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Investigation of cryogenic Er:YAG lasers for Gravitational Wave Interferometry

BY

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Contents

Abstract

High power, stable single frequency laser sources are required for gravitational wave interferometry. The next generation of interferometers may require laser sources in the 1.3-1.65 µm band for use with Si test masses and InGaAs photodetectors. We propose a high power cryogenic Er:YAG laser operating at 1.618 µm for this purpose, adapting existing knowledge about cryogenic Yb:YAG lasers developed at the University of Adelaide.

To produce such a laser, further information is required about the viability of Er:YAG in high power, single frequency operation. In this thesis, I report this investigation of the spectroscopy of Er:YAG at room temperature and at cryogenic temperatures ($\approx$ 77 K) and investigate a variety of wavelengths for diode pumping of an Er:YAG slab laser.

Spectroscopy indicates that diode pumping for the 77 K laser slab will be most effective in the 1450-1480 nm absorption band, most specifically at the 1453 nm absorption peak. I describe methods for cooling a 1470 nm diode below 0 °C to pump this 1453 nm Er:YAG absorption. The cooled diode exhibits up to 9 % increase in slope efficiency and improved beam divergence compared to room temperature operation.

I then describe the construction and characterisation of CW Er:YAG lasers at both 300 K and 77 K, tuning the pump wavelength in the 1450-1480 nm band. At 300 K, I demonstrate an Er:YAG laser with 4.5 W output power when pumped with 30 W of diode power at 1468 nm, and just under 4 W of output power when pumped with 34 W of diode power at 1456 nm. Both lasers have a threshold of approximately 12 W incident pump power. The laser pumped at 1468 nm also demonstrates a greater slope efficiency relative to incident pump power: 28 % compared to 20 % when pumped at 1456 nm.

The development of a preliminary cryogenic Er:YAG laser is also reported. Despite sub-optimal mounting materials and geometries, we demonstrate a cryogenic laser with 5.5 W output power and approximately 6 W threshold under comparable pumping conditions to the 4.5 W 300 K laser pumped at 1468 nm. Unfortunately subsequent studies of the cryogenic slab laser are not comparable to the 300 K Er:YAG laser due to electrical damage to the diode that significantly reduced diode power and changed pumping conditions. Nevertheless, these results provide valuable information on the sensitivity of end-pumped cryogenic lasers to mounting conditions and pump focusing that are useful for a future high power design.

Statement of Originality

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Supervisors: Emeritus Prof. Jesper Munch
Associate Prof. Peter Veitch

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α	Absorption coefficient (cm^{-1})
α_T	Coefficienct of linear thermal expansion
β	Inversion fraction
λ	Wavelength (general)
λ_l	Laser wavelength
λ_p	Pump wavelength
σ or σ_a	Absorption cross-section (cm^2)
σ_e	Emission cross-section (cm^2)
θ	Far-field divergence half-angle
Ω	An arbitrary phase
A	A positive constant
c	The speed of light
$\frac{dn}{dT}$	Change of material refractive index with respect to temperature
$E(x,T)$	The energy of an excited state x, at temperature T
E_1 and E_2	The electric field amplitude of the reference arm and slab arm of the interferometer respectively
f	Used to represent the focal length of a lens
f_L and f_U	Fractional occupation of the lower and upper lasing states respectively
$F(x)$	Boltzmann occupation factor of a state x
G	Laser gain, used in the form $I_{out} = I_{in}\exp(Gz)$
$\hbar$	The reduced Planck's constant
I	Intensity
I_{in}	Input intensity, before gain or absorption has been applied. Used to represent the background spectrum.
I_{out}	Output intensity, after gain or absorption has been applied. Used to represent the spectrum of a sample.
k	Boltzmann's constant
k_x	The wave number

K	Thermal conductivity
L	Length
L_1 to L_4	The lowest four energy "bands" in Er:YAG, see Figure 2.2
m	An integer
M^2	Beam quality, "times diffraction limited"
n	Refractive index
N	Number density of ions in the material(in cm^{-3})
N_L and N_U	Number density of ions in the lower and upper lasing states respectively
P_{change}	The change in power from the mean value P_{signal}, used to calculate intensity stability
P_{signal}	The mean value of the laser output power, used to calculate intensity stability
t	Time
T	Temperature
TEM_{00}	The fundamental Transverse ElectroMagnetic mode
w_0	Radial beam width

List of Acronyms

aLIGO	Advanced LIGO
AR	Anti-Reflection
ASE	Amplified Spontaneous Emission
CR	Cross-Relaxation
CW	Continuous Wave
DI	De-Ionised
ESA	Excited State Absorption
FBG	Fibre Bragg Grating
GRIN	GRaded INdex
GWI	Gravitational Wave Interferometers
HR	High Reflectivity
LIDAR	LIght Detection and Ranging
LIGO	Laser Interferometer Gravitational wave Observatory
MOPA	Master Oscillator Power Amplifier
NA	Numerical Aperture
ND	Neutral Density
NPRO	Non Planar Ring Oscillator
OSA	Optical Spectrum Analyser
OPL	Optical Path Length
QD	Quantum Defect
RF	Radio Frequency
SBS	Stimulated Brillouin Scattering