LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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LIGO II PRE-STABILIZED LASER CONCEPTUAL DESIGN

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Table of Contents

1 Introduction

1.1 Purpose

The purpose of this document is to present a conceptual design that shows that the requirements presented in *LIGO II Pre-stabilized Laser (PSL) Design Requirements*, LIGO- T000035-W are reasonable and realizable.

The principal intended audience for this document is the LIGO II Detector team.

1.2 Scope

This document details the expected challenges and a conceptual design solution generated to meet the requirements presented in *LIGO II Pre-stabilized Laser (PSL) Design Requirements*, LIGO-T000035-W.

This document provides a brief discussion of the requirements for the PSL and where these requirements come from. It gives an overview of the PSL subsystem - what is and what is not included in the PSL subsystem, its location in the LVEA, the relationship between the PSL and other LIGO II subsystems, and its features and capabilities. Schemes to implement the frequency and power stabilization loops are presented, along with their estimated performance levels.

1.3 Document Organization

1.3.1 Acronyms

AOM Acousto-Optic Modulator (optical hardware)

AR Anti-Reflection (optical coating)

ASD Amplitude Spectral Density

ASE Amplified Spontaneous Emission

CCD Charge Coupled Device

CDS Control and Data System (detector subsystem)

COC Core Optics Components (detector subsystem)

CVI CVI Laser Corporation, Albuquerque, New Mexico

DC Direct Current (steady state - low frequency)

EOM Electro-Optic Modulator (optical hardware)

FSS Frequency Stabilization Servo

GW Gravitational Wave

HAM Horizontal Access Module

HR High Reflector (optical coating or mirror)

HWP Half-Wave Plate (optical hardware)

ILO Injection-Locked Oscillator

IO Input Optics (detector subsystem, formerly named Input / Output Optics)

IFO Interferometer

LHO LIGO Hanford Observatory

LIGO Laser Interferometer Gravitational-Wave Observatory

LLO LIGO Livingston Observatory

LPMC Laser Pre-ModeCleaner

LSC Length Sensing / Control (detector subsystem)
or LIGO Scientific Collaboration

LVEA Laser and Vacuum Equipment Area (of the LIGO observatories)

MIT Massachusetts Institute of Technology

MO Master Oscillator

MOPA Master-Oscillator-Power-Amplifier (laser configuration)

Nd:YAG Neodymium-doped Yttrium Aluminum Garnet (laser gain medium)

NPRO Non-Planar Ring Oscillator (laser geometry)

PBS Polarizing Beam Splitter (optical component)

PDH Pound-Drever-Hall (reflection locking technique)

PCPC Phase-Correcting Pockels Cell

PMC Pre-ModeCleaner

PSD Power Spectral Density

PSPD Power Stabilization PhotoDetector

PSL Pre-Stabilized Laser (detector subsystem)

PZT Piezoelectric Transducer (electro-mechanical component)

REO Research Electro-optics, Inc. in Boulder, Colorado

RF Radio Frequency

RFAM Radio Frequency Amplitude Modulation

RIN Relative Intensity Noise

SNL Shot Noise Limit

SEI Seismic Isolation (detector subsystem

TBD To Be Determined

1.3.2 Applicable Documents

1.3.2.1 LIGO Documents

LIGO II Pre-stabilized Laser (PSL) Design Requirements, LIGO-T000035-W

180 W Nd:YAG Laser Specifications, LIGO-C000060-00-D

LSC White Paper on Detector Research and Development, LIGO-T990080-00-D

(Infrared) Pre-stabilized Laser (PSL) Design Requirements - LIGO T970080-09-D

(Infrared) Pre-stabilized Laser (PSL) Conceptual Design - LIGO T970087-04-D

(Infrared) Pre-stabilized Laser (PSL) Final Design - LIGO T990025-04-D

(Infrared) Pre-stabilized Laser (PSL) Electronics Design Requirements, LIGO- T970115-00-C

IR PSL CDS Conceptual Design Document, LIGO-T970114-00-C

Frequency Stabilization: Servo Configuration & Subsystem Interface Specification, LIGO T970088-00-D

1.3.2.2 Non-LIGO Documents

Monolithic, unidirectional single-mode Nd:YAG ring laser, Thomas J. Kane and Robert L. Byer, Optics Letters, 10, pp 65-67 (1985).

Frequency stabilization of a monolithic Nd:YAG laser by controlling the power of the laser-diode pump source, B. Willke, S. Brozek, K. Danzmann, V. Quetschke, S. Gossler, Optics Letters 25 (14) (2000)

Frequency and intensity noise of an injection-locked Nd:YAG ring laser, D.J. Ottaway, P.J. Veitch, C. Hollitt, D. Mudge, M.W. Hamilton and J. Munch, Appl. Phys. B 70, pp.1-6 (2000)

The GEO stabilized laser system and the current lock technique, B. Willke, O.S. Brozek, K. Danzmann, C. Fallnich, S. Gossler, H. Luck, K. Mossavi, V. Quetschke, H. Welling and I. Zawischa, in Gravitational Waves: Third Edoardo Amaldi Conference, ed S. Meshkov, (AIP, NY, 2000) pp.215-221

1.3.3 Definition of Terms

Gaussian Beam A TEM_{00} beam of electromagnetic radiation such as that often produced by lasers, in which the transverse electric field varies as $E = E_0 e^{-r^2/w^2}$, where w is the beam spot size.

M^2 or M value The parameter M or M^2 is a measure of the departure of a Gaussian beam from a pure TEM_{00} mode. If the mode were a pure TEM_{00} mode, then $M^2 = 1$. The beam waist-divergence product for a non-ideal TEM_{00} mode is M^2 that of a TEM_{00} mode.

Modulation index If the electric field of a phase modulated laser is written as

$E(t)=E\ \exp[j(\omega t+\Gamma \mathrm{Sin}(\omega_m t))]$, then the amplitude of the phase modulation, Γ, is referred to as the modulation index.

Spot size The characteristic size for a Gaussian laser beam, defined as the distance (radius) at which the electric field drops to 1/e times the value on axis.

2 System overview

2.1 Introduction

The PSL subsystem includes the following elements:

- The LIGO II Laser including power supplies and cooling system.
- Frequency stabilization control loop utilizing a rigid reference cavity suspended in vacuum on a vibration isolation stack, electro-optic modulator for fast frequency correction, and control of master oscillator frequency fluctuations via feedback to the master oscillator piezo-electric actuator (PZT).
- Overall power control of the light exiting the modecleaner and entering the main interferometer. This will include a high power photodetector that is located downstream of the modecleaner and may be mounted inside the vacuum envelope on the seismic isolation table.
- A triangular pre-modecleaner to attenuate power fluctuations at RF frequencies. It is housed in a sealed vessel to reduce atmospheric pressure-induced optical path length changes.

It does NOT include:

- Mode matching lenses or steering mirrors that are part of the Input Optics Detector Subsystem (IO).
- Electro-optic modulators for sideband frequencies utilized outside of the PSL subsystem.

2.2 Features / Capabilities

The LIGO II PSL conceptual design is based on the LIGO I PSL. It incorporates the following features.

- Wideband input for the IO frequency control actuator
- Tidal actuator input for very low frequency control of laser frequency by the Length Sensing and Control subsystem (LSC).

It incorporates the following changes and improvements based on experience gained from the commissioning of the LIGO I PSL:

- The sample of the laser output beam that is directed to the reference cavity is picked off AFTER the pre-modecleaner (PMC) in order to improve beam quality incident on the reference cavity and suppress frequency noise induced by the PMC due to length fluctuations of the PMC cavity . This couples the PMC and FSS loops.
- The PMC is mounted inside a sealed container in order to eliminate atmospheric pressure-induced optical path length changes.
- The number of optical mounts is kept to a minimum and all mounts are extremely rigid in order to reduce frequency fluctuations induced by optical mount vibrations.
- The laser table is mounted on an active vibration isolation system to reduce the relative motion of optical components due optical table vibrations induced by seismic motion. This

is also expected to reduce Doppler shifting induced by table motion relative to the suspended reference cavity and modecleaner.

- Beam pipes enclosing the majority of the propagation path of both the main laser beam and the sample beam directed toward the reference cavity for frequency stabilization.
- Environmental control including an optical table enclosure with acoustic shielding and a laser area enclosure that provides additional acoustic shielding and enhances laser safety.

2.3 PSL Location

The PSL will be located in the vicinity of the HAM chamber that contains the suspended input optic for the modecleaner. At this stage, the exact length and configuration of the modecleaner has not been decided, hence the precise location of the PSL cannot be determined. The performance of LIGO I PSL, has been found to be adversely affected by local acoustic noise. For this reason the LIGO II PSL will be enclosed in a soundproof room with all electronics racks mounted outside the room. As with the LIGO I PSL, the LIGO II PSL shares an optical table with the IO subsystem.

2.4 The IO / PSL Optical Table

The IO/PSL optical table is the same one that was used for the LIGO I interferometers, a 16 ft. x 5 ft. x 24 inch thick Newport Research Series (RS4000) table. The midpoint between the flat mirrors in the PSL pre-modecleaner is the optical interface location between the PSL and IO subsystems. The properties of the beam (waist size and position) exiting the PMC are very well defined. This makes mode matching from this point into the modecleaner far simpler than for the LIGO I PSL and serves to isolate beam parameter changes in the PSL from the IO.

2.5 Laser Room

In order to enhance both laser safety and acoustic isolation, a laser room is constructed around each PSL. The dimensions of the room are approximately 20 ft. wide by 30 ft. long (along the long axis of the IO/PSL table) by 10 ft. high. The electronics racks located adjacent to the LIGO I IO/PSL optical tables are moved back about six feet in order to exclude them from the Laser Room.

2.6 Optical Layout and Control Strategy

Figure 2.6-1 shows a schematic of the optical layout and control strategy. Note that the beam directed toward the reference cavity for frequency stabilization is split off from the main output beam AFTER the PMC. This scheme has two advantages:

- The light incident on the reference cavity is closer to pure TEM_{00} mode and hence the spurious noise effects of the higher order modes on the photodetector are reduced.
- The reference cavity control loop measures and suppresses any additional frequency noise added to the beam by the PMC and all optical components, such as mirror mounts, upstream of the pick off point.

Note that in the actual optical layout, the components will be situated such that the beam directed into the reference cavity will be propagating in the same direction as the beam directed into the modecleaner. This is done to make Doppler shifts caused by table motion relative to the suspended (and therefore relatively stationary in inertial space) reference cavity and modecleaner common-mode.

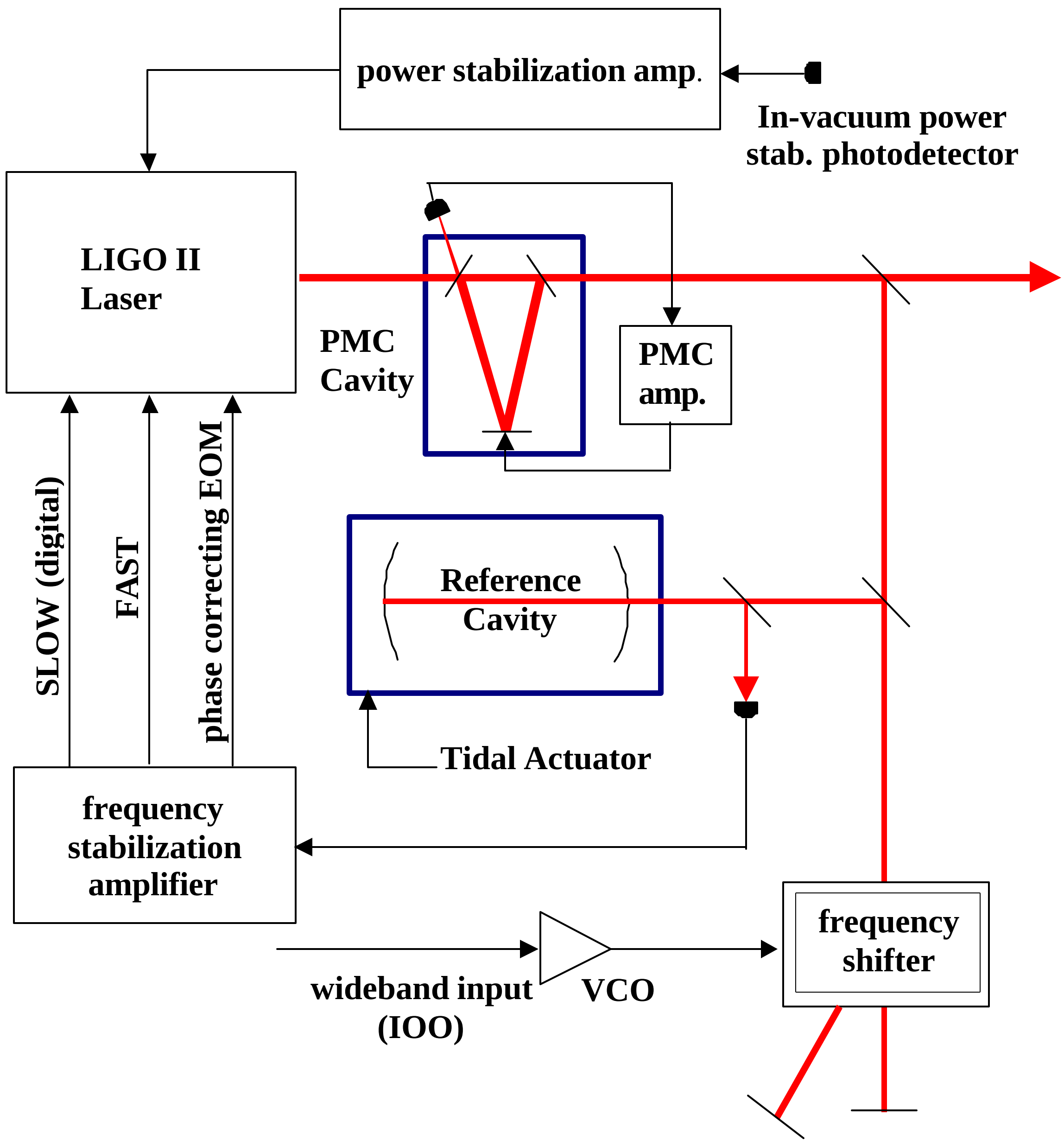

Figure 2.6-1 A schematic of the optic layout of the LIGO II PSL

The optical train of the PSL is kept as short as practicable with the minimum number of adjustable and fixed mirror mounts. Two fixed mounts are provided to bring the LIGO II laser output beam to the 3” optical height utilized on the IO/PSL optical table. Two adjustable mirror mounts are provided for alignment into the pre-modecleaner. The frequency shifter AOM utilizes a mount that allows adjustment relative to the input beam and one adjustable mount is utilized for retro-reflection of the shifted beam back through the AOM. Two adjustable mounts are utilized to align the beam into the reference cavity with two fixed mirrors in a periscope raising the beam to the level required for the reference cavity. All mirrors that are required to fold the optical path for space considerations are fixed mounts. All EOMs are mounted on goniometer-type mounts that enable alignment by moving the EOM rather than the steering the beam into the EOM. Lens mounts can be adjusted then locked in the final position. All polarizing beam splitters are on fixed mounts.

All stray optical beams of more than 1 mW power are dumped in a manner that seeks to minimize coupling of backscattered light and that provides for laser safety. Note that very high quality coatings will be required on all optical surfaces. The power transmitted when a 200 W beam is incident on an HR coating with a transmittance of around 10^{-3} will be in the order of several hundred milliwatts.

2.7 Facilities Interfaces

The PSL will rely on the LIGO observatory facility for the supply of the mains electrical power, temperature and humidity control, and space and utilities for the laser power supplies and chillers.

2.8 Remote Control

All PSL controls will be actuated via the CDS detector subsystem. The performance of the PSL will be monitored continuously and logged to allow comparison with previous performance levels. The computer system will also control the lock acquisition sequence.

3 The LIGO II Laser

3.1 Overview

The conceptual design for the LIGO II Laser is based on the premise in *LSC White Paper on Detector Research and Development*, LIGO-T990080-00-D, that “The Nd:YAG pre-stabilized laser design resembles that of LIGO I, but with the addition of several stages of amplification following the present 10 W laser.” For reasons that will be explained in detail below, the LIGO 10-W laser (subsequently referred to at the LIGO I Laser) is modified to deliver 20 watts of laser power. This capability has been demonstrated by the manufacturer, Lightwave Electronics, Inc., and we propose working with them to make operation at the 20-watt level a standard capability. A pre-modecleaner, similar to the LIGO I design, is placed after the 20-W front end to filter high frequency intensity noise and beam spatial imperfections before the amplification stages. This pre-modecleaner is referred to as the Laser Pre-ModeCleaner (LPMC). Two amplification stages employing end-pumped, zig-zag slab amplifiers increase the laser power to 80 watts and then to 180 watts. All powers quoted are in a circular TEM_{00} mode.

Although this PSL conceptual design will be developed as an all MOPA scheme, areas where an injection-locked oscillator might provide significant advantages are noted. The advantages and disadvantages of an injection-locked oscillator compared with an all MOPA scheme are discussed in Appendix 1.

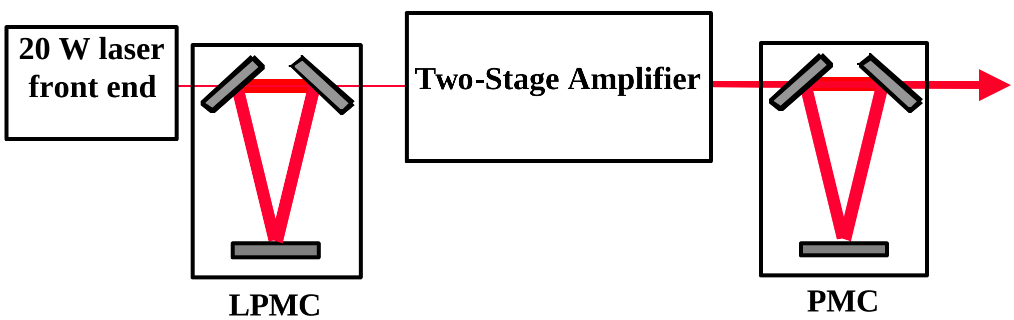

Figure 3.1-1 Schematic of LIGO II laser showing LIGO I front end, laser pre-modecleaner, and amplification stages.

3.2 Target Specifications

The LIGO project has solicited letters of intent from commercial companies who may have an interest in designing and fabricating the LIGO II laser. For this solicitation, a list of target specifications was generated. The full list of target specifications can be found in the document *LIGO II Laser TARGET Specifications* (LIGO-C000060-00-D). A summary of the target specifications for the LIGO II laser is provided in Table 4.

Parameter	Specification
1. type of laser	Nd:YAG
2. wavelength	1064 nm
3. power in a circular TEM_{00} mode	>180 W
4. power in all other modes	< 36 W
5. polarization extinction ratio	500:1 in the vertical plane
6. relative power fluctuations	$< 10^{-5}$ /$Hz^{1/2}$ between 100 Hz and 10 kHz $< 10^{-6}$ /$Hz^{1/2}$ between 100 kHz and 3 MHz $< 10^{-9}$ /$Hz^{1/2}$ above 25 MHz (2 times shot noise limit for 100 mA of photodected current
7. frequency fluctuations	$< 2 \times 10^{3}$ Hz/$Hz^{1/2}$ at 100 Hz $< 2\times10^{2}$ /$Hz^{1/2}$ at 1 kHz
8. reliability: mean time between failure (MTBF) minimum time between required beam alignment adjustment	 > 10 000 hours > 500 hours

The predicted performance of the LIGO II Laser in this conceptual design differs from the LIGO II Laser target specifications as follows:

The maximum power in non-TEM_{00} modes is 10% of the TEM_{00} power or 18 watts for the concept laser. This is significantly less than the 36 watts allowed by the target specifications.

The RIN at 25 MHz for a 100 mA sample of the 180 watt output of the concept laser is predicted to be about .09 dB above the shot noise for 100 mA. This is about a factor of 140 below the 6 dB level given in the target specifications. The conceptual design would have to be significantly modified if the LIGO II laser were to be as noisy as the target specifications allow.

3.3 LIGO I Laser Front End

In this conceptual design, we utilize a LIGO I Laser modified to produce 20 watts of output power. The LIGO I Laser was originally designed to deliver 10 watts of output power. The project has taken delivery of 6 of these 10 watt LIGO I lasers and has gained over 2 years of operating experience. The version delivered to the LIGO Hanford Observatory has been running continuously for almost two years with minimum down time. We assume that Lightwave will have developed the capabilities of the 10-W laser to deliver 20 watts with similar noise performance to the 10-W model.

3.4 Laser pre-modecleaner

A pre-modecleaner, similar in design to that utilized after the laser in the LIGO I PSL, is positioned after the 20-W front end. This laser pre-modecleaner (LPMC) serves to reduce RIN at the RF modulation frequency, to filter the spatial mode of the beam, and to define the beam parameters, waist size and location, before the final amplification stages. This prevents excess intensity noise and higher order beam content from being amplified by the subsequent amplifier stages. This will relax the requirements on the PMC. The optimum design of the LPMC is discussed in Section 6.3.3

The laser pre-modecleaner also decouples the LIGO I Laser Front End from the amplification stages for the purposes of alignment and modematching. This is a desirable feature as the LIGO I Laser Front End can be replaced in the event of failure, without having to re-align and modematch to the down-stream amplifier stages.

3.5 Amplifier Stages

3.5.1 Proposed Design

The amplifier stages take the beam from 20 W to 200 W, 180 W of which is expected to be in a TEM_{00} mode. The numbers presented here are extremely conservative with respect to the required pump power. The spec on pump power leaves a 30% margin to allow for degradation of the diodes over time and the slabs operate at about 20% of their stress fracture limit.

Amplification is accomplished in two stages, as shown in Figure 3.5-1

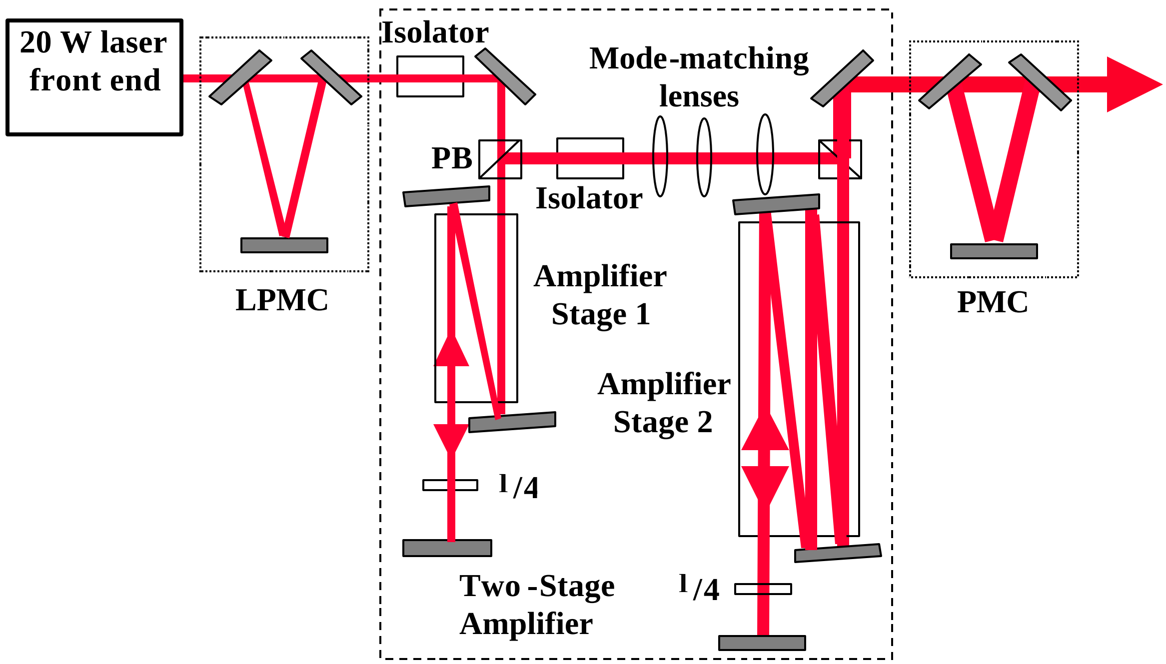

Figure 3.5-1 A schematic of the proposed LIGO II 180 W Laser layout showing the LPMC, PMC and the medium (stage 1) and high (stage 2) power amplifiers.

The input to each stage uses three or four mode matching lenses. The amplifiers are edge-pumped zig-zag slabs of Nd:YAG with conduction cooling and normal incidence end faces (See Figure 3.5-2). They have an SiO_2 coating on the total internal reflection faces, an AR coating at 1064 nm on the end faces and an AR coating at 808 nm on the edge faces. Two flat mirrors that are HR at 1064 are used to steer the beam in the slab and a quarter wave plate (λ/4), curved HR mirror and polarizing beam splitter (PBS) are used to create a second pass having orthogonal polarization.

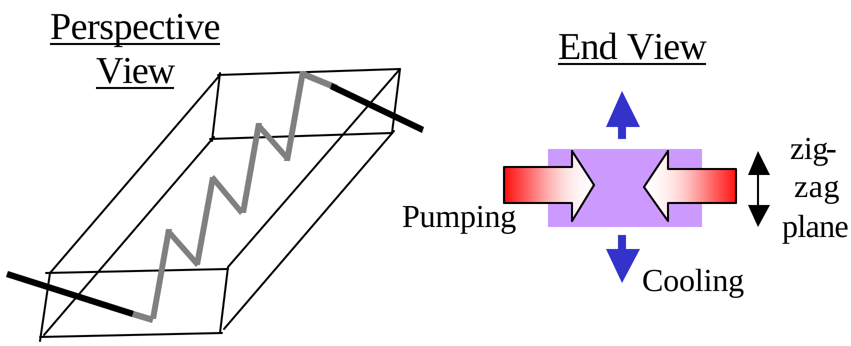

Figure 3.5-2 A perspective and end view of the crystals used in the two optical amplifiers

The mechanical and optical parameters for the first and second amplification stages are given below

Stage 1 :20 W input -> 80W output

- Slab dimensions:
    - Thickness = 1.2 mm
    - Width = 4.4 mm
    - Length = 17.1 mm
    - Doping = 1% at.
- End faces have 35 degree angle (same as internal bounce angle).
- Pump power = 600 W from fiber coupled laser diodes
- Small signal gain for each group of three passes = $e^{2.6}$ =13.9 (this slab has three passes in each direction, see Fig.3.5-1)

Stage 2 : 80 W input -> 200 W output

- Slab dimensions:
    - Thickness = 1.5 m
    - Width = 7.3 mm
    - Length = 29.9 mm
    - Doping = 1% at.
- End faces have 35 degree angle (same as internal bounce angle).
- Pump power = 1100 W from fiber coupled laser diodes

- Small signal gain for each group of four passes = $e^{2.5}$ = 12.5 (this slab has four passes in each direction, see Fig. 3.5-1)

These design results are based on an extrapolation of the performance of the current test-bed amplifier in use at Stanford University. It has the following performance:

- Slab dimensions:
  - Thickness = 1.5 mm
  - Width = 4.5 mm
  - Length = 38 mm
  - Doping = 1% at.
- End faces are at Brewster's angle
- Pump power = 250 W from fiber coupled laser diodes
- Small signal gain per pass = $e^{0.7}$ = 2.0
- Power before amplifier = 8.5 W
- Power after first three passes = 22.2 W
- M^2 before amplifier = 1.1
- M^2 after first three passes = 1.3

This test-bed amplifier was only used in a single group of three passes due to the use of the Brewster windows on the crystal entry and exit faces. It is thought that this test-bed amplifier could have produced between 30 and 40 watts if it were return passed for a total of six passes. To do this would require the removal of the Brewster angle windows as in the amplifiers described above.

3.5.2 Power Scaling Challenges

3.5.2.1 Beam quality

Scaling the amplifier to higher powers requires increasing the number of passes through the amplifier. Care must be taken to prevent reduction of the beam quality by residual thermal distortions in the amplifier. If beam quality is a problem, using smaller crystals could be a solution. Since the pump light in this case in confined to a smaller volume, the gain will be higher. The higher gain may allow operation with fewer passes and thus less accumulated phase error.

3.5.2.2 Parasitic Oscillations

As the small signal gain of the slabs is increased, parasitic oscillations become more difficult to avoid. We do not believe that the gain in the proposed slabs will be high enough to induce parasitic oscillations. However, these effects are sensitive to small changes in the crystal geometry, so any changes to the design should be undertaken with this in mind.

3.5.2.3 Depolarization

In the current Stanford test-bed there is a small amount of depolarization loss (a few percent) near the edges at full pump power. This is due to thermally induced stress in the laser crystal. This loss can be reduced by a more even distribution of the pump light from the fibers. Slabs operating at higher pump power densities will need to take this in to account in the design of the pumping structure.

3.5.3 Estimates of output properties

3.5.3.1 RMS power noise

The Stanford testbed typically operates with 10^{-3} rms relative power noise in open loop and we expect similar performance for the proposed system. We believe that this is mainly due to fluctuations in the pump power.

3.5.3.2 RF power noise

The amplifier chain has a total power gain of 180/20=9, so the output beam will be about 1+2*(G-1)=17 times above the shot noise limit for the full output power (assuming that the 20W input is at the SNL). Filtering this level of relative intensity noise to the required levels is discussed in Section 6.2.

3.5.3.3 Frequency Noise

The amplifiers will add some small phase noise at 100 Hz due to temperature fluctuations and amplified spontaneous emission (ASE). Calculations show that these effects are not significant but measurements on the testbed system are needed to confirm this.

3.5.4 Configuration of laser diodes and power supplies

Fiber delivery of the laser diodes light allows the laser diodes and their power supplies to be located a long distance from the laser itself. The multimode optical fiber has losses of 4 dB/km at 808 nm, so moving the laser diodes 100 meters from the laser will only reduce the power delivered by 5%. Each laser diode should deliver 30 to 40 W of power so 40 to 50 diodes will be needed for the entire amplifier system. If the diodes are powered with groups of six in series, seven or eighth power supplies will be required. This number of commercial power supplies could fit in a standard 18” rack that is 6’ tall. The temperature of each group of diodes will need to be controlled to match the absorption wavelength of the Nd:YAG. This is usually accomplished by mounting the diodes on thermoelectric coolers and using a temperature servo to control the heat flow through the thermoelectric cooler and thus the temperature of the diode.. The power supplies for the thermoelectric coolers could easily be made to fit in a second 18” rack. The transistors used to drive the thermoelectric coolers should be mounted on water cooled heat sinks to reduce acoustic emission due to the cooling fans that would be required if forced convection were used.

3.6 Summary of Anticipated Challenges

The most obvious challenge in the LIGO II Laser design is achieving power amplification without significantly degrading the beam quality of the amplified beam. It is expected that the Stanford Group will commence testing a 100-W output power version of these amplifiers in November, 2000. If the amplifiers introduce significant beam distortions due to increased phase errors, a scheme using a deformable mirror to compensate for these may be employed. Such a scheme is currently being developed by the Stanford Group and is described in Appendix 2.

3.7 Alternative Laser Designs

Injection-locked oscillator (ILO) laser architectures offer an alternative and perhaps superior method for producing the 180-W laser output power. In the minimal modification to the all-MOPA configuration, the 20-W MOPA would be replaced by a 20-W ILO. In this configuration, the LPMC would likely not be required because the 20-W ILO should have much better beam quality and lower excess intensity noise at RF frequencies than the 20-W MOPA, as discussed in Appendix 1.

The Two-Stage Amplifier could also be replaced by an ILO. A candidate high power laser is being developed for this purpose at The University of Adelaide. This laser employs a stable/unstable resonator as discussed in Appendix 3. This configuration should result in efficient production of a high quality laser beam that has less excess RF intensity noise than the 180-W MOPA. Initial results indicate an efficiency of at least 20%, which would significantly reduce the cost of the high power stage. Further, the expected lower excess RF intensity noise would allow the finesse of the PMC, and thus the circulating power, to be reduced, as shown in Appendix 1.

4 Frequency Stabilization

4.1 Overview

The frequency noise requirements are the same as those for the LIGO I PSL. Because the conceptual design incorporates the LIGO I laser as a front end, and because we do not expect a significant amount of additional frequency noise to be added by the high-power amplification stages, the frequency stabilization scheme for the LIGO II PSL is identical to that that employed for the LIGO I PSL. In Appendix 4, we describe potential improvements in the frequency stabilization system that might be implemented if the requirements were to be tightened.

The global interferometer frequency stabilization scheme employs nested loops utilizing the increasing frequency sensitivity of three Fabry-Perot cavities; the PSL reference cavity, the IO mode-cleaner, and the interferometer's 2-km- or 4-km-long arm cavities using the LSC common-mode signal. The reference cavity for the LIGO II PSL will be a linear, fixed-spacer reference cavity that is suspended on a vibration isolation system inside a vacuum chamber. The three PSL frequency actuators are:

1) Control of the master oscillator (NPRO) temperature, commonly referred to as the SLOW actuator.
2) A PZT bonded to the master oscillator crystal, which changes the frequency via strain-induced optical path length changes, commonly referred to as the FAST actuator.
3) High-frequency control of the optical phase via an electro-optic modulator located after the laser front end in the 20-W output beam.

A "wideband" actuator input is provided to the IO detector subsystem for further stabilization of frequency fluctuations. This input shifts the frequency of the sampled beam directed to the reference cavity using an acousto-optic modulator (AOM) that is driven by a voltage-controlled oscillator (VCO).

A "tidal actuator" input is provided for very low-frequency frequency correction via changes in the temperature of the reference cavity. Both of these actuators are similar in design to those utilized in the LIGO I PSL, and, of course, will utilize any improvements implemented during operation of the LIGO I PSL.

4.2 PSL Frequency Stabilization Requirements

The frequency stabilization requirements for the PSL are identical to those for the LIGO I PSL. They are summarized in Table 4.2-1 and shown by the green line in Figure 4.4-1.

Frequency range	Allowed frequency noise (Hz/rtHz)
40 Hz to 100 Hz	$< 0.1 \times (100/f)^{2.5}$
100 Hz to 1 kHz	$< 0.1 \times (f/100)$
> 1 kHz	< 0.01 Hz

Table 4.2-1 PSL frequency stabilization requirements

4.3 Free-running Frequency Noise

It is expected that the free running frequency noise of the 180-W laser will be dominated by the free-running frequency noise of the NPRO. This statement is equivalent to the assumption that the spontaneous emission in the amplifier stages does not add a significant amount of additional frequency noise to the 180-W laser. This assumption can be verified by a beat measurement between a fraction of the light sampled after the high power amplifiers and the light from the NPRO.

As the conceptual design utilizes a LIGO I laser, enhanced to produce 20 W output power, we expect that the free-running frequency noise of the LIGO II front end will be the same as for the LIGO I laser. The frequency noise of the LIGO I laser is limited by the frequency noise of the NPRO. The typical frequency noise of a free running NPRO is approximately 10kHz/f Hz/√Hz, where f is the frequency of interest.

4.3.1 Required Control Loop Performance

As we expect the free-running frequency noise to be the same as that of the LIGO I PSL laser, and because the frequency stabilization sensor and actuators are identical to the LIGO I PSL, the required control loop performance is also identical to what was needed for LIGO I.

4.4 Frequency Control Loop Performance Estimates

The LIGO II PSL frequency stabilization strategy is identical to that of the LIGO I PSL. Therefore, our performance estimate is based on the actual performance of the LIGO I PSL. Figure 4.4-1 shows the LHO 2k PSL frequency noise measured by the 15-m suspended modecleaner. The solid green line represents the PSL frequency noise requirements. As the figure shows, the frequency noise was significantly improved between January 2000 and June 2000. The improvements were the result of optimization of the optical and electronic components and operating parameters in the frequency stabilization control loop. While the measured noise levels are still significantly above the requirements at many frequencies, the improvements made to date give some insight into what is presently limiting the noise performance and further improvements are expected.

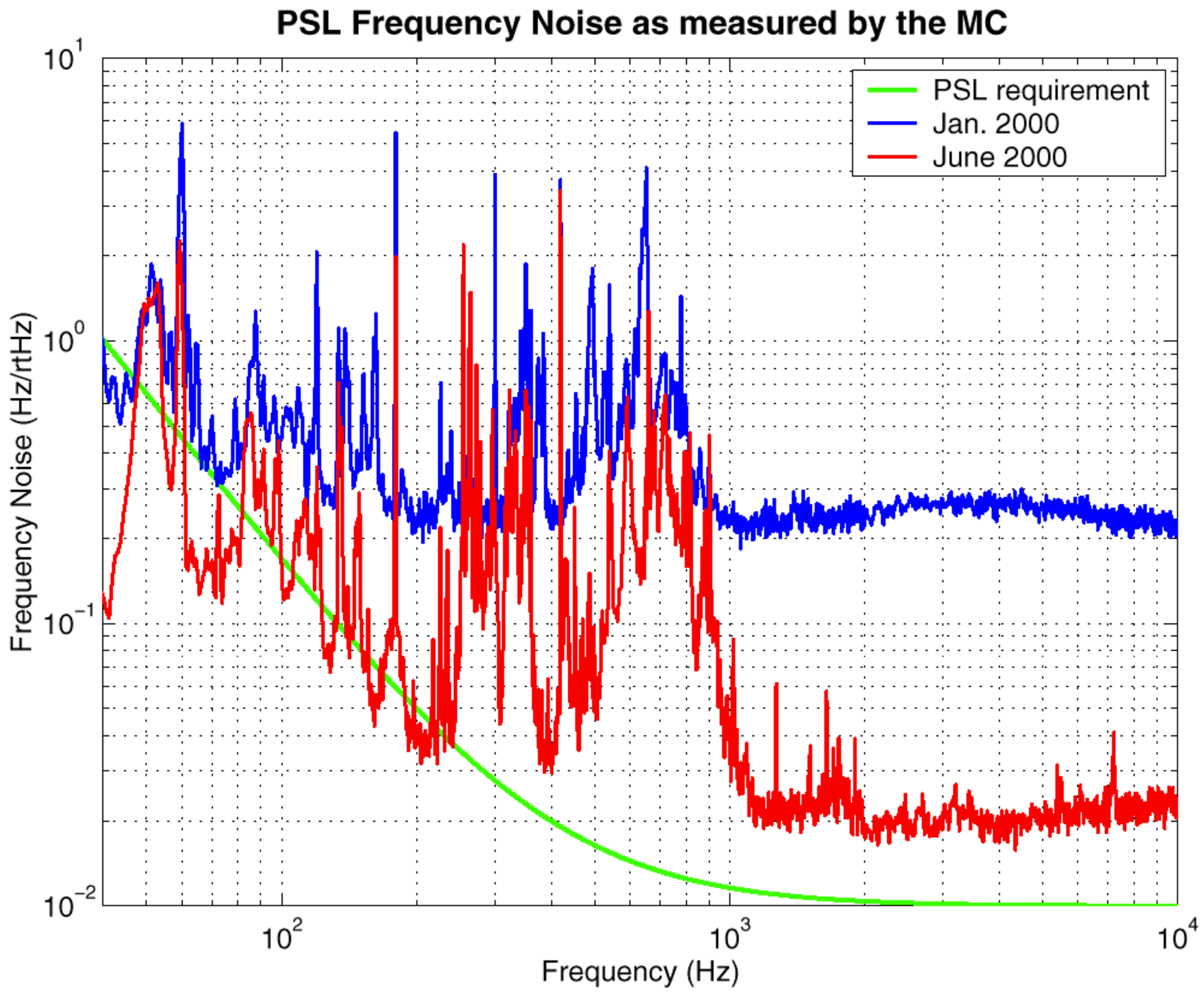

Figure 4.4-1 Measured LIGO I WA 2k PSL frequency noise performance

The 2k IFO. PSL is extremely sensitive to acoustic noise. Several of the narrow spikes in the noise spectrum result from acoustic emission by equipment in the LVEA. One example is the power supply fans in the residual gas analyzers operating in the LVEA. A significant broadband source is the fans in the equipment racks that are located within a few feet of the IO/PSL optical tables in the LVEA. We are presently installing acoustic absorber panels inside the laser table enclosure for the LHO 2k PSL. We are also installing an acoustic absorbing "skirt" around the optical table to reduce acoustic coupling to the lower surface of the table. For LIGO II, we propose constructing a room around the PSL area that is similar to what was constructed at LLO. The electronics racks next to the IO/PSL table would be moved back about six feet so that they would be outside the PSL room. The room should provide 20 to 40 dB of acoustic isolation

We believe that the PMC, which is operated in air, is also a significant source of acoustic-induced frequency noise. For LIGO II, both the LPMC and the PMC are housed inside evacuated chambers.

Another potential source of frequency noise is air-current-induced optical path length changes. For LIGO II, we seek to minimize this effect by keeping all optical path lengths as short as possible and by installing beam pipes, approximately one inch in diameter, wherever feasible, in both the main optical beam path and the optical path leading to the reference cavity.

Finally, mirror mounts have been identified as a source of acoustic- and vibration-induced noise. As described in more detail in Section 2.6 the optical layout has been optimized to minimize the number of mirror mounts.

4.5 Summary of Anticipated Challenges

The frequency stabilization strategy for the LIGO II PSL is almost identical to that for the LIGO I PSL. The only significant difference is that the beam directed toward the reference cavity is sampled AFTER the PMC rather than inside the laser head as in the LIGO I PSL. Because the PMC can introduce frequency changes as the length of the PMC is varied, the frequency control loop is coupled to the PMC length control loop. The frequency stabilization control loop will have to accommodate the PMC pole at approximately 1.6 MHz and the loop cross coupling. If a laser pre-modecleaner is used the servo loop will need to accommodate the LMPC pole at approximately 400 kHz (refer to Section 6.2).

As mentioned above, the LIGO I PSL has not yet met the LIGO I frequency noise specifications, but we assume that it will by the time the LIGO II PSL design matures.

4.6 Frequency Stabilization of an ILO Laser

It has been shown that the frequency noise of injection locked 5- to 12-W Nd:YAG lasers is just that of the NPRO master laser[1,2] It is reasonable to expect that the frequency noise of an 180-W ILO would also be that of the master laser. Thus, any frequency stabilization strategy developed for the 180-W all-MOPA system could be applied to an 180-W ILO system.

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[1] *Frequency and intensity noise of an injection-locked Nd:YAG ring laser*, D.J. Ottaway, P.J. Veitch, C. Hollitt, D. Mudge, M.W. Hamilton and J. Munch, Appl. Phys. B 70, pp.1-6 (2000)

[2] *The GEO stabilized laser system and the current lock technique*, B. Willke, O.S. Brozek, K. Danzmann, C. Fallnich, S. Gossler, H. Luck, K. Mossavi, V. Quetschke, H. Welling and I. Zawischa, in Gravitational Waves: Third Edoardo Amaldi Conference, ed S. Meshkov, (AIP, NY, 2000) pp.215-221

5 External frequency control

5.1 Wideband Actuator

For additional frequency noise reduction, the PSL provides a "wideband" actuator that is utilized by the modecleaner and long-arm loops to further reduce frequency fluctuations. The "wideband" actuator changes the PSL output frequency by changing the drive frequency to an acousto-optic modulator situated in the optical path to the reference cavity. This is commonly referred to as the "frequency shifter," and the variable frequency drive as the voltage-controlled oscillator or VCO. All of the optical, and electronic hardware and software for the wideband actuator are identical to those utilized for LIGO I. Of course, any improvements implemented during the LIGO I commissioning and operation phases will be utilized for LIGO II.

5.1.1 Requirements

The requirements for the LIGO I wideband frequency control input are summarized in the following table:

Response: Magnitude: DC-100 kHz Magnitude: f > 100 kHz Phase	 Flat within 2dB (100 kHz/f) × (Average response below 100 kHz) Phase lag at 100 kHz: $\phi < 20$ degrees
Range	± 5 MHz

5.1.2 VCO

It appears that the frequency noise performance of the LIGO I PSL is presently limited by the noise in the VCO above 1 kHz. Better noise performance can be obtained by using a VCO with a lower range. For LIGO II the range could possibly be reduced to ± 1 MHz to obtain a better frequency noise performance above 1 kHz. This depends on the design of the LIGO II modecleaner and experience gained with LIGO I. A trade off between the range of the VCO and its noise will have to be considered.

5.2 Tidal Actuator

The tidal actuator enables reduction in the actuation range of both the seismic fine actuators and the suspension controllers by changing the PSL output frequency in response to common-mode changes in the long arm lengths induced by earth tides. This is accomplished by changing the temperature of the reference cavity. The hardware, electronics and software for the tidal actuator are identical to those utilized for LIGO I.

6 Intensity Noise Stabilization

6.1 Low Frequency Power Variations

The requirement for low frequency power variation is: "The low frequency variation in the PSL output power shall be less than 1% peak to peak over any 24hr period". This requirement is the same as the specification for the LIGO I PSL. This specification should be achievable by simply monitoring the output of each amplification stage. The monitor signals can then be used in a low bandwidth digital servo that controls the drive current to each amplification stage. Using this scheme will ensure that any correction will be fed back to amplification stage responsible for the power fluctuation and not disturb a correctly operating amplification stage.

6.2 Fractional Light Power Fluctuations in the GW Band

6.2.1 Performance Requirements

The output of the PSL must be stabilized such that the relative intensity noise as measured at the output of the modecleaner is less than 3 10^{-9} 1/√Hz for 10 Hz <f<10 kHz. This requirement is driven by the need to limit the effect of radiation pressure noise on the modecleaner mirrors. A similar level of power stability is needed for the light entering the power-recycling cavity. To achieve this a photodetector located after the modecleaner will be utilized. It may be necessary to locate this photodetector inside the vacuum envelope on one of the vibration isolation stacks.

6.2.2 Free-running Relative Power Fluctuations

The intensity noise of high power MOPA systems is generally limited by the intensity noise of the laser diodes used to pump the high power amplifiers. Hence the free running relative intensity noise of the 180-W laser in the GW band is likely to be comparable to that of the LIGO 10-W laser. Based on this the free-running relative intensity noise[3] is likely to be as follows:

Frequency Band	Relative power fluctuations
10 Hz-1kHz	-80 dB/Hz
1 kHz-100 kHz	[-80+40 log (1 kHz/f)] dB/Hz

It should be noted that these specifications do not include the effects of line harmonics, which can increase the intensity noise significantly between 60 Hz and 780 Hz.

6.2.3 Modecleaner Effect on the Intensity Noise of the PSL

The light from the PSL passes through the modecleaner before it is incident on the main interferometer. The current thinking from the IO group is that the linewidth of the modecleaner will be less than 2kHz. The intensity modulation transfer function of the modecleaner is that of a low pass filter with a corner frequency equal to half the linewidth. Therefore this will provide passive

[3] Personal communication with P. King and R. Abbott

filtering of the PSL intensity noise. Assuming a corner frequency of 1 kHz, the free-running intensity noise at the exit of the modecleaner will be as follows:

Frequency Band	Relative power fluctuations
10 Hz-1kHz	-80 dB/Hz
1 kHz-10 kHz	[-80+60 log (1 kHz/f)] dB/Hz

The bw pass filter action of the modecleaner will also add a pole to the open loop transfer function of the intensity noise suppression servo. This will need to be considered in the overall design of the feedback loop.

6.2.4 Required Control Loop Performance

The loop gain required to suppress the free running intensity noise of the laser at the output of the modecleaner (assuming a modecleaner cavity pole frequency= 1kHz) to the target specification is as follows:

Frequency Band	Loop Gain
10 Hz-1kHz	90 dB
1 kHz-10 kHz	[90 - 60 log (f/1kHz)] dB

6.2.5 Power Stabilization Photodetector

The photocurrent required to achieve a shot-noise relative sensitivity of $3\ 10^{-9}$ 1/√Hz is 30 mA. Photodiodes are routinely available that can provide significantly more photocurrent than 30 mA. Noise calculations, with the PD mounted in a transimpedance amplifier configuration, show that the sensitivity of the PD is not limited by Johnston noise in the feedback resistor. Further, commercially available low noise operational amplifiers (op-amp) are available such that current and voltage noise sources in the op-amps are not a limiting factor to shot-noise-limited detection at the frequencies of interest.

The most likely limit to the performance of the intensity noise stabilization servo is beam jitter coupling into the signal measured by the photodetector via spatial inhomogeneities in the photodetector responsivitity. Measurements performed by M. Petersheim at GEO have shown that the change in the responsivity of an InGaAs photodetector can be as high as 2% per mm. The fluctuations in the position of the output beam of the LIGO I modecleaner have been measured outside the vacuum envelope and found to be as high as 1nm/√Hz at 20 Hz. The preceding two numbers set a lower limit of 2×10^{-8} $Hz^{-1/2}$ at 20 Hz on the achievable relative intensity noise. It should be noted that the quoted pointing stability of the modecleaner is an upper limit on the true pointing stability of the modecleaner. This is due to the measurement being performed outside the vacuum envelope with the position sensorl not having the full isolation of the HAM tables.

If the afore mentioned measurement is limited by movement of the external table then additional improvement could be gained by mounting the monitor photodetectors inside the vacuum envelope on the HAM tables. In this case both the in-loop and out-of-loop[4] photodiodes will need to be mounted on the HAM table inside the vacuum envelope. Hence both photodiodes will need to be vacuum compatible.

The limits on intensity noise stabilization due to beam jitter are generally a low frequency effect (<100 Hz). Recent intensity stabilization experiments performed on an NPRO laser by the Glasgow group[5] have shown that a relative intensity noise stability of 5×10^{-9} $1/\sqrt{Hz}$ above 100 Hz is achievable. This level was achieved without the beam stabilizing effect of a modecleaner. With a modecleaner it is anticipated that this performance can be extended down to 30 Hz.

Transfer of frequency control of the NPRO from the PZT to the pump current may further reduce the beam jitter on the 180 Watt laser beam (see Appendix 4).

6.2.6 Power Actuators

6.2.6.1 DC Power Adjust Actuator

The DC output power level will be adjusted by feedback to the current of diode drivers of each amplification stage

6.2.6.2 Current Shunt Actuator

The power actuator for the control of intensity noise in the GW band will be the diode drive current to the last amplification stage. This will be controlled using a current shunt developed by R. Abbott and P. King[6]. This current shunt has a phase lag at 100 kHz of 125 degrees. If higher bandwidth is required, a Pockels cell actuator controlling the output power of the master laser could be utilized.

6.2.7 Power Stabilization Control Loop Amplifier

To achieve the required intensity noise suppression at 10 kHz, a unity gain frequency of 100 kHz will be required. At 100 kHz the current shunt has a phase lag of 125 degrees and the modecleaner pole will introduce an additional 90 degrees of phase lag. Hence for servo loop stability at least one phase lead stage will need to be incorporated at 50 kHz. This will probably not be enough phase lead so an additional stage will need to be incorporated at 75 kHz.

6.3 Power Fluctuations at the GW Modulation Frequency

6.3.1 Performance requirements

The amplitude spectral density of the relative power fluctuations (RIN) at the gravitational wave detection modulation frequency, assumed to be 25 MHz in this document, is required to be less than 1.005 times the shot noise limit for 5 watts of laser power (the power expected at the dark port

[4] A second, out-of-loop, photodetector may be utilized to assess the performance of the intensity noise suppression servo.

[5] Private communication with K. Strain, University of Glascow

[6] *Diode-pumped Nd:Yag Laser Intensity Noise Suppression Using a Current Shunt*, R. Abbott and P. King, accepted for publication in Rev. of Sci. Instr., 2000.

of the interferometer due to contrast defects). However, recently a DC readout scheme for the LIGO II interferometer has been proposed. If adopted, this will significantly ease the requirements on the relative intensity noise at 25 MHz. Furthermore, it appears likely that the LIGO II interferometers will employ output modecleaners that would drastically reduce the light level at the dark port.[7]

6.3.2 Free-running noise estimate

The free running intensity noise at RF frequencies depends on the properties of the laser front end used, plus the properties of the laser pre-modecleaner. The output of the LIGO II laser can be predicted using the formalism introduced by T. Ralph *et al.* [8]. A brief description of this formalism will be presented in the next few paragraphs. It has been used to generate an estimate of the likely free-running performance of the LIGO II laser given different laser pre-modecleaner cavity half-linewidths. In this formalism the intensity noise of beam is specified as the measured power spectral density of the beam divided by the shot noise limit, and is denoted by V.

When a laser beam is amplified using an optical amplifier the intensity noise of the output is given by

$$V_{output} = H(V_{input} + 1) - 1 \qquad (1)$$

where V_{input} is the intensity noise at the input to the amplifier and H is the power amplification factor of the amplifier.

When a laser beam is passed through a resonant Fabry-Perot cavity such as the PMC the change in relative intensity noise is given by:

$$V_{output} = \frac{1}{1 + (f/f_c)^2}(V_{input} - 1) + 1 \qquad (2)$$

where V_{input} is the intensity noise at the input to the resonant cavity, f_c is the cavity half-linewidth and f is the frequency at which the intensity noise is being measured.

The relative intensity noise of a sample of a beam is given by:

$$V_{sample} = 1 + \eta(V_{input} - 1) \qquad (3)$$

where V_{input} is the intensity noise of the main beam and η is the sample fraction.

Using a measurement of the intensity noise of a 130 mW sample of a 10-watt LIGO I laser and then applying Equation 3, the intensity noise of th LIGO I laser has been estimated to be 166 times

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[7] Both the DC readout scheme and the output modecleaner are design developments that occurred after most of this document was written. If adopted, they would significantly reduce or eliminate the performance requirements for filtering of relative intensity fluctuations at 25 MHz. This would allow reduction in the finesse of both the LPMC and the PMC, and perhaps even elimination of one of them. It would also reduce the advantages an ILO (see Appendix 1) over a MOPA for the laser front end.

[8] See Appendix 3 of *(Infrared) Pre-Stabilized Laser (PSL) Conceptual Design* LIGO-T970087-04-D

the shot noise limit for 10 watts[9]. By applying Equation (1) to this result the free-running intensity noise of the 20 W LIGO I front-end is estimated to be about 333 times the shot-noise limit for 20 watts. By applying the first two equations to this estimate, the free-running intensity noise of the LIGO II laser can be estimated for various laser pre mode cleaners at 25 MHz. The results are as follows:

Cavity half-linewidth of LPMC (f_{LPMC})	**V_{LPMC}**	**V_{180}**
None	333	3005
1.6 MHz	2.35	29.1
0.38 MHz	1.08	17.8

The two chosen cavity half-linewidths of the LPMC are analyzed because:

- 1.6 MHz is the linewidth of the present LIGO I PMC which has been extensively studied
- 0.38 MHz is the linewidth required to meet the LIGO II intensity noise specification with equal circulating powers in the PMC and the LPMC.

6.3.3 Pre-modecleaner design

The PMC requirements are dependent on the chosen LPMC. The table below shows the expected cavity half-linewidth of the PMC and the predicted circulating powers for both the LPMC and the PMC compared with that of the circulating power of the LIGO 1 PMC.

f_{LPMC}	LPMC Circ. power	V_{LPMC}	V_{180}	f_{PMC}	PMC Circ. Power
None	N.A	333	3005	0.27 MHz	100 ×
1.6 MHz	2 ×	2.35	29.1	2.8 MHz	10 ×
0.42 MHz	7.8 ×	1.09	17.8	3.7 MHz	7.8 ×

In this table, f_{LPMC} and f_{PMC} are the cavity half-linewidths of the LPMC and the PMC, respectively. V_{LPMC} and V_{180} are the ratios of the RIN PSD to the SNL PSD for the LPMC and 180 watts of light, respectively. The values quoted for the circulating power are relative to the circulating power in the LIGO I PMC (0.135 MW/cm^2). The LIGO I PMCs have been running for longer than one year in air with no obvious degradation in performance. Further, the LIGO I PMC has been operated for short periods with 10 watts of input power in the high-finesse mode where the finesse is about 4000 instead of the normal low- finesse value of about 225. No adverse effects of the higher circulating power were observed.

[9] Analysis by R. Savage of data taken at Caltech by P. King and B. Willke. See LIGO-G000154-00-W, *Performance of the LIGO Pre-stabilized Laser System*, pages 13-14. To be published in the proceedings of the Ninth Marcel Grossman Conference on General Relativity, Rome, 2000.

The same cavity linewidth can be obtained with reduced circulating intensity by increasing the Free Spectral Range (FSR) of the cavity. For a cavity with a fixed number of cavity mirrors this may only be achieved by increasing the mirror spacing. Increasing the PMC cavity length has some associated practical problems, such as decreasing the resonant frequency of the PMC fused silica spacer for example. The resonant frequency of the LIGO I PMC has been measured to be about 13 KHz. Significantly increasing the spacer length would bring the first spacer resonance into the GW band.

If a 20-W injection-locked laser front end were utilized rather than the LIGO I laser (refer to Appendix 1), the LPMC could be eliminated (from the standpoint of RIN at 25 MHz) and the required LIGO II PMC half bandwidth would be about 3.7 MHz. This is the same PMC that would be required if a LIGO I front-end was used with a LPMC that had a half cavity linewidth of 0.42 MHz.

This is an area of the design where using a high power injection-locked oscillator instead of a MOPA provides a clear advantage. If a 180 W injection-locked oscillator was used for the LIGO II laser, the PMC would require a half-cavity linewidth of 8.3 MHz which results in a circulating power of only 3.5 times that of the LIGO 1 PMC.

6.4 Summary of Anticipated Challenges

The most significant challenge for intensity noise stabilization is achieving a level of 3×10^{-9} $1/\sqrt{Hz}$ at 10 Hz. The likely limitation here is the coupling of beam wander into intensity noise via spatial variations in the responsivity of the in-vacuum power stabilization photodetectors. This problem will need to reviewed in conjunction with the IO and LSC group to set maximal allowable beam wander at the exit of the modecleaner and the maximum allowable surface non-uniformities in the in-vacuum power stabilization photodetector. A vacuum compatible high power photodiode has not yet been fabricated by LIGO. Although there is no apparent reason to suspect that this will not be possible, significant amounts of engineering will be required to bring it to fruition.

6.5 Intensity Noise of an ILO

It has been shown that the GW-band relative intensity noise (RIN) of injection-locked 5- to 12-W Nd:YAG lasers satisfies the LIGO-I specification[10,11] , and that it can be further reduced by feedback to the drive current of the slave laser pump diodes. Since the GW-band intensity noise is caused by fluctuations in the intensity of the pump diodes in both the MOPA and ILO configurations, it is reasonable to expect that any intensity stabilization strategy developed for the 180-W all-MOPA system could be applied to a 180-W ILO system.

The intensity noise at the RF frequencies is much lower for an ILO than for a MOPA however, due to better gain saturation. Thus, the stabilization scheme required to reduce the excess RF intensity noise of the MOPA system could be significantly simplified if using an ILO. It is shown in

[10] *Frequency and intensity noise of an injection-locked Nd:YAG ring laser*, D.J. Ottaway, P.J. Veitch, C. Hollitt, D. Mudge, M.W. Hamilton and J. Munch, Appl. Phys. B 70, pp.1-6 (2000)

[11] *The GEO stabilized laser system and the current lock technique*, B. Willke, O.S. Brozek, K. Danzmann, C. Fallnich, S. Gossler, H. Luck, K. Mossavi, V. Quetschke, H. Welling and I. Zawischa, in Gravitational Waves: Third Edoardo Amaldi Conference, ed S. Meshkov, (AIP, NY, 2000) pp.215-221

Appendix 1 that the lower RF intensity noise of an ILO system allows the LPMC to be discarded and the finesse of the PMC, and thus the circulating power, to be significantly reduced.

7 Reliability and Maintenance

7.1 System-level Requirements

The PSL is required to operate continuously, without loss of 'lock' (even for short times), for 40 hours during normal seismic conditions (90% percentile TBD for either site).

Appendix 1. Injection-locked Oscillator

An injection-locked oscillator (ILO) PSL offers significant advantages compared to the all-MOPA baseline configuration:

- improved beam quality
- improved efficiency laser and PSL
- much lower excess relative intensity noise at RF frequencies.

All of these advantages have been demonstrated at the 5-15 W level and will soon be demonstrated at higher power levels.

ILO's are perceived to be less reliable than MOPA's as the frequency of the slave laser(s) must be servo controlled to be sufficiently close to that of the master laser. However, long-term injection-locking of 5-15W ILOs has been demonstrated by a number of groups. Further, the superior beam quality and lower excess intensity noise of the ILO will simplify the PSL as the LPMC, its associated servo and the wavefront-correction systems are not required, and the circulating power in the PMC is significantly reduced compared to that for the all-MOPA configuration (see below).

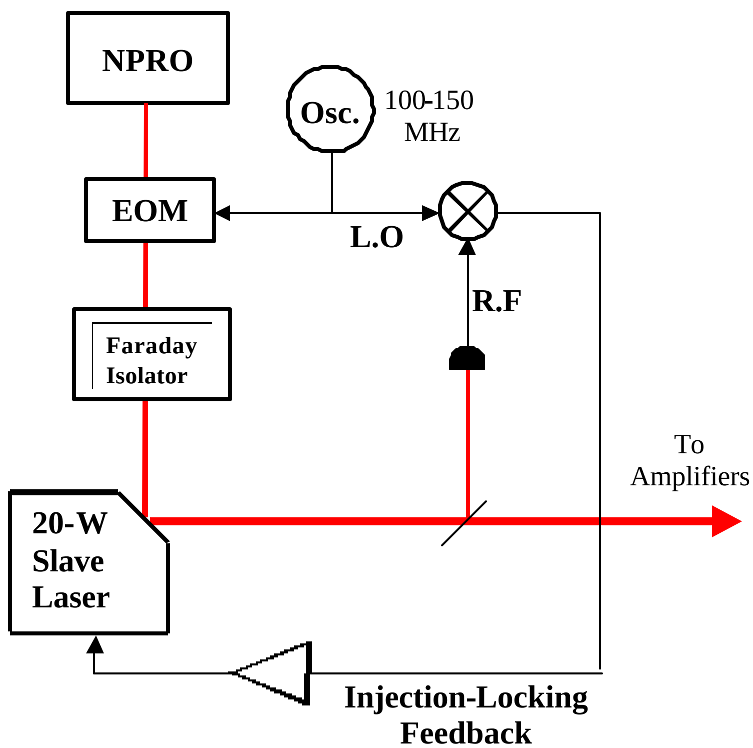

Figure A1 1 Schematic of a 20 W injection-locked oscillator

In a minimal modification of the all-MOPA configuration, the 20-W MOPA would be replaced by a 20-W ILO. The optical layout of the 20 W ILO is shown in Figure A1 1. In this system the output of the monolithic NPRO laser is 'amplified' using a diode pumped, injection-locked, 20-W, ring slave laser. Long-term injection-locking is accomplished using a Pound-Drever-Hall-like servo control that actively controls the frequency of the slave mode to be within 10% of the center of the injection-locking range. The frequency of the slave is adjusted by applying a voltage to two PZT actuators on which resonator mirrors are mounted. One PZT has a large dynamic range while the other has a wide bandwidth.

The output of the 20-W ILO is expected to be an almost diffraction-limited ($M^2 \approx 1$) TEM_{00} mode. The frequency noise in the GW-band will be essentially identical to that of the NPRO master oscillator and thus will satisfy the LIGO II laser frequency noise specification.

The free-running relative intensity noise (RIN) in the GW-band will be about 10^{-5} /Hz$^{1/2}$ at 100 Hz. Stabilization of the intensity noise to less than 10^{-6} /Hz$^{1/2}$ at 100 Hz by feedback to the drive current of a slave laser pump diode has been demonstrated[12]. The reduction factor in that demonstration was limited by the low bandwidth of the diode driver. This could be improved by utilizing a current shunt actuator.

The expected RIN at RF frequencies can be calculated (refer to footnote 12, below)

$$RIN^2 = V_p = 1 + \frac{RIN_m^2}{F_R(2e/I)} \qquad F_R = 1 + \frac{\left(\omega_R^2 - \omega^2\right)^2}{\omega^2 \omega_{lock}^2} \qquad (1)$$

where RIN_m^2 is the residual intensity noise of the master laser, ω_R is the relaxation-oscillation frequency of the free-running slave laser, ω_{lock} is the injection-locking range, P and I are the detected power and the associated photo-current. Using the parameters from the paper referenced in footnote 12 and f = 25 MHz, Equation (1) becomes

$$V_p = 1 + \frac{8.8 \times 10^{-21}}{(2e/I)} \qquad (2)$$

The expected RF intensity noise of several ILO-based configurations and the required PMC half-linewidth, f_c, are summarized below:

Configuration	V_{output}	V_5	f_c (MHz)
180-W MOPA	27.1	1.72	3.0

[12] *Frequency and intensity noise of an injection-locked Nd:YAG ring laser*, D.J. Ottaway, P.J. Veitch, C. Hollitt, D. Mudge, M.W. Hamilton and J. Munch, Appl. Phys. B 70, pp.1-6 (2000)

20-W ILO, H = 9 PA	20.5	1.54	3.4
90-W ILO, H = 2 PA	6.5	1.15	6.7
180-W ILO	4.5	1.10	8.3

For a 20-W ILO, V_{20} = 1.42 which is less than that of the 20-W MOPA after filtering by the LPMC, and so the LPMC should not be required. After amplification V_{180} = 20.5 and thus V_5 = 1.54, which would require a PMC half-bandwidth of 3.4 MHz. The circulating power in the PMC would therefore be 10% less than for the all-MOPA system but would still be about 9 times larger than for the LIGO I PMC.

Using a more powerful ILO would further reduce the PMC circulating power. A (three-stage) 90-W injection-locked oscillator followed by an H = 2 amplifier would result in a PMC half-bandwidth of 6.7 MHz. For an all-ILO PSL V_5 = 1.10, which would result in only a 3.5 times increase in the circulating power in a LIGO I style PMC.

Appendix 2. Beam Quality and Adaptive Optics

This Appendix has been included to describe the current status of phase-front correction of laser beams using deformable mirrors. It is based on the work being conducted by the Byer group at Stanford University. This technology may be required if it proves to be to technically difficult to produce a diffraction limited beam from the high power amplifier. The primary causes of beam distortion in the optical amplifiers are also considered.

Since the output intensity from both optical amplifier stages is well above the saturation intensity, no significant beam distortion is expected due to spatially varying saturation. The primary beam distortions will be due to thermal effects in the slab itself. A deformable mirror will provide correction of distortions to optimize power extraction from the final amplifier pass and to allow active mode matching to the IO chain. Although final experimental verification of the adaptive optics system has yet to be completed, some design decisions can be made based on experience with adaptive optics and general optical design arguments.

The dominant aberrations induced on the laser when transmitting through the slab amplifiers are spherical lensing and astigmatism. There are almost certainly higher-order aberrations, but they are much smaller. Further measurement needs to be made on the laser amplifier before specifying the number of actuators on the mirror, but if only astigmatism needs correction, we have fabricated and tested some cylindrical deformable mirrors that will return the beam to a spherical wavefront with a single actuator. If higher order aberrations need compensation, two actuators will be needed on the mirror for each spatial period of the aberration.

The silicon membrane deformable mirror with high-order aberration compensation capability being developed at Stanford currently uses a 3 mm spacing between actuators. (This is not a fundamental limit of the architecture, but will serve as a design point for this document.) Since the LIGO laser beam in the laser amplifier is going to be roughly 1 mm in diameter, a beam-expanding telescope would be required to fit the laser onto the deformable mirror. Further, the mirrors being fabricated at Stanford are being coated for reflectivity with gold. (This is not the only coating choice available, but a low-stress dielectric coating has not been applied due to financial constraints.) However, even with the relatively lossy gold coating these mirrors can withstand 10 W of 1064 nm light focused to a <1 mm spot.

The adaptive optics system design is based on the current wavefront measurement data, the current state of the deformable mirror technology at Stanford, and a guess at the important aberrations of the system. The mirror will be placed between first and second passes of the final amplifier. A fallback plan is to place it before the first amplifier if power handling becomes an issue (this is not preferable because it complicates the feedback control. A beam-expanding telescope is used to match the beam to the size of the mirror. The mirror will need approximately 25 actuators to compensate for low-order aberrations. (Such a mirror can be purchased now from OKO technologies if the aberrations are very small.) Finally a Hartmann-type wavefront sensor will be used to measure the wavefront after the amplifier. A dielectric plate near Brewster's angle would be best for sampling the beam for the wavefront sensor. The wavefront sensor will need at least one aperture for every actuator, but over sampling is preferred to avoid alignment and waffle- mode problems.

With a complex optical system like this amplifier chain, the M2 metric fails to give a thorough characterization. Using RMS wavefront error from spherical gives more precise information. This metric does not give any spatial frequency information though, so decomposing the wavefront into Zernike polynomials or the laser into its Hermite-Gaussian modes may be needed. We expect that the RMS wavefront error will be able to be reduced to roughly the measurement noise of the wavefront sensor, which is typically a few nanometers or roughly l/300.

Appendix 3. High power, stable/unstable resonator Nd:YAG lasers

Unstable resonators are often used for producing very high power lasers. They allow efficient coupling to an extended gain volume and can produce laser beams that are diffraction-limited. However, they necessarily have high resonator output-coupling and thus are not suitable for CW Nd:YAG, as it has only low gain. The gain requirements can be relaxed by using a stable/unstable resonator and a graded-reflectivity mirror (GRM) as the output coupler[1].

Adelaide University is developing a power-scalable, 100-W, stable/unstable resonator Nd:YAG laser, shown in the Figure A3-1, below, for use in an injection-locked chain of lasers.

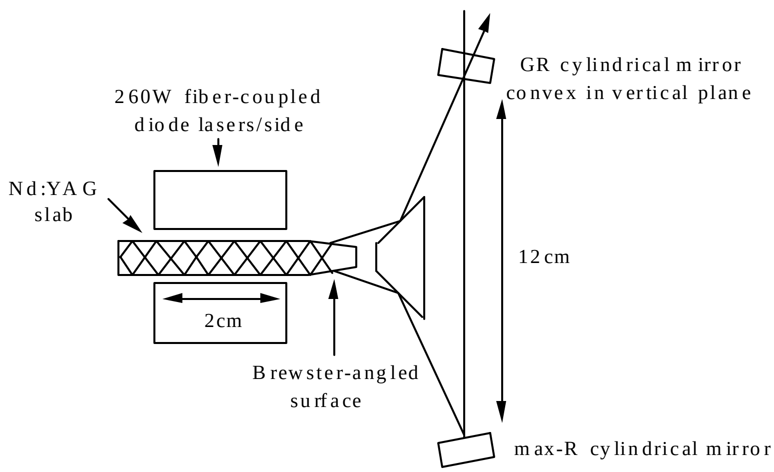

Figure A3-1: Layout of the Adelaide University 100W laser. The resonator is unstable in the vertical plane, and stable in the plane of the zig-zag.

Proof-of-principle experiments have been completed successfully. In these experiments it was confirmed that the gain and loss of the gain medium agreed with the values used in the modeling, and control of the thermal lensing in the unstable plane and single-frequency operation of a stable/unstable-resonator CW standing-wave Nd:YAG laser were demonstrated[2]. They are presently awaiting delivery of the gain medium and GRM for the 100W stable/unstable ring laser demonstration.

[1] *High power diode-laser pumped cw solid-state lasers using stable-unstable resonators*, D. Mudge, P.J. Veitch, J. Munch, D. Ottaway and M.W. Hamilton, IEEE J. Select. Topics Quantum Electron. 3 (1), pp.19-25 (1997)

[2] *Power scalable TEM00 cw Nd:YAG laser with thermal lens compensation*, D. Mudge, M. Ostermeyer, P.J. Veitch, J. Munch, B. Middlemiss, D.J. Ottaway and M.W. Hamilton IEEE J. Select. Topics Quantum Electron. 6 (4), pp.1-7 (2000)

Appendix 4. Potential Frequency Servo Performance Enhancements

Frequency Fluctuation Sensor

A quasi-monolithic ring-cavity together with the Pound-Drever-Hall readout scheme, form the frequency fluctuation sensor for the PSL. A new design of the reference cavity could consist of a fused silica spacer, a fused silica prism, and three mirrors which are optically contacted to the spacer (maybe silicate bonding is an option here). The ring design is chosen to avoid back reflection of the light into the laser system. Other advantages of a ring design are that only light of the correct polarization state is sensed and the finesse of the reference cavity can be changed by rotating the polarization direction of the injected light. Fused silica is chosen to give a low thermal noise level and a low thermal expansion coefficient, which is still high enough to allow for thermal tuning of the cavity resonance frequency. The reference cavity is suspended in vacuum within a wire sling, which is clamped to the tips of cantilever blades to provide one stage of horizontal and one stage of vertical seismic isolation. The pendulum resonances are damped by co-located active feedback control. This design of the reference cavity and it's suspension is similar to the one used by the GEO600 project. Performance data from the GEO600 system, such as the equivalent frequency noise in the GW-band relative to an 8m suspended modecleaner will be available by the end of 2000.

Reference Cavity

The physical and optical parameters for the reference cavity are listed in the following table:

Material	Fused silica
Thermal expansion coefficient	$\Delta l / l \approx 5x10^{-7}$
Round trip length	427 mm
Free spectral range	702 MHz
Transversal mode spacing	107 MHz
Finesse	10000
Lowest mechanical resonance	~10 kHz

Noise budget of the reference cavity

An estimation of the noise contributions from various noise sources is shown in Figure A4-1, below. The shot noise was calculated for 10mW of detected power, a modulation index of 0.5, mode-matching of 0.8 and detector quantum efficiency of 0.85. The seismic curve represents the expected frequency noise due to Doppler shifting caused by motion of the reference cavity relative to the interferometer. We assume a seismic noise of $10^{-7}/f^2$ m/√Hz for Fourier frequencies above

1Hz and a pendulum resonance frequency of 1Hz for the curve labeled “seismic noise suspended.”. A mechanical Q of 10^5 and the structural damping model was assumed for the thermal noise calculation.

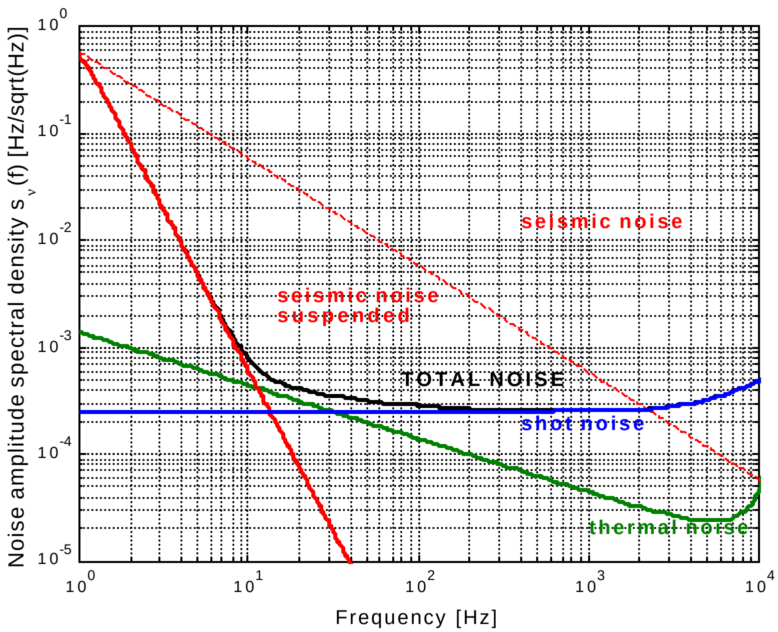

Figure A4-1 Expected noise budget of a GEO600-type reference cavity.

Suspension and vibration isolation system

To reduce the apparent frequency noise introduced by the Doppler effect of the frequency reference cavity, which is moving with respect to the suspended interferometer, the reference cavity is suspended in a wire sling. The sling is attached to the tip of a set of four cantilever blades. The pendulum provides one stage of horizontal isolation whereas the blades reduce the vertical motion of the cavity. (A commonly used coupling coefficient of vertical motion into horizontal motion of a pendulum suspension is 0.01). Therefore for Fourier frequencies above 100 Hz the un-isolated vertical seismic-noise would be higher than the isolated horizontal noise if no vertical stage were used.) A schematic drawing of the suspension system is shown in Figure A4-2, below.

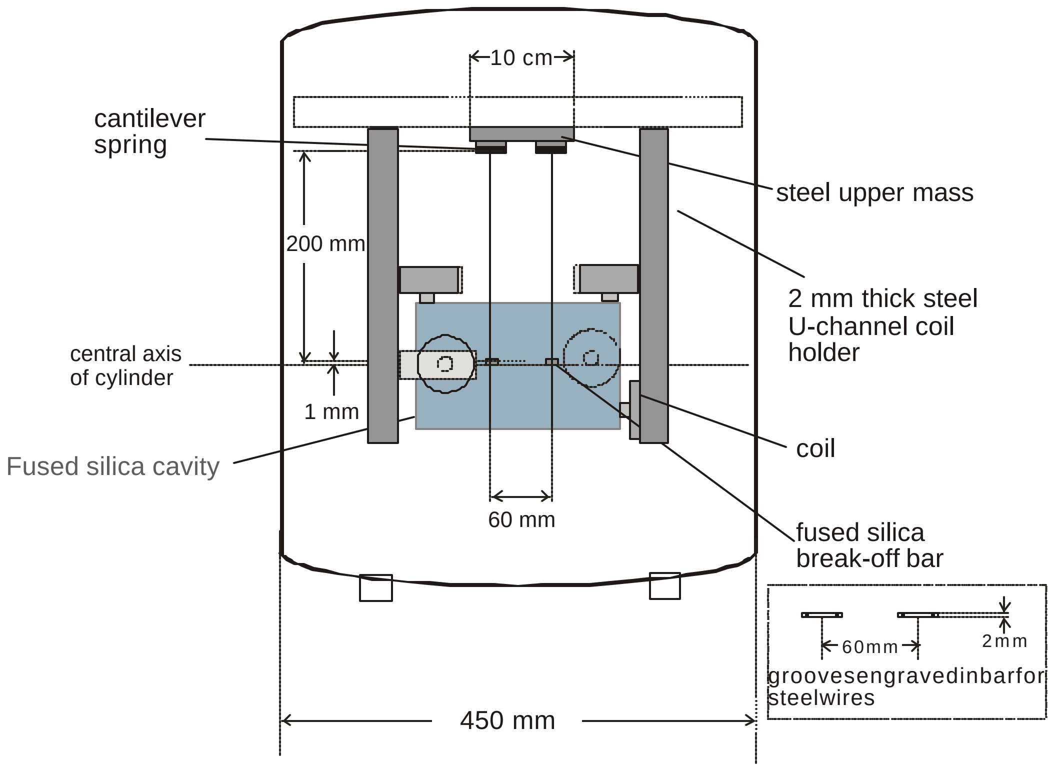

Figure A4-2 Schematic of the GEO style suspension used for the reference cavity

The pendulum motion is damped by an active control system with a servo bandwidth of less than 10 Hz and steep low pass filtering above 10 Hz. A shadow sensor together with a flag glued to the spacer are used as the position sensor of the feedback control system and magnet-coil units serve as the actuator. To avoid contamination of the low-loss cavity mirrors the shadow sensor/coil units are encapsulated in glass. A similar system is under test in the GEO group and results of these tests will be available by the fall of 2000.

NPRO pump diode current control - PDC actuator

In the frequency range between 0.5 Hz and 50 kHz two different frequency control actuators could be used:

- A piezo electric transducer (PZT) mounted on top of the laser crystal which changes the laser frequency by stress-induced birefringence
- The current of the NPRO laser-diode pump source (PDC) which changes the laser frequency due to temperature-induced changes in the index of refraction of the YAG crystal.

A frequency stabilization servo that uses the PZT actuator has been successfully demonstrated in the LIGOI PSL. The actuator coefficient of this actuator is approximately 4 MHz/V (flat up to 100 kHz) and its range is +/- 200 MHz. However there are some disadvantages associated with the use of this actuator:

The PZT response shows resonances for frequencies as low as 100 kHz. These resonances limit the crossover frequency between the PZT and the EOM actuators to approximately 10 kHz. This means that the EOM has to cope with the laser noise at 10 kHz, which has the danger of saturation in the EOM path.

Furthermore, there are significant cross couplings between a voltage injected into the PZT path and the intensity and the pointing of the NPRO output beam.

These problems can be avoided by using the PDC actuator. This is because a noisy pump current is the main source of the free running NPRO frequency noise, a frequency stabilization servo which uses this current actuator simultaneous reduces the NPRO intensity fluctuations.

This current lock technique was demonstrated by the GEO group[1]. The actuator coefficient is 1 MHz/mA @ 10Hz and falls like 1/f up to the relaxation oscillation frequency (

Both actuators might be used in the LIGO II PSL. A trade-off based on more experience with the PDC actuator and the pointing-noise tolerance of the high power stages could be made before the PSL final design review.

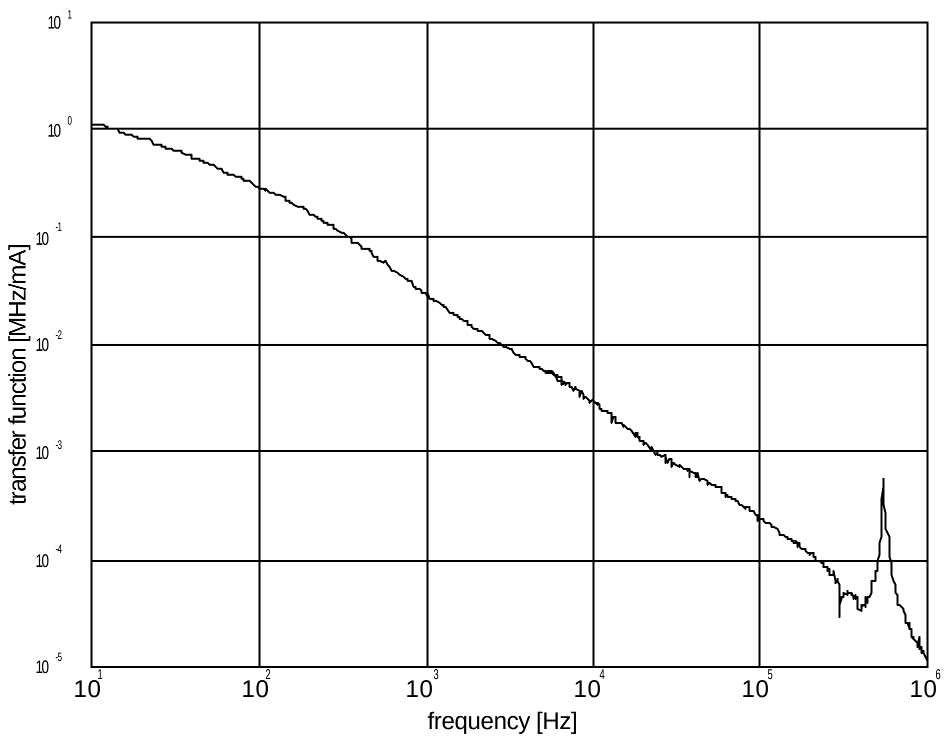

Figure A4-3 NPRO pump diode current to NPRO optical frequency transfer function.

[1] *Frequency stabilization of a monolithic Nd:YAG laser by controlling the power of the laser-diode pump source*, B. Willke, S. Brozek, K. Danzmann, V. Quetschke, S. Gossler, Optics Letters 25 (14) (2000)