pumped mid-infrared fibre laser' and the work presented in it are my own. I confirm that:

- This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution to Ori Henderson-Sapir 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 acknowledge that copyright of published works contained within this thesis (as listed below) resides with the copyright holder(s) of those works.
- I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library Search, the Australasian Digital Theses Program (ADTP) and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

Signed: ______________________________

Date: ______________________________

For ***Annetay****, who deserves a PhD in patience.*

THE UNIVERSITY OF ADELAIDE

Abstract

Faculty of Science
School of Physical Sciences

Doctor of Philosophy

by Ori Henderson-Sapir

There is an urgent need for efficient and compact sources of coherent mid-infrared wavelength radiation (3-5 μm). Cost-effective and bright mid-infrared sources will lead to exciting new sensing applications, ranging from the remote sensing of greenhouse gases, such as CO_2 and methane, to analysis of trace gases in exhaled breath for disease marker identification.

The last decade has seen a continuing increase in the output power of various types of mid-infrared sources, such as optical parametric oscillators and amplifiers, quantum cascade lasers and fibre lasers. However, advances in brightness, efficiency, peak power and tunability are still necessary for many applications.

In this thesis, we describe a new concept for a fibre laser based on Er^{3+} doped ZBLAN glass that operates in the mid-infrared with lasing centred around 3.5 μm. We used a novel dual-wavelength pumping (DWP) scheme to achieve world-leading efficiency for this material and an output power of 260 mW.

The DWP technique uses long-lived excited states in our Er^{3+} ion doped ZBLAN glass gain medium to improve the Stokes efficiency. A low power, 985 nm pump source excites ions from the $^4I_{15/2}$ ground state to the long lived $^4I_{11/2}$ state. A large fraction of the ion population can be stored in this level because of its long lifetime, creating a "virtual ground state." A concurrent 1973 nm pump source is then used as the main pump source. This pump excites the ions further to the upper laser level $^4F_{9/2}$. Post lasing, the 1973 nm pump cycles the ions between the "virtual ground state" at $^4I_{11/2}$ and the $^4F_{9/2}$ level. The first pump at 985 nm maintains the population in the "virtual ground" as this population is diminished by spontaneous emission and energy-transfer processes, which eject ions from the lasing cycle.

In this thesis, we review the literature and the current state-of-the-art in mid-infrared fibre lasers. An overview of the spectroscopic properties of Er^{3+}:ZBLAN relevant to mid-infrared operation is presented. The difficulties and issues associated with the creation of mid-infrared radiation are discussed and our spectroscopic investigations of ZBLAN glass and glass fibres are summarised.

Multiple wavelengths were used as pump sources for our DWP laser. Our investigation of the optimal wavelength for the DWP technique and the development of suitable sources is described as well. The 3.5 μm laser system is discussed, including the full characterisation of the laser. The thesis is concluded with a summary of the results and an outlook for the future.

Acknowledgements

First and foremost, I would like to thank my supervisors David Ottaway and Jesper Munch. Without their guidance and advice this work would not have been possible.

During my PhD, I had the pleasure of working with a great bunch of people. The academics and students from the Optics Group, Alex Dinovitser, Andrew Malouf, David Hosken, Eleanor King, Huichao Luo (Nicky), Ka Wu, Keiron Boyd, Matt Heintze, Miftar Ganja, Murray Hamilton, Myles Clark, Muddassar Naeem, Nick Chang, Nikita Simakov, Peter Veitch and Sophie Hollit, were always available and happy to lend a hand or equipment and to provide advice.

Many others within the Institute for Photonics and Advanced Sensing (IPAS) have also helped along the way with advice and equipment including: Alexandre Frabcois, Andre Luiten, Andrew Richardson, Chris Kalnins, Chris Perella, Dale Godfrey, David Lancaster, Elodie Janvier, Eric Schartner, Fiorina Piantedosi, Georgios Tsiminis, Heike Ebendorff-Heidepriem, Herbert Fu, James Anstie, Kevin Kuan, Kristopher Rowland, Matt Henderson, Michael Oermann, Nigel Spooner, Olivia Towers, Philip Light, Piers Lincoln, Richard White, Sara Leggatt, Sean Manning, Sebastian Ng, Shahraam Afshar, Tanya Monro and Tilanka Munasinghe.

Special thanks are due to the School of Physical Sciences professional staff who were always there to help: Adrian Giffen, Adrian Selby, Alastair Dowler, Blair Middlemiss, Bob Chivell, Carol Maelzer, Jeanette Roulston, John Cameron, Katie Burton, Mary Odlum, Trevor Waterhouse, Ramona Adjoran, Sharon Leech, Neville Wild, Wayne England and Wendy Brown.

Last but not least is my family who was always there for me, my parents Aya and Yossi Sapir, my brother Yoav and sister Tali and Barbara, Bill and Benjamin Henderson, who always believed in me and provided encouragement and support. I am thoroughly indebted to all of you, for long phone conversations and your physical presence in Australia during some difficult times. Finally, I would like to thank my wife, partner and friend, Annetay, for her enduring love and support throughout this long journey. Without her I would have never made it to the finish line.

Thank you.

Contents

List of Figures

List of Tables

Abbreviations

Abbreviation	Meaning
AM	**A**mplitude **M**odulation
AR	**A**nti-**R**eflective
ASE	**A**mplified **S**pontanous **E**mission
BPF	**B**and **P**ass **F**ilter
CaF_2	**C**alcium **F**luoride
CW	**C**ontinous **W**ave
CR	**C**ross-**R**elaxation
DUT	**D**evice **U**nder **T**est
DWP	**D**ual-**W**avelength **P**umping
EDFA	**E**rbium **D**oped **F**ibre **A**mplifier
Er	**E**rbium
ESA	**E**xcited **S**tate **A**bsorption
ET	**E**nergy **T**ransfer
ETU	**E**nergy-**T**ransfer-**U**pconversion
FBG	**F**ibre **B**ragg **G**rating
FTIR	**F**ourier **T**ransform **I**nfra**R**ed
GSA	**G**round **S**tate **A**bsorption
HeNe	**He**lium **Ne**on
HR	**H**ighly **R**eflective
InGaAs	**I**ndium **G**alium **A**rsenide
InSb	**I**ndium **S**tibium (antimonide)

LD	**L**aser **D**iode
LIA	**L**ock **I**n **A**mplifier
LPF	**L**ong **P**ass **F**ilter
MIR	**M**id **I**nfra**R**ed
MP	**M**ulty **P**honon
NA	**N**umerical **A**perture
OAP	**O**ff-**A**xis **P**arabola
PbSe	**P**lumbum (lead) **S**elenide
RE	**R**are-**E**arth
SBS	**S**timulated **B**rillouin **S**cattering
SE	**S**timulated **E**mission
Si	**S**ilicon
SCS	**S**uper **C**ontinuum **S**ource
SRS	**S**timulated **R**aman **S**cattering
TEC	**T**hermo **E**lectric **C**ooler
Tm	**T**hulium
TFL	**T**hulium **F**ibre **L**aser
TTL	**T**ransistor **T**ransistor **L**ogic
ZBLAN	**Z**irconium **B**arium **L**anthanum **A**luminium **N**atrium (sodium)

Symbols

Symbol	Meaning
A_{clad}	Inner cladding area of a double-clad fibre
A_{core}	Area of fibre core
A_{ed}, A_{md}	Electric and magnetic dipole transitions radiative rates
A_{ij}	Radiative decay rate from level i to level j
A_r, A_{nr}, A_m	Radiative, non-radiative and measured decay rates of an energy level
b_i	Boltzmann factor for level energy i
c	Speed of light
C	Material dependant constant
C_s	Number of Stark levels in manifold
dl	Discretisation length of a fibre
e	Charge of electron
E, E_0	Absorbance and background absorbance
E_{ij}	Energy difference between each Stark level to the lowest Stark level of the same manifold
E_{s0}	Separation between the lowest Stark levels of two manifolds
f_{pump}, f_{probe}	Pump and probe beam modulation/chopping frequencies
g_0	Small signal gain coefficient
g_i	Degeneracy of level i
h	Planck constant

h_c	Convective heat transfer coefficient
I_0	Launched intensity
$I_{1973nm\,with\,pump}(\lambda_2)$, $I_{1973nm}(\lambda_2)$	Transmitted intensity of the 1973 nm band light with and without pump
I_{in}	Incident intensity
$I_{incident\,800nm}(\lambda_1)$	Incident 800 nm band intensity on fibre
I_{out}	Transmitted intensity
$I_{out\,800nm\,pump}(\lambda)$, $I_{out800nm}(\lambda_1)$	800 nm band light intensity transmitted through the fibre with and without pump
I_s	Saturation intensity
I_{single}, I_{double}	Fluorescence intensity from a single or double pass along a pumped fibre
I_u, I_p	Transmitted probe beam intensity in the unpumped and pumped cases
I_z	Fluorescence intensity at location z along the fibre
J	Total angular momentum
K	Host dependant constant
K_s	Slope of curve
k_B	Boltzmann constant
k_i	Thermal conductivity of layer i
l	Fibre length
LS	Host-independent reduced matrix parameters for specific dopant specie
Δl	Segment of fibre
m_e	Mass of electron
n	Refractive index

n_{inv}, $n_{inv\,th}$	Inversion average density and average density at laser threshold
$\hat{n}$	Parameter based on refractive index used in Judd-Ofelt analysis
$N_{^4I_{9/2}}$, $N_{^4I_{11/2}}$, $N_{^4I_{13/2}}$	Ion population density at the $^4I_{9/2}$, $^4I_{11/2}$ and $^4I_{13/2}$ levels
NA_b	Numerical aperture of cladding of fibre
N_e, $N_{excited}$	Total excited ion population
$\overline{N_e}$	Average over fibre of excited ion density
N_g, N_{ground}	Ground state population
$N_{ground\,with\,pump}$	Ground state population when pump is on
N_{Higher}	Population density of all excited states combined
N_i	Population density at energy level i
$N_i(z)$	Population density at energy level i at position z along a fibre
N_{Er}	Doping density
N_l, N_u	Partition function of lower and upper laser level manifolds
p	Number of phonons
P	Power
P_1	Power of first pump source
P_2	Power of second pump source
P_{abs}, P_l	Absorbed and launched pump power
P_{ed}, P_{md}	Calculated electric and magnetic dipole oscillator strength
P_{exp}	Measured dipole oscillator strength
$P_{in_i}(z, \lambda)$	Launched power of pump i at position z along the fibre and wavelength λ
$P_{inc_i}(\lambda)$	Incident power of pump i at wavelength λ

P_{out}	Laser output power
P_{sat}	Pump saturation power
P_{th}	Pump power at laser threshold
$R,\ R_1,\ R_2$	Mirror reflectivity
$R'_1,\ R'_2$	Equivalent reflectivity
R_F	Fresnel reflection
Q_0	Heat load density
r_{core}	Radius of fibre core
$R_{P_1\,GSA},\ R_{P_1\,ESA}$	Ground and excited-state absorption rate of the first pump
$R_{P_2\,ESA}$	Excited-state absorption rate of the second pump
$R_{SE\,ij}$	Stimulated emission rate from level i to level j
T	Temperature
T_0	Temperature at centre of fibre core
T_c	Temperature of coolant
$T_I(r),\ T_II(r)$	Temperature in regions I and II at radial coordinate r relative to centre of fibre core
$\lVert U^{(t)} \rVert$	Host-independent reduced matrix parameters for specific dopant type
$V_{v\,core}$	Doped core volume
$V_{\#\,core}$	Normalised frequency (V-number) of the fibre core
W_{ij}	Rate of two ion cross-relaxation or energy-transfer upconversion process involving ions from energy levels i and j
$W_{MP}(T)$	Multi-phonon rate
W_P	Pump rate
$W_{P_{GSA}}, W_{P_{ESA}}$	Ground state and excited-state absorption pump rates

α	Absorption coefficient
α', α''	Host dependant constants
α_c, α_d	Absorption coefficient in the core and cladding of a fibre (in cm^{-1})
$\alpha_{cdB/m}$	Absorption coefficient in the core (in dBm^{-1})
$\alpha_{eff_i}(z,\lambda)$	Effective absorption coefficient of pump i in the cladding of a fibre, at position z along the fibre and wavelength λ
β_{ij}	Branching ratio from level i to level j
γ	Inversion factor
δ	Cavity losses coefficient
ΔE	Energy gap
ΔT	Temperature difference
ϵ	Net free energy difference between the manifolds of two energy levels
η	Efficiency coefficient
η_B	Overlap coefficient between laser and pump modes
η_{in_i}	Launch efficiency of pump i
$\eta_{internal}$	Laser internal slope efficiency i
η_{op2op}	Optical-to-optical efficiency of a dual-wavelength pumped laser
η_s	Laser slope efficiency
η_{St}	Stokes efficiency (Quantum defect)
$\eta_{NR,GSA}$, $\eta_{NR,ESA}$	Fractions of energy lost to heat with every ground-state or excited-state absorption transition
$\eta_{R\,GSA}(\lambda)$, $\eta_{R\,ESA}(\lambda)$	Fractions of ions undergone ground-state and excited-state absorption transition

η_Q	Quantum efficiency
$\eta_{Q_{pump}}$	Fraction of absorbed pump power that is deposited as heat in the fibre
λ	Wavelength
λ_b	Absorption band barycentre
λ_{pi}	Wavelength of pump i
$h\nu_{max}$	Maximum phonon energy
ν_b	Absorption wavenumber barycentre
ν_{Laser}	Laser frequency
$\sigma_{800nm}(\lambda_1)$	Ground state absorption cross-section at a certain wavelength within the 800 nm band
$\sigma_{ESA\,1970nm}(\lambda_2)$	Excited-state absorption cross-section at a certain wavelength within the 1973 nm band
σ_{abs}	Absorption cross-section
σ_e	Emission cross-section
$\sigma_{ESA_{^4I_{13/2}}}(\lambda_1)$, $\sigma_{ESA_{^4I_{11/2}}}(\lambda_1)$	Excited-state absorption of 800 nm band light on the $^4I_{13/2} \rightarrow {}^2H_{11/2}$ and $^4I_{11/2} \rightarrow {}^4F_{3/2}$ transition, respectively
$\sigma_{P_1\,GSA}$, $\sigma_{P_1\,ESA}$	Ground and excited-state absorption cross-sections of the first pump
$\sigma_{P_1\,GSA\,em}$, $\sigma_{P_1\,ESA\,em}$	Emission cross-sections on the GSA and ESA transitions of the first pump
σ_{P_2}	Excited-state absorption cross-section of the second pump
$\sigma_{P_2\,em}$	Emission cross-section on the transition of the second pump
σ_{SE}	Emission cross-section
τ_f	Upper laser level intrinsic lifetime

$\tau_{i_{eff}}$	Effective lifetime of energy level i with energy-transfer processes
$\tau_i,\ \tau_{i_{int}}$	Intrinsic lifetime of energy level i
τ_{r_i}, τ_r	Radiative lifetimes of an energy level
$\tau_{nr},\ \tau_m$	Non-radiative and measured lifetimes of an energy level
ϕ	Photon flux density
ω	Angular frequency
Ω_t	Judd-Ofelt parameters

"Seek and you will find"	*"יגעת ומצאת – תאמין"*
Matthew 7:7	בבלי מגילה ו׳ ב׳