Development of continuous-wave Tm:YAlO$_3$ lasers for high power applications

by

Ka Shun Wu

A thesis submitted for degree of

Doctor of Philosophy

in

The University of Adelaide

School of Physical Sciences

October 2015

Statement of Originality

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 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;

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;

The author acknowledges 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 catalogue, 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: …………………………………………………

Supervisors: Prof. Jesper Munch, Dr. David J. Ottaway, A/Prof. David Lancaster

Abstract

Thulium and holmium lasers operating near 2 μm are required for applications in various industries, such as remote sensing and detection, spectroscopy, surgery and optical countermeasures. High power lasers with high brightness are necessary for many of these applications, with fibre lasers often preferred due to their various advantages. However, a major drawback of fibre lasers is the brightness requirement on the pump source, which needs to have moderate to high brightness in order to couple light into the fibres efficiently. Such pump sources are often prohibitively expensive.

A possible solution is the use of brightness converters. Brightness converters are lasers that are designed such that the output brightness is significantly greater than that of its pump source, and is sufficiently bright to pump fibre lasers efficiently. For example, by using a thulium-doped solid-state laser as a brightness converter, holmium-doped fibre lasers can be pumped efficiently by cheap, high power but low brightness diode stacks.

Thulium-doped $YAlO_3$ lasers are ideal for this purpose: their emission wavelength corresponds to the peak absorption of holmium in silica, high power diode stacks are readily available at its absorption wavelength, and it is a crystal with a high damage threshold. However, $Tm:YAlO_3$ lasers suffer from significant self-pulsing, which can lead to unstable gain-switching of the holmium-doped fibre laser as well as risking damage due to the high peak power.

In this thesis, I describe the investigation and development of $Tm:YAlO_3$ lasers as high power brightness converters and pump sources. A detailed analysis of the self-pulsing is conducted using a 6.5 W $Tm:YAlO_3$ laser. The self-pulsing is shown initially to be consistent with an unstable relaxation oscillation in the gain medium. A model based on significant excited-state absorption at the lasing wavelength is shown to reproduce the experimental results. The assumed cross-section required for this process is tested in a further experiment, which rules out this theory. The Tm:$YAlO_3$ laser is then analysed as a chaotic system, with results from time delay embedding and the 0–1 test for chaos indicating strongly that the laser system is chaotic. To the best of my knowledge, this is the first analysis and evidence of Tm:$YAlO_3$ lasers as a chaotic system.

I describe the suppression of the self-pulsing using a method applicable to high power. Using this feedback system, the Tm:$YAlO_3$ laser is shown to produce a stable, continuous-wave output. To the best of my knowledge, this is the first demonstration of the suppression of such strong self-pulsing.

This thesis also describes the design and development of a high power Tm:$YAlO_3$ laser using a novel geometry, which in principle is capable of several hundred watts of output power. This design aims to combine the superior thermal handling of disk lasers with the ease of pumping and laser design of the slab laser. A comprehensive model of such a laser is described, and the development of the laser up to the construction stage is presented.

Acknowledgements

First and foremost, I would like to thank my supervisors Jesper Munch, David Ottaway and David Lancaster for all of the support and guidance they have provided me through the course of my PhD. In the same vein, I would like to thank Peter Veitch, who has essentially been an additional supervisor for me.

To David Hosken: words cannot express my gratitude for all of your help and advice throughout my PhD. Without it, I would have been so lost.

To the members of the Optics group: Eleanor, Keiron, Matt, Miftar, Murray, Myles, Nick, Ori, Sophie, and the rest of the group: thank you for all the discussions and help in the lab. To those that have graduated, thank you for showing me that it is in fact possible!

To Blair, Neville and Trevor: I am very grateful for all the excellent technical assistance and advice you have provided.

To the staff at the school, Carol, Jeanette, Katie, Mary, Ramona, Sharon, Wayne, and the front office staff: thank you for the all the administrative support.

I would like to thank those in the OSA/SPIE student chapter, for making my PhD journey so enjoyable and giving me much needed morale boosts. Hosting the KOALA conference was one of the highlights of my PhD experience, and thank you for making it so successful with me! I will miss organising and attending the events.

Finally, I am eternally grateful to my parents, Georgia, and my close friends for being there for me through my journey. Without the love and support from all of you, I would not have made it to the finish line.

Contents

List of Symbols....vii

List of Figures....xi

List of Tables....xix

1 Introduction....1

  1.1 Mid-infrared lasers....1

    1.1.1 Thulium and holmium lasers....2

  1.2 Beam quality and brightness....4

    1.2.1 Fibre lasers as high-brightness sources....5

    1.2.2 Brightness converters....6

  1.3 Thulium-doped brightness converter....7

    1.3.1 Crystal host....7

    1.3.2 Tm:$YAlO_3$ laser properties....9

      1.3.2.1 Sellmeier's Equation....10

    1.3.3 Self-pulsing in Tm:$YAlO_3$ lasers....11

      1.3.3.1 Pulse suppression techniques....12

    1.3.4 Tm:$YAlO_3$ laser systems....13

    1.3.5 Laser geometry....14

  1.4 Thesis overview....15

2 Low-power Tm:$YAlO_3$ cuboid laser....17

  2.1 Introduction....17

  2.2 Absorption spectroscopy of Tm:$YAlO_3$....18

  2.3 Initial cuboid laser....20

    2.3.1 Laser design....20

      2.3.1.1 Thermal lensing....21

      2.3.1.2 Cavity mode modelling....24

2.3.2 Laser operation 25
2.3.2.1 Output power 25
2.3.2.2 Output spectrum 26
2.3.2.3 Polarisation 27
2.3.3 Beam quality 28
2.3.4 Temporal properties 30
2.3.4.1 Water Vapour as a Saturable Absorber 31
2.4 Cuboid laser Mk-II 33
2.4.1 Laser design 33
2.4.2 Laser operation 34
2.4.3 Beam quality 36
2.4.4 Temporal properties 37
2.5 Feedback control system 39
2.5.1 Simple model of the laser transfer function 40
2.5.2 Modelling of a proportional feedback system 42
2.5.2.1 Poles analysis 47
2.5.3 Implementation 48
2.5.4 Demonstration of pulse suppression 49
2.5.5 Measuring the open-loop laser transfer function 50
2.6 Chapter summary 52
3 Model of the laser dynamics 53
3.1 Introduction 53
3.2 Tm:YAlO$_3$ energy levels 54
3.3 Rate equations 55
3.3.1 Physical parameters 56
3.3.2 Calculated parameters 57
3.3.3 Solving the differential equations 59
3.4 Temporal dynamics 59
3.5 Linearized rate equations 61
3.6 Laser transfer function 64
3.7 Without excited-state absorption 65
3.8 Feedback modelling 68
3.9 Chapter summary 72
4 Excited-state absorption 73

4.1 Introduction 73
4.2 Direct measurement of excited-state absorption – theory 74
4.2.1 Ion transitions 74
4.2.2 Expected probe beam transmission profile 75
4.2.3 Calculation of the excited-state absorption cross-section 77
4.3 Direct measurement of excited-state absorption – experimental design 78
4.3.1 Predicted transmission change 80
4.4 Characterisation of laser sources 80
4.4.1 Beam profile at the crystal 80
4.4.2 Laser output spectra 82
4.5 Probe beam transmission 83
4.6 Calculation of the ESA cross-section 87
4.7 Remodelling of the laser dynamics 89
4.8 Evidence of chaos 92
4.8.1 Time delay embedding 93
4.8.2 Average mutual information 94
4.8.3 False nearest neighbours 95
4.8.4 Surrogate data testing 97
4.8.5 Chaos analysis of a Tm:YAlO$_3$ laser 98
4.8.6 "0-1" test for chaos 105
4.9 Conclusion 107
5 Moderate-power Tm:YAlO$_3$ slab laser 109
5.1 Introduction 109
5.2 Laser design and modelling 109
5.2.1 Slab geometry 111
5.2.2 Pumping geometry 112
5.2.3 Thermal modelling 114
5.2.4 Resonator design 116
5.2.5 Laser threshold 118
5.2.5.1 Stark splitting and the Boltzmann distribution 119
5.2.5.2 Estimated threshold pump power 122
5.2.6 Laser head design and assembly 122
5.3 Pump diode characterisation 124
5.3.1 Pump diode specifications 124

5.3.2 Water cooling 125
5.3.3 Emission wavelength and pump absorption 126
5.4 Laser operation 128
5.4.1 Output power 128
5.4.2 Output spectrum 129
5.5 Temporal properties 130
5.6 Chaos analysis of the slab laser 133
5.7 Thermal distortions – optical wedging 135
5.8 Chapter summary 138
6 High-power Tm:$YAlO_3$ ThOR slab laser 141
6.1 Introduction 141
6.2 ThOR slab design 142
6.2.1 Comparison with a standard slab 142
6.3 Thin-film-coated laser design 144
6.3.1 Laser design summary 145
6.3.2 Slab geometry 146
6.3.2.1 Crystal growth striations 148
6.3.3 Pumping geometry 149
6.3.3.1 Two-diode configuration 149
6.3.3.2 Four-diode configuration 150
6.3.4 Resonator design 152
6.4 Modelling of the laser performance 154
6.4.1 Pump absorption 154
6.4.2 Dopant thickness 157
6.4.3 Zigzag laser mode 158
6.4.4 Refractive index mismatch due to dopant 159
6.4.5 Threshold and maximum output power 161
6.5 Laser head design 163
6.5.1 Flatness of the cooling blocks 164
6.6 Internal scatter loss 165
6.6.1 Measurement of internal scatter loss 166
6.7 Diode pumping of ThOR slab 168
6.8 Chapter summary 170
7 Conclusion 173

7.1 Thesis summary 173
7.2 Future directions 174
7.2.1 Self-pulsing of Tm:YAlO$_3$ lasers 174
7.2.2 Development of the Tm:YAlO$_3$ ThOR slab 175
A Publications 177
A.1 Publications associated with this work 177
A.1.1 Self-pulsing in Tm-doped YAlO$_3$ lasers: Excited-state absorption and chaos 177
A.1.2 Suppression of self-pulsing in Tm:YAlO$_3$ lasers via current feedback 185
A.1.3 Self-pulsing and excited-state absorption in Tm:YAlO$_3$ 190
A.1.4 Suppression of self-pulsing behaviour in Tm:YAlO$_3$ lasers via pump diode-current feedback 191
B Mechanical drawings 195
B.1 Slab laser 195
B.2 ThOR slab laser 198
C Programming code 203
C.1 Matlab code 203
C.1.1 Tm:YAlO$_3$ laser dynamics 203
C.1.1.1 TmYAlO_model.m 203
C.1.1.2 laser_param.m 204
C.1.1.3 Rate_Equations.m 206
C.1.1.4 find_onset.m 207
C.1.1.5 TmYAlO_model_linear.m 208
C.1.1.6 Rate_Equations_linear.m 209
C.1.1.7 n_YAlO.m 210
C.1.2 Tm:YAlO$_3$ ThOR slab modelling 210
C.1.2.1 ThOR_modelling.m 210
C.1.2.2 ThOR_pump_abs.m 215
C.1.2.3 Tm_YAlO_Boltzmann.m 218
C.1.2.4 doped_undoped_interface.m 220
C.1.2.5 beam_guiding.m 221
C.1.2.6 n_YAlO.m 222
C.1.2.7 n_silica.m 222

C.1.3 Gaussian beam propagation 223
C.1.3.1 Gaussian_beams.m 223
C.1.3.2 eigenmode.m 224
C.1.3.3 propagate.m 225
C.1.3.4 gauss_addgraphics.m 227
C.1.3.5 Components 228
C.1.4 M^2 estimation 230
C.1.4.1 M2_fit.m 230
C.1.4.2 M2_fitting.m 233
C.2 Mathematica (optica) code 234
C.2.1 Pumping of Tm:$YAlO_3$ ThOR slab 234
D Circuit diagrams 237
D.1 Diode current feedback circuit 237
E Assembly procedures 239
E.1 Tm:$YAlO_3$ slab laser 239
E.2 Tm:$YAlO_3$ ThOR slab laser 240
F Brewster’s angle ThOR slab 243
References 245

List of Symbols

α_p	Pump absorption
γ	Ratio of ESA cross-section to GSA cross-section
ζ	Damping constant
η_q	Quantum efficiency
η_{red}	Density-reduction scaling parameter
η_{slope}	Slope efficiency
θ	Far-field divergence angle
θ_B	Brewster's angle
θ_{inc}	Angle of incidence
λ	Wavelength
σ	Laser emission cross-section
σ_{ESA}	ESA cross-section at the lasing wavelength
σ_p	Pump absorption cross-section
τ_{CR}	Cross-relaxation time constant
τ_{delay}	Transport delay time
τ_{in}	Time constant of the input high-pass filter
τ_{out}	Time constant of the output low-pass filter
τ_{RT}	Round-trip time constant
ϕ	Intra-cavity laser photon density
ω	Beam size (radius)
ω_0	Waist size (radius)
ω_v	Natural frequency (angular) of relaxation oscillation
ω_{CR}	Frequency (angular) for cross-relaxation
ω_{FB}	Frequency (angular) of the high-pass filter

ω_{pump}	Beam size (pump)
Ω	Solid angle
a_{ijkl}	Cross-relaxation and co-operative up-conversion rates from level i, k to j, l
A_{laser}	Laser mode area
A_{pump}	Pump mode area
c	Speed of light
d	Dimension
$D_c(n)$	Modified mean square displacement
E_{pump}	Pump photon energy
f	Focal length
f_l	Boltzmann thermal occupation factor for lower lasing level
f_u	Boltzmann thermal occupation factor for upper lasing level
g	Gain coefficient
G_{amp}	Amplifier gain
G_{DC}	DC gain
$G_{feedback}$	Feedback gain
K	Median linear correlation coefficient with time for 0–1 test
l	Length of the laser gain medium
l_{air}	Length of the air within the cavity
$L_{Interface}$	Loss due to scatter at the interface
L_{RT}	Total round-trip loss
$L_{Scatter}$	Loss due to bulk scatter
M	Molar mass
n	Refractive index
N	Population density of Tm:$YAlO_3$
N_{Av}	Avagadro’s number
N_i	Population density of energy level i
P_{losses}	Pump power required to overcome losses
P_{max}	Maximum attainable output power
P_{out}	Output power
P_{pump}	Pump power
P_{th}	Threshold pump power
P_{trans}	Pump power required to achieve transparency

R	Reflectivity
R_d	Euclidean distance between two points in dimension d
R_p	Pump rate
r_c	Cavity photon decay rate
r_{ij}	Natural decay rate from i to j (j omitted if to ground state)
r_s	Reflection coefficient for an incident s-polarisation beam
r_{sp}	Spontaneous radiative decay rate
T	Temperature
T_{eq}	Equilibrium transmission
T_{ns}	Nanosecond time scale transmission
$T_{\mu s}$	Microsecond time scale transmission
T_{OC}	Transmission of the output coupler
z_0	Distance of the beam waist
AoI	Angle of incidence
AOM	Acouto-optic modulator
AR	Anti-reflective
ASE	Amplified spontaneous emission
CAD	Computer-aided design
CW	Continuous-wave
DI	Deionised
ESA	Excited-state absorption
FEA	Finite element analysis
FFT	Fast Fourier transform
FWHM	Full-width half maximum
GRIN	Gradient-index
GSA	Ground-state absorption
HeNe	Helium-neon
HT	High transmission
HR	High reflectivity
N.A.	Numerical aperture
ODE	Ordinary differential equation
OPO	Optical parametric oscillator
OSA	Optical spectrum analyser

LIST OF SYMBOLS

PD	Photodetector
PRF	Pulse repetition frequency
RMS	Root mean square
ThOR	Thin outer-region-doped
TIR	Total internal reflection
YAG	Yttrium aluminum garnet ($Y_3Al_5O_{12}$)
YAP	Yttrium aluminum perovskite ($YAlO_3$)
YLF	Yttrium lithium fluoride

List of Figures

Figure 1.1: Atmospheric transmission in the mid-infrared wavelength region [4]. 2

Figure 1.2: Energy level diagram for thulium and holmium, including the transitions involved in lasing. 3

Figure 1.3: Summary of the pumping sequence. 6

Figure 1.4: Energy level diagram Tm:YAG, Tm:$YAlO_3$ and Tm:YLF, including Stark-splitting of the levels [63], [67]. 8

Figure 1.5: Absorption spectrum of holmium-doped silica, and the emission wavelength of Tm:YAG (dashed), Tm:$YAlO_3$ (solid) and Tm:YLF (dotted). Reproduced from [40] © Astro Ltd. Reproduced by permission of IOP Publishing. All rights reserved. 8

Figure 1.6: Refractive index along each axis of $YAlO_3$ as a function of wavelength. 11

Figure 2.1: Tm:$YAlO_3$ cuboid geometry and crystal axes alignment. 18

Figure 2.2: Measured absorption spectra for each axis from Tm:$YAlO_3$ sample (top), and absorption spectra from literature (bottom). Reprinted, with permission, from [72] © 1995 IEEE. 19

Figure 2.3: Schematic (top) and photo (bottom) of the initial Tm:$YAlO_3$ laser. The laser crystal is held within the copper cooling blocks. 21

Figure 2.4: Temperature distribution for 10 W of total absorbed heat. Cooling is through the top and bottom surfaces. 23

Figure 2.5: Calculated temperature profile in the vertical direction (*z*-axis) along the centre of the beam path (blue) and quadratic fit to the central pumped region (red). 23

Figure 2.6: Fundamental cavity mode for 3 W (blue) and 5 W (green) total absorbed heat. The shaded area represents the crystal. 24

Figure 2.7: Laser output power versus total absorbed pump power, with 1.7 W threshold of and 62.5% slope efficiency. 25
Figure 2.8: Output spectrum of the Tm:$YAlO_3$ laser averaged over several sweeps. 26
Figure 2.9: Beam quality measurement in the horizontal (a,c) and vertical (b,d) directions for the laser operating at an output power of 2 W (a,b) and 4 W(c,d). 29
Figure 2.10: Sample near-field beam profile at 2 W output power. 30
Figure 2.11: Temporal output of the Tm:$YAlO_3$ laser at 500 mW output power, and a high-resolution trace showing the typical pulse separation (inset)....31
Figure 2.12: Typical laser pulse width and pulse separation for different pump diode input currents....32
Figure 2.13: Schematic of the modified Tm:$YAlO_3$ laser Mk-II....33
Figure 2.14: Fundamental cavity mode for 3 W (blue) and 5 W (green) total absorbed heat. The shaded area represents the crystal....34
Figure 2.15: Laser output power versus total absorbed pump power, with 1.8 W threshold of and 56% slope efficiency....35
Figure 2.16: A sample output spectrum of the Tm:$YAlO_3$ laser Mk-II....35
Figure 2.17: Beam quality measurement for the Tm:$YAlO_3$ laser Mk-II operating at an output power of 2 W (a)-(b) and 4 W(c)-(d). 36
Figure 2.18: Sample near-field beam profile at 4 W output power. 37
Figure 2.19: Temporal output of the Tm:$YAlO_3$ laser Mk-II at 1 W output power. 38
Figure 2.20: High temporal resolution trace of one output ‘burst’ with an exponential fit to the pulse peaks....38
Figure 2.21: Dependence of oscillation frequency on output power for two different cavity lengths....39
Figure 2.22: Block diagram of a system with negative feedback....40
Figure 2.23: Schematic of the laser system with proportional feedback used in Simulink....42
Figure 2.24: Simulated output of the laser in Simulink for open loop operation. 44
Figure 2.25: Bode plot of the open loop transfer function, *G*(*s*), from simulation....44
Figure 2.26: Simulated output of the laser in Simulink for closed loop operation....45

Figure 2.27: Bode plot of the closed loop transfer function, $G(s) / (1 + G(s)H(s))$, from simulation........ 45

Figure 2.28: Bode plot of the transfer function of the feedback section, $H(s)$, from simulation........ 46

Figure 2.29: Bode plot of the loop transfer function, $G(s)H(s)$, from simulation........ 46

Figure 2.30: s-plane plot of the poles of the closed-loop transfer function for different feedback gains for three different cases: a near-zero cross-relaxation lifetime, a 3 μs cross-relaxation lifetime [122], and a 3 μs cross-relaxation lifetime plus an additional low-pass filter at 200 kHz. The values of gain used to calculate the locations of the poles ranged from 0 at the open-loop pole location through 0.1, 0.2… to 0.99. The movement of the poles with increasing gain is denoted by the dotted arrow........ 47

Figure 2.31: Schematic of the implementation of proportional feedback........ 48

Figure 2.32: Output power for open-loop (top) and closed-loop (bottom) operation........ 49

Figure 2.33: The output spectrum of the Tm:YAlO$_3$ laser Mk-II at 4 W output power with feedback (blue) and when free-running (green)........ 50

Figure 2.34: Measured (solid blue line) and modelled (dashed black line, best-fit using Equation 2.7 with $G = 0.7$, $\omega_v = 2\pi \cdot (87{,}000\text{ Hz})$, and $\zeta = 0.025$) transfer functions of the Tm:YAlO$_3$ laser........ 51

Figure 2.35: Bode plot of the loop transfer function........ 51

Figure 3.1: The first four energy levels of Tm:YAlO$_3$ with corresponding transitions........ 54

Figure 3.2: The output of the laser model, showing the photon emission (top) and population densities with time. Significant oscillatory behaviour can be observed in all cases, which do not damp out with time........ 60

Figure 3.3 Bode plot of the modelled laser transfer function........ 64

Figure 3.4: Bode plot of the transfer functions of the population densities........ 65

Figure 3.5: The output of the laser model in the absence of ESA, showing the photon emission (top) and population densities with time........ 66

Figure 3.6: Bode plot of the modelled laser transfer function, without ESA........ 67

Figure 3.7: Bode plot of the transfer functions of the population densities........ 67

Figure 3.8: Circuit diagram representing the feedback loop........ 68

Figure 3.9: The output of the laser model with feedback, showing the photon emission (top) and population densities with time...70
Figure 3.10 Bode plot of the modelled laser transfer function with feedback...............71
Figure 3.11: Bode plot of the transfer functions of the population densities.................71
Figure 4.1: Two primary avenues for de-excitation of Tm^{3+} ions after excitation by a short pump pulse at 1.2 μm, via (a) ESA, and (b) no ESA. 75
Figure 4.2: Expected probe transmission trace during and after the short pulse. 76
Figure 4.3: Simplified schematic of the ESA measurement experiment. 78
Figure 4.4: Beam profile of the probe beam (left) and OPO pulse (right) at the focal point (pixel size: 100 × 100 μm). 81
Figure 4.5: Gaussian fits for the two axes of the probe beam (a) – (b) and of the OPO beam (c) – (d). 81
Figure 4.6: Spectrum of the probe beam from the Tm^{3+}-doped fibre laser. 82
Figure 4.7: Spectrum of the OPO beam, averaged over many pulses. 83
Figure 4.8: AC-coupled probe beam signal in the microsecond range, with an exponential fit. 84
Figure 4.9: AC-coupled probe beam signal in the millisecond range, with an exponential fit. 84
Figure 4.10: Photodetector output during and after a short pulse with both beams (blue), probe beam blocked, i.e. OPO leakage (green) and electrical background when both beams were blocked (red). 86
Figure 4.11: The OPO pulse as observed by the extended InGaAs photodetector with 500- Ω termination (top) and 50-Ω termination (bottom)..........................86
Figure 4.12: Signal from the photodetector with background and OPO leakage removed, with an exponential fit to the latter part of the curve. 87
Figure 4.13: Experimental trace (blue) and fit (red), compared to the expected curves for a voltage drop corresponding to $\gamma = 0.65$ (green). 88
Figure 4.14: The output of the laser model with $\gamma = 0.08$, showing the photon emission (top) and population densities with time...90
Figure 4.15 Bode plot of the modelled laser transfer function for $\gamma = 0.08$....................91
Figure 4.16: Bode plot of the transfer functions of the population densities for $\gamma = 0.08$. 91
Figure 4.17: Lorenz-like pulsation of the laser intensity in far-infrared NH_3 lasers. Reprinted from [89], with permission from Elsevier. 92

Figure 4.18: Plot of $y = \sin(t)$ sampled at $\Delta t = 0.1$ (left) and its phase space structure in two dimensions $[y(n), y(n + 10)]$ (right). 94
Figure 4.19: An illustration of the concept of false nearest neighbours. The two-dimensional structure (top) contains false neighbours near [0, 0] due to it being a projection from a three-dimensional structure (bottom) 96
Figure 4.20: Temporal output from the reconstructed Tm:$YAlO_3$ laser Mk-II. 99
Figure 4.21: Power spectral density of the output signal. 99
Figure 4.22: Surrogate data sets for no dynamical processes (a) and a linear stochastic system (b), and their corresponding power spectral densities (c) and (d) respectively. 100
Figure 4.23: Average mutual information for the measured laser intensity (blue) and surrogate data sets for a linear stochastic system (green) and one with no dynamical processes (red). 101
Figure 4.24: False nearest neighbours for the measured laser intensity (blue) and surrogate data sets for a linear stochastic system (green) and one with no dynamical processes (red), with an expanded plot of higher embedding dimensions (inset). 101
Figure 4.25: Phase space structure of the measured data from opposing viewing angles, showing a clear surface-like structure with an attractor at the centre. The colour variations are for ease of viewing purposes only. 103
Figure 4.26: Phase space structure of the linear stochastic surrogate data, showing little to no structure. The colour variations are for ease of viewing purposes only. 104
Figure 4.27: Phase space structure of the white noise surrogate, showing no structure. The colour variations are for ease of viewing purposes only. 104
Figure 4.28: Plot of p versus q for the laser intensity data, with $c = 1.9206$. 106
Figure 5.1: Schematic of Tm:$YAlO_3$ slab laser 110
Figure 5.2: Tm:$YAlO_3$ slab geometry and crystal axes alignment. 111
Figure 5.3: Pump geometry of the slab laser, showing the side view (top), top view (middle) and pump beam at the slab location (red dot). Unit is mm. 113
Figure 5.4: Cross-sections of the heat deposition within the slab, with a central cross-sectional slice shown in the inset. 115
Figure 5.5: Modelled temperature distribution within the slab, with a central cross-sectional slice shown in the inset. 115

Figure 5.6: Modelled thermal-induced stress within the slab, with a central cross-sectional slice shown in the inset 116
Figure 5.7: Fundamental resonator mode for 200 W heat deposition in the vertical direction (blue) and horizontal direction (purple). 117
Figure 5.8: Boltzmann distribution for the Stark split levels in the upper and lower lasing manifolds for Tm:$YAlO_3$. Red denotes Stark levels involved in lasing at 1.94 μm. Note the two closely-spaced lines in the upper lasing manifold result in an effective Boltzmann factor of double the individual f_{upper} value. 120
Figure 5.9: Dependence of required inversion fraction for transparency on temperature. 121
Figure 5.10: Full assembly of the final laser head design. 123
Figure 5.11: End-on view of the laser head, showing the two copper cooling blocks, the slab (grey) and the copper apertures. 123
Figure 5.12: The 720 W pump diode stack, mounted on a Delrin block. The emitter bar width is 10 mm, with a total stack height of 18 mm. 125
Figure 5.13: In-house DI water manifold for supplying DI water to the diodes. 126
Figure 5.14: Diode stack emission wavelengths at different cooling water temperatures, at an output power of 200 W. The *b*-axis absorption of Tm:$YAlO_3$ (green) is for reference. 127
Figure 5.15: Laser output power versus absorbed pump power, with an $R = 65\%$ output coupler. 128
Figure 5.16: A sample output spectrum of the Tm:$YAlO_3$ slab laser. 129
Figure 5.17: Normalised intensities at different laser output powers such that the average power is scaled to unity. 130
Figure 5.18: Histograms of the normalised powers at different output powers 131
Figure 5.19: Normalised spectral density (oscillation frequency) at different output powers. 132
Figure 5.20: Dependence of oscillation frequency on output power. 132
Figure 5.21: Average mutual information for the laser when operating at 15 W. 133
Figure 5.22: False nearest neighbours for the laser when operating at 15 W. 134
Figure 5.23: Phase space structure of the laser time series when operating at 15 W. The colour variations are for ease of viewing purposes only. 134

Figure 5.24: Splitting of the HeNe laser beam through the slab during pumping, the result of thermal distortions. 136
Figure 5.25: “Double wedge” thermal distortions induced due to localised heating through pump absorption. Green arrows denote the pump beams, and blue arrows denote cooling. 136
Figure 5.26: Mach Zehnder interference patterns of the slab under no pumping (left) and 100 of absorbed pump light (right). 137
Figure 5.27: Fringe pattern along the vertical axis at the centre of the slab (dotted line in previous figure), with a quadratic fit to the central region and linear fits to the sides. 138
Figure 6.1: Illustration of the ThOR slab design – thin doped regions directly next to heat sinks, with an undoped region in between doped regions. 142
Figure 6.2: Modelled thermal-induced stress within the ThOR slab (top) and a standard slab (bottom) for 300 W of deposited heat. 143
Figure 6.3: Polarisations required within the slab. The use of Brewster’s angle for entry and exit requires different end faces angled along specific planes. 145
Figure 6.4: Summary of the laser design (top view), incorporating the pump light (green) and laser mode (red). 145
Figure 6.5: Schematic of the laser slab geometry 146
Figure 6.6: Relative intensity of the evanescent field for the laser and pump beams. 147
Figure 6.7: Optica output of the initial configuration with two pump diodes in the side view (top left) and top view (bottom left), and the rays incident on the slab. 150
Figure 6.8: Optica output of the final configuration with four pump diodes in the side view (top left) and top view (bottom left), and the rays incident on the slab. 151
Figure 6.9: Top view of the folded zigzag laser mode through the ThOR slab. 152
Figure 6.10: Modelled laser resonator mode ($^1/e^2$) in the vertical (blue) and horizontal directions (red). Note the grey area represents the slab with the zigzag path unfolded. 153

Figure 6.11: Modelled laser resonator mode in the vertical (blue) and horizontal directions (red), with an intra-cavity telescope in the vertical direction. Note the grey area represents the slab with the zigzag path unfolded 153

Figure 6.12: Graphical representation of the method used to estimate the pump absorption, showing the emitters and rays for pump diode 1 (top) and the rays' propagation along the slab (bottom). 156

Figure 6.13: Modelled laser path with 5 bounces per side with the unabsorbed pump beam, showing sufficient clearance between the two. 158

Figure 6.14: Maximum theoretical slope efficiency (top) and incident threshold (bottom) for different round-trip loss and output coupler reflectivity. 162

Figure 6.15: Maximum theoretically attainable power based on the Rigrod analysis for different round-trip loss and output coupler reflectivity. 162

Figure 6.16: Laser head assembly for the Tm:$YAlO_3$ ThOR slab. 163

Figure 6.17: Photographs of the securing copper block after assembly before (left) and after (right) remachining of the surfaces, showing significant improvement in uniformity of the crush on the indium after machining. 164

Figure 6.18: Photographs of the pre-cut laser crystal, with visible scatterers in the diffusion bond (left) and bulk crystal (centre). A HeNe laser beam is used to highlight the severity of the scatter loss through the crystal (right). 165

Figure 6.19: Microscope image of the hazy region in the diffusion bond. 166

Figure 6.20: Broadband absorption spectra along the *c*-axis of the Tm:$YAlO_3$ in the ThOR slab; the dashed line denotes 1470 nm. 167

Figure 6.21: Photograph of the ThOR slab under 790 nm pumping. 168

Figure 6.22: Output from the Mach-Zehnder interferometer for an incident pump power of 0 W (left), 10 W (centre) and 20 W (right), showing significant thermal distortions under pumping. 169

Figure 6.23: Transmission spectra through the two regions of the ThOR slab. 170

List of Tables

Table 1.1: Selected properties of three crystal hosts for thulium [63]–[66]. Preferential properties are shown in bold. 7

Table 1.2: Selected properties of Tm:$YAlO_3$ [65], [69], [71]–[76]. 10

Table 1.3: Sellmeier coefficients for the different axes of $YAlO_3$ [77] 10

Table 1.4: Selected published Tm:$YAlO_3$ systems with high output power and/or slope efficiencies. 14

Table 2.1: Parameters for the proportional feedback modelling. 43

Table 3.1: Definition of terms in Equation 3.1 56

Table 3.2: Tm:$YAlO_3$ physical parameters [63], [85], [127]. 56

Table 3.3: Transition rates between energy levels [63], [85], [128]. 57

Table 3.4: Measured parameters from the Tm:$YAlO_3$ cuboid laser. 57

Table 5.1: Relevant pump diode parameters. 112

Table 5.2: Estimated laser threshold pump powers for different output coupling fraction. 122

Table 5.3: Specifications of the 720 W pump diode stacks. 124

Table 6.1: Thermal handling comparison between the ThOR slab and a standard slab for 300 W heat deposition in the doped region from optical pumping. 144

Table 6.2: Pump absorption for single and double passing. 155

Table 6.3: Thermal handling comparison between two dopant layer thicknesses. 157

Table 6.4: Lattice constants and volumes for Tm:$YAlO_3$ and undoped $YAlO_3$. 159

Table 6.5: Calculated densities and refractive index for undoped and 4% at. Tm:$YAlO_3$. 160