Deployable Stable Lasers for Gravitational Wave Interferometers

by

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Abstract

The most promising technique for the direct, ground-based detection of gravitational waves is the use of advanced interferometric gravitational wave detectors. These detectors use long-baseline Michelson interferometers, where the critical enabling component is the laser. The laser required for these interferometers must provide a low noise, single frequency, diffraction limited, high power TEM_{00} beam. Very importantly, the laser beam must be available continuously and without the need for operator intervention.

In this thesis I describe the development and characterisation of injection-locked 10 W Nd:YAG lasers, designed specifically for use at the Australian Consortium for Interferometric Gravitational Astronomy (ACIGA) High Power Test Facility (HPTF) in Western Australia, and on the Japanese TAMA 300 gravitational wave interferometer (GWI). The starting point was a 5 W laboratory laser that had demonstrated the proof-of-principle; however this laser had insufficient power, inadequate reliability, and was not suitable for deployment to a remote site. I describe the development of this laser technology and design to realise reliable, long-term operation and field deployability, while satisfying the requirements for a GWI, with the final laser system bearing little resemblance to the proof-of-principle system. Injection-locked lasers were successfully installed at the ACIGA HPTF and at TAMA 300 in June 2004 and September 2005 respectively.

The 10 W laser uses a Nd:YAG Coplanar Pumped Folded Slab (CPFS) gain medium. The slab is side-pumped using a temperature controlled, fast-axis collimated, custom laser diode array, and conduction cooled in the orthogonal direction. Interferometry is used to measure the thermal lensing within the gain medium; these measurements are used to design a single-mode, travelling-wave slave resonator. The entire slave laser is temperature controlled and mounted on an integrated, air-cooled base. The thermal design is validated by extensive thermal testing.

Long-term and robust injection-locking is achieved by using a servo system based on the Pound-Drever-Hall technique. I describe the development of a split feedback servo system to provide increased frequency stabilisation loop bandwidth and show that long-term injection-locking of the slave laser to a low power non-planar ring oscillator (NPRO) master laser produces a single frequency output at $\sim$ 10 W with $\mathrm{M}^2_{x,y} \lesssim 1.1$.

Finally, the noise of the injection-locked laser is characterised. Relative intensity noise measurements demonstrate stability comparable to current GWI laser sources, while the results of a heterodyne beat measurement show that the 10 W injection-locked laser output has frequency noise limited by the NPRO input.

The laser installed at the ACIGA HPTF has been used to investigate the effects of increased intracavity laser powers on next-generation interferometers, with the laser described in this thesis being the key enabling component of this research.

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.

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List of Symbols

Throughout this thesis, several symbols will be used repeatedly to represent specific quantities or parameters, the following is a list of these symbols and short descriptions for the readers convenience. This list is not exhaustive but every effort has been made to maintain conformity of symbols used here. Wherever possible standard symbols and notation have been used which appear in most laser texts.

α_o	...	Bulk scatter loss coefficient
γ	...	Lens duct parameter related to the transverse variation of the index of refraction
γ_0	...	Growth rate of the cavity field due to the saturated gain of the slave laser
γ_2	...	Population decay rate
γ_c	...	Cavity decay rate
γ_e	...	External decay rate due to the output coupling
ϵ	...	Laser gain medium dielectric constant
η_B	...	Beam overlap between the pump volume and laser mode
η_q	...	Quantum efficiency
η_s	...	Stokes factor
η_{tot}	...	Product of Quantum efficiency and Stokes factor
θ_1	...	Total Internal Reflection bounce angle in the laser crystal
θ_B	...	Brewster's Angle (= 61.2094^o for Nd:YAG)
θ_{beam}	...	Total beam separation angle
θ_{exit}	...	Slab beam exit angle, from parallel side
θ_N	...	Slab nose angle
κ	...	Cavity signal to atomic polarisation coupling coefficient

ν_L	...	Lasing frequency
$h\nu_L$	...	Energy per laser photon
σ_{21}	...	Stimulated emission cross-section
τ_c	...	Slave laser resonator round trip time
τ_f	...	Fluorescence lifetime of the upper laser level
ω_a	...	Laser gain medium centre frequency
ω_c	...	Resonant frequency of the optical cavity
ω_{lock}	...	Maximum permissible difference between the free-running slave and master laser frequencies that will allow injection-locking
ω_m	...	Frequency of the injected master laser
$\omega_s(t)$	...	Frequency of the free-running slave laser
$\Delta\phi$	...	Steady-state difference in phase between the master laser and the injection-locked slave laser
$\Delta\phi_{IF}(t)$	...	Phase difference between the injection-locked slave laser and frequency shifted master laser
$\Delta\omega_a$	...	Laser gain medium linewidth
$\Delta\omega_{lock}$	...	Full width of the locking range
Θ_{sa}	...	Thermal resistance (from the heatsink to ambient)
Abs	...	Absorption within the slab
A_{beam}	...	Beam cross sectional area
A_{eff}	...	Effective aperture of the beam propagating out of the slab
a_r	...	Hard aperture radius
E_m	...	Amplitude of the injected master field
E_s	...	Amplitude of the free-running slave laser
f_0	...	Characteristic focal length
f_{duct}	...	Effective focal length of the lens duct
FSR	...	Free spectral range
$\tilde{g}(\omega)$	...	Amplitude gain of the cavity
g_o	...	Small signal gain coefficient
$G(\omega)$	...	Net round-trip gain magnitude
$G_{rt}(\omega)$	...	Complex round-trip gain of the laser cavity
h	...	Height of the slab

h_p	...	Pump region height
I_s	...	Saturation intensity
K_{MIX}	...	Calibration factor for the double balanced mixer
l	...	Geometric pathlength in the crystal
l_c	...	Overall length of the slab
l_g	...	Total path length in the gain region
l_p	...	Pump region length (parallel-side)
l_s	...	Parallel-side-length of the slab
$Loss_{BulkScatter}$	...	Bulk scatter loss
$Loss_{EXT}$	...	External losses
$Loss_{TIR}$	...	Scatter losses at TIR surfaces
$Loss_{TIRbounce}$	...	Loss per TIR bounce
m	...	Matrix half trace
M^2	...	Beam quality parameter
M_x^2	...	Beam quality parameter (x-direction)
M_y^2	...	Beam quality parameter (y-direction)
n_0	...	Lens duct index of refraction at optical axis
n_g	...	Number of ground state atoms per unit volume
$n(r,z)$	...	Radially varying refractive index
N_B	...	Number of slab TIR bounces
p	...	Travelling-wave cavity perimeter length
P_{master}	...	Laser power incident on the output coupler
P_{out}	...	Standing-wave output power
P_p	...	Total pump power deposited in the pump volume
P_{slave}	...	Free-running output power of the slave laser
Q	...	Heatsink cooling power
R	...	Reflectivity
T_a	...	Ambient temperature
T_{oc}	...	Transmission of the slave laser output coupler
T_s	...	Heatsink temperature
V	...	Volume (pumped)
V_c	...	Mode volume of the cavity

$V_{IF}(t)$	...	Voltage fluctuations at the “IF” output of the mixer
V_s	...	Loss factor per single pass of the resonator
w_1	...	Master laser beam waist
w_2	...	Slave laser beam waist
w	...	Width of the slab
w_m	...	TEM_{00} beam radius
w_p	...	Pump region width
W_p	...	Pumping rate
AoI	...	Angle of incidence
AOM	...	Acousto-optic modulator
AR	...	Anti-reflection
CCD	...	Charge coupled device
CPFS	...	Coplanar-Pumped Folded-Slab
EFL	...	Effective focal length
EOM	...	Electro-optic modulator
FI	...	Faraday isolator
FW	...	Forward-wave
HD	...	High dynamic range
HF	...	High frequency range
HR	...	High reflection
IF	...	Intermediate frequency (mixer output)
LO	...	Local oscillator (mixer input)
PDH	...	Pound-Drever-Hall technique
PID	...	Proportional, integration and differentiation gain stages
PZT	...	Piezoelectric transducer
RIN	...	Relative intensity noise
RW	...	Reverse-wave
TEC	...	Thermoelectric cooler
TEM_{00}	...	Transverse Electromagnetic Mode of zeroth order
TIR	...	Total Internal Reflection
TM	...	Transverse Magnetic Mode

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