LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
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| **Technical Note** | **LIGO-T970087-04 -** | **D** | 10/16/97 |

# (Infrared) Pre-stabilized Laser (PSL) Conceptual Design

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*Distribution of this draft:*

LIGO Nd:YAG Prestabilized Laser (PSL) Subsystem Design
Requirements Review Board (refer to LIGO-L970426-00-D)

This is an internal working note
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# 1 INTRODUCTION

## 1.1. Purpose

The purpose of this document is to present a conceptual design that shows that the requirements presented in *(Infrared) Pre-stabilized Laser (PSL) Design Requirements*, LIGO T970080-00-D are reasonable and realizable.

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

## 1.2. Scope

This document details the expected challenges and a conceptual design solution generated to meet the requirements presented in *(Infrared) Pre-stabilized Laser (PSL) Design Requirements*, LIGO T970080-00-D.

The document provides a brief discussion of the requirements of 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 subsystems, and the features and capabilities of the laser. A brief description of the heart of the PSL, the LIGO 10-W Laser, is included. Schemes to implement the frequency and power stabilization loops are presented, along with their calculated performance levels. An estimate of the output power delivered to **IOO** from the PSL is presented.

Scenarios for various stages of lock acquisition for the PSL are described. Both internal and external diagnostics modes are described. Features of the computer control interface are listed. A policy on reliability and maintenance is formulated.

## 1.3. Document Organization

### 1.3.1. Acronyms

| | |
|---|---|
| AOM | Acousto-Optic Modulator (optical hardware) |
| ASD | Amplitude Spectral Density |
| CCD | Charge Coupled Device |
| CDS | Control and Data System (detector subsystem) |
| COC | Core Optics Components (detector subsystem) |
| DC | Direct Current (steady state - low frequency) |
| EOM | Electro-Optic Modulator (optical hardware) |
| GW | Gravitational Wave |
| HWP | Half-Wave Plate (optical hardware) |
| IOO | Input Optics (detector subsystem, formerly named Input / Output Optics) |
| LIGO | Laser Interferometer Gravitational-Wave Observatory |
| LSC | Length Sensing / Control (detector subsystem) |
| 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 Aluminium Garnet (laser gain medium) |
| NPRO | Non-Planar Ring Oscillator (laser geometry) |
| NPRO-PSL | Pre-stabilized NPRO used for stabilization technique development work and presently being operated as the laser source for the PNI at MIT. |
| PDH | Pound-Drever-Hall (reflection locking technique) |
| PMC | Pre-mode-cleaner |
| PNI | Phase Noise Interferometer at MIT |
| PCPC | Phase-Correcting Pockels Cell |
| PSD | Power Spectral Density |
| PSPD | Power Stabilization Photodetector |
| PSL | Pre-Stabilized Laser (detector subsystem) |
| PZT | Piezo-electric Transducer (mechanical hardware) |
| RF | Radio Frequency |
| RIN | Relative Intensity Noise |
| SEI | Seismic Isolation |
| TBD | To Be Determined |
| TFP | Thin Film Polarizer (optical hardware) |
| VCO | Voltage-Controlled Oscillator (electronics hardware) |

## 1.3.2. Applicable Documents

### 1.3.2.1 LIGO Documents

- Civil Construction Facilities *Design Configuration Control Document, Final Issue, July 3, 1996* LIGO-C960703-0
- *Lightwave Preliminary Design Review Documentation Package*, LIGO-C970712-00-R
- *LIGO Naming Conventions*, LIGO-E950111-A-E
- *Detector Subsystems Requirements*, LIGO-E960112-06-D
- *LIGO 10-W Laser Specifications*, LIGO-E970055-00-D
- *NPRO-PSL Conceptual Design*, LIGO-T960089-00-D
- *Frequency-stabilization in LIGO*, LIGO-T960164-00-D
- *NPRO frequency stabilization*, LIGO-T970051-00-R
- *NPRO-PSL Performance Data and System Documentation*, LIGO-T970052-00-D
- *The Effect of Earth Tides on LIGO Interferometers*, LIGO-T970059-01-D
- *(Infrared) Prestabilized Laser (PSL) Design Requirements*, LIGO-T970080-00-D
- *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, Opt. Lett., **10**, pp65-67 (1985).
- *Sub-Hertz Relative Frequency Stabilization of Two-Diode Laser-Pumped Nd:YAG Lasers Locked to a Fabry-Perot Interferometer,* Timothy Day, Eric K. Gustafson, and Robert L. Byer, IEEE Journal of Quantum Electronics, **QE-28**, pp1106-1117 (1992).
- *Ultrahigh-spectral purity laser for the VIRGO experiment*, F. Bondu, P. Fritschel, C. N. Mann

and A. Brillet, Optics Lett, **21**, 582 (1996)
- *Ring Mode Cleaner for the Initial LIGO 10 Watt Laser* - Internal Report - Noboru Uehara
- *Series 126 Diode-pumped Non-planar Ring Laser Users Manual*, Lightwave Electronics, Inc.

### 1.3.3. Definition of Terms

| | |
|---|---|
| Gaussian beam | A 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. |
| HEPA filter | A high efficiency particulate air filter that removes solid airborne particles. |
| Lightwave | Lightwave Electronics Inc., 1161 San Antonio Rd., Mountain View CA 94043. |
| LIGO 10-W Laser | The 10-W Nd:YAG laser being developed by Lightwave Electronics Inc. under contract with LIGO. |
| $M^2$ 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-$TEM_{00}$ mode is $M^2$ that of a $TEM_{00}$ mode. |
| modulation index | If the phase of the laser is represented by $\omega_0 t + \beta \sin \omega_m t$, then the amplitude of the phase modulation, $\beta$, 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 maximum value, $E_0$ (at $r = 0$). |

# 2 SYSTEM OVERVIEW

The PSL contains the laser source for the LIGO interferometers and is therefore situated at the beginning of the optical train. As shown in Figure 1, the PSL passes the pre-stabilized laser radiation to **IOO** which in turn passes it to **COC**. Laser frequency correction signals are passed to the PSL from both **IOO** and **LSC**. The principal signal interface for the PSL is with **CDS**.

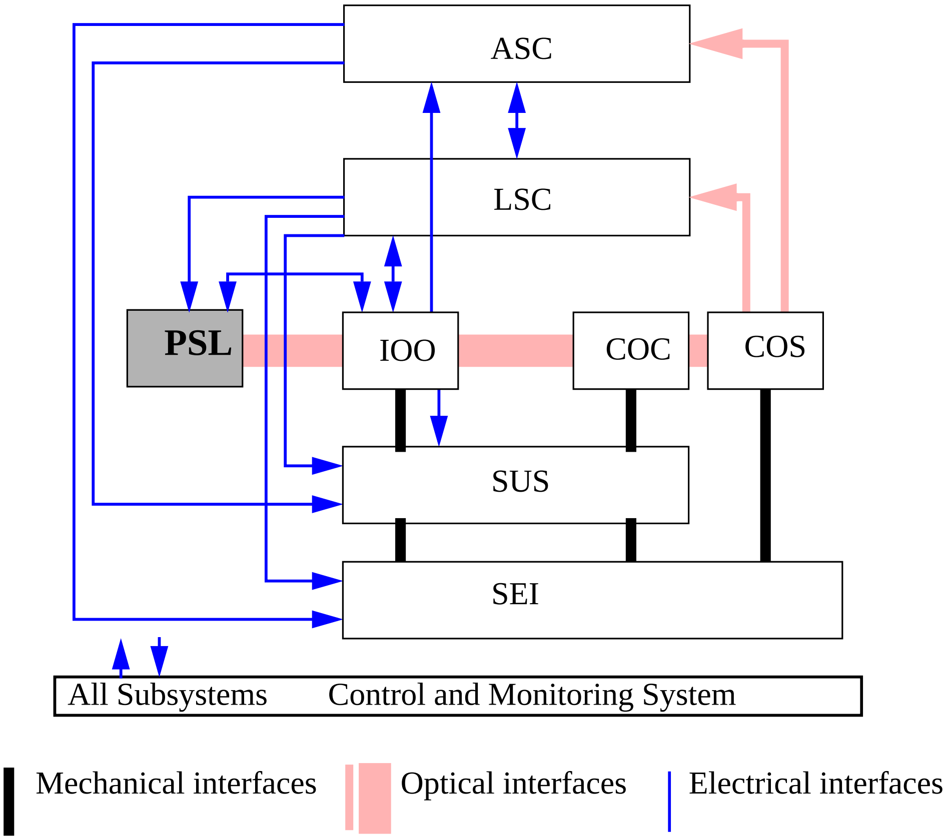

**Figure 1: Block diagram showing the relationship of the PSL to other detector subsystems.**

## 2.1. Introduction

The PSL subsystem includes the following elements:

- The LIGO 10-W Laser with power supply and recirculating water chiller.
- Frequency stabilization control loop including electro-optic, acousto-optic and PZT actuators, frequency reference cavity (including vacuum enclosure and thermal enclosure), RF photodetector, and mode matching optics.
- Power stabilization control loop including a pre-mode-cleaner, a sampled beam from **IOO** and a power stabilization photodetector.
- Optical components including polarizing beamsplitters, mirrors, Faraday isolator, quarter and half-waveplates.
- Environmental control including optical table enclosure and reference cavity temperature controller.
- Optical table, optical table enclosure and the optical table vibration isolation systems. **IOO**, not PSL, is responsbile for the specification of the optical table and the vibration isolation system.

It does NOT include:

- Mode matching lenses or steering mirrors for the input optics.

- Electro-optics for modulation frequencies used outside the PSL subsystem.

## 2.2. PSL Location

Figure 2 shows the location of the PSL and **CDS** electronics racks in the LVEA. The distance from the middle of the **IOO /** PSL optical tables to the middle of the **CDS** electronics racks is approximately 9 ft. (**TBD** by PSL pending updated as-built drawings). The distance from the middle of the **IOO** / PSL optical tables to the recirculating water chiller is approximately 14 ft. (**TBD** by PSL pending updated as-built drawings) for the WA4k inteferometer and 40 ft. (**TBD** by PSL pending updated as-built drawings) for the WA2k interferometer.

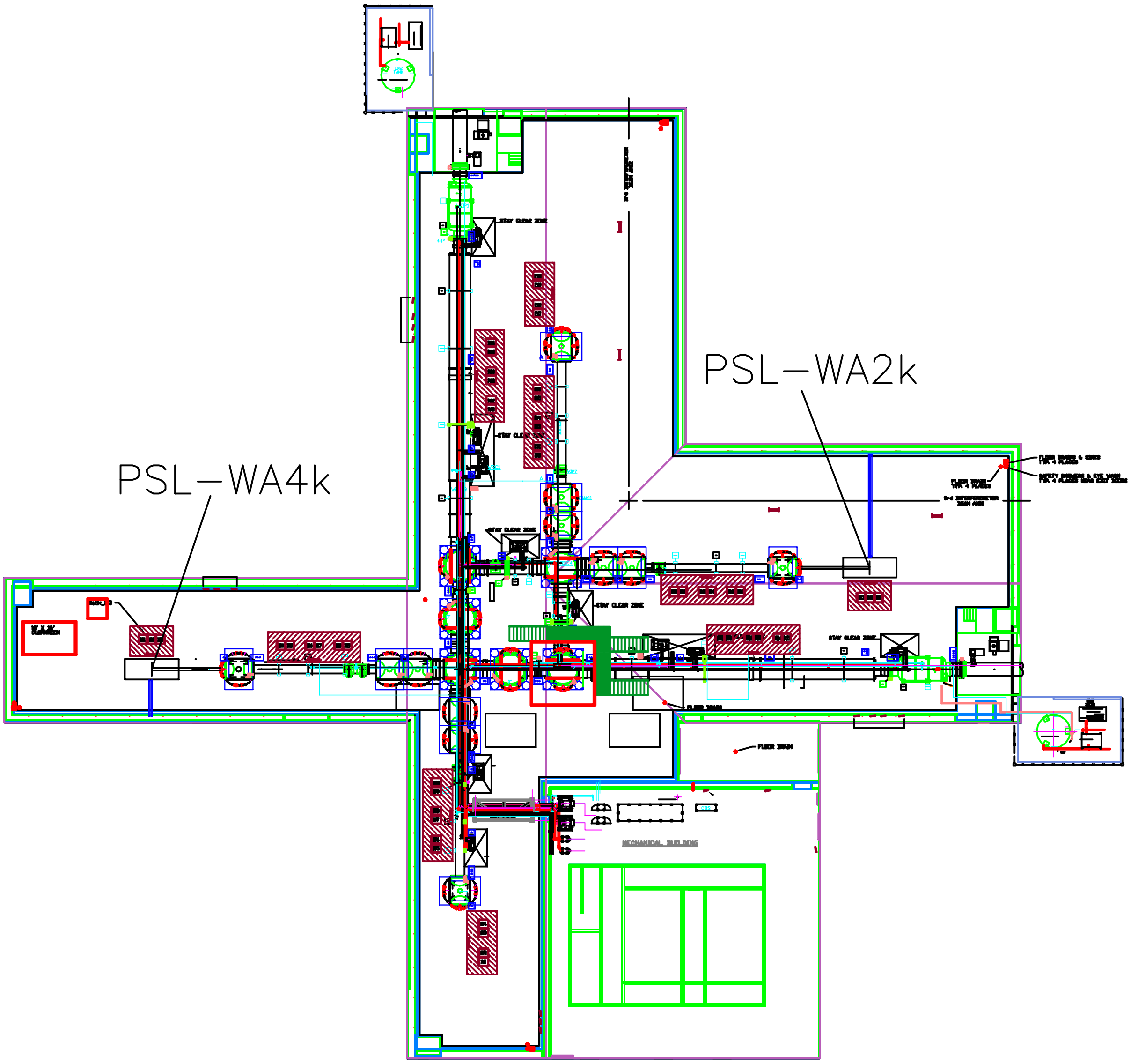

Figure 2: The Hanford, WA LVEA floor plan.

## 2.3. The IOO / PSL Optical Table

Figure 3 shows the partition of the **IOO** / PSL optical table between PSL and **IOO** and the coordinate system employed in describing the interface between the PSL and **IOO**.

The whole **IOO** / PSL optical table is surrounded by a free-standing enclosure.

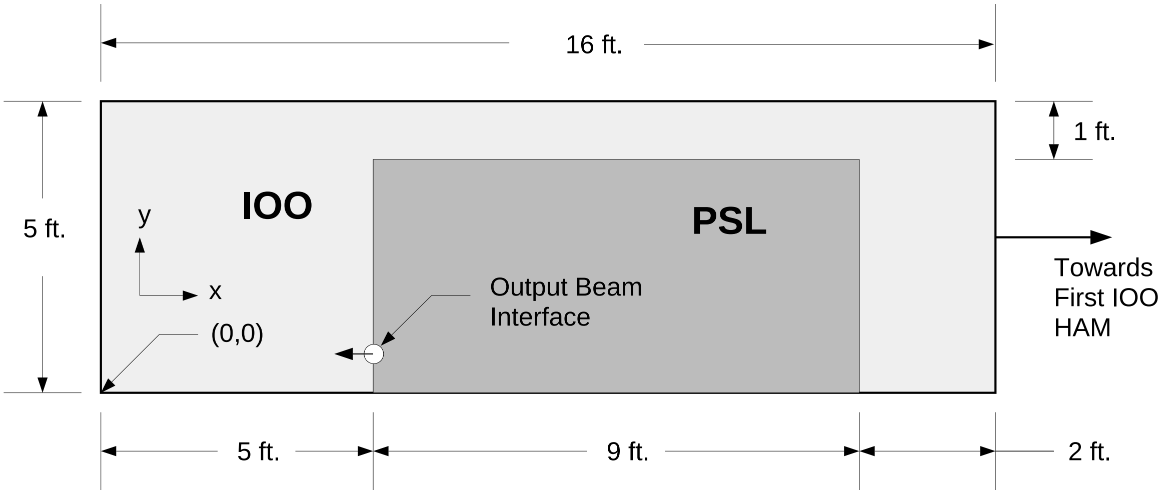

Figure 3: Relative positions of the PSL and IOO areas on the shared PSL / IOO optical table.

## 2.4. Optical Layout

Figure 4 shows a schematic of the optical layout of the PSL. The output of the LIGO 10-W Laser is passed through a phase-correcting electro-optic modulator (EOM) and goes through a ring pre-mode-cleaner, before being delivered to **IOO**. For frequency stabilization, a small fraction of the output of the LIGO 10-W Laser is sampled with a beamsplitter and directed towards the reference cavity EOM. This beam is double passed through an acousto-optic modulator (AOM). The counter-propagating beam from the AOM is separated by a quarter-wave plate and polarizing beamsplitter and directed to the reference cavity. The same technique is used to direct the light reflected from the reference cavity to an RF photodetector. For power stabilization, a small fraction of the **IOO** output beam is sampled and directed towards a power stabilization photodetector.

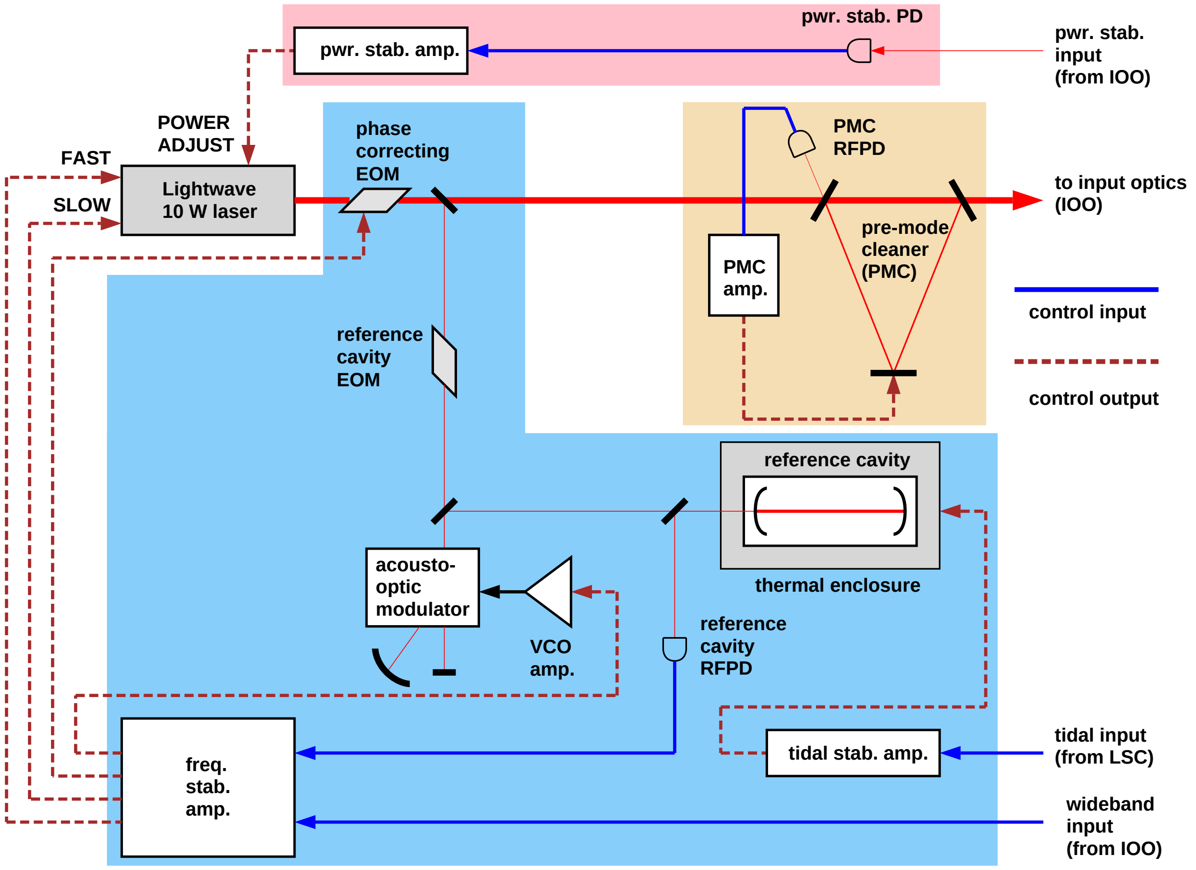

Figure 4: Optical layout schematic of the PSL.

## 2.5. Facilities Interfaces

The PSL will rely on the LIGO facility for the supply of the mains electrical power, temperature and humidity control, space for the recirculating chillers and interconnecting water hoses and interface cables.

## 2.6. Remote Control

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

## 2.7. Features / Capabilities

The PSL will have internal frequency and power actuators and sensors that can accommodate correction signals from **IOO** and **LSC**. PSL will provide a wideband frequency control input for frequency correction signals from the **IOO** mode-cleaner servo. The PSL will provide a tidal input for making the laser frequency track the common mode length changes of the interferometer's arms at tidal time scales.

Furthermore, the PSL will operate in modes that will permit diagnostics of downstream subsystems, the details of which are given in Chapter 9. The PSL features the following external diagnostic modes:

- Beam finding (BF) mode, where the modulated output power of the PSL has a square waveform of modulation depth ~ 50% at a modulation frequency of 2 Hz. BF mode is used in locating optical beams prior to fine alignment.
- Cavity ringdown (CR) mode, where the output power can be modulated sinusoidally or by a square wave with a modulation depth between 1% and 10%. CR mode is activated to measure ringdown times of the various optical cavities in the interferometers.
- System diagnostics (SD) mode, where the output power and the frequency of the PSL can be modulated. SD mode is used to perform system-level signal diagnostics. In this mode the power stabilization and frequency stabilization control loops (either or both) remain locked.
- Calibrated Power Reduction (CPR) mode, where the output power of the PSL can be reduced from full power to 10 mW in a calibrated manner.

# 3 PHYSICAL IMPLEMENTATION

## 3.1. Physical Implementation

The PSL assumes the LIGO facilities meet the environmental, acoustic and vibration specifications detailed in the Civil Construction Facilities *Design Configuration Control Document, Final Issue, July 3, 1996* LIGO-C960703-0.

## 3.2. Optical Table Enclosure

The whole **IOO** / PSL optical table will be enclosed in a 17 ft. x 6 ft. x 6.5 ft. high free-standing enclosure. The walls of the enclosure are made from sliding lightweight aluminum honeycomb panels, attached to a rigid steel frame. The enclosure will help isolate the PSL from acoustic noise, air currents, stray light and dust. A light plastic, or rubber, skirt is fitted around the edge of the optical table and the enclosure to prevent any dust rising from the LVEA floor contaminating components mounted to the optical table. Also around the enclosure will be a cable tray to house signal cables from the PSL and its associated electronics. Electrical connections from the outside of the enclosure to the inside are provided for by a series of BNC feedthroughs all around the enclosure. Incandescent lighting is provided inside the enclosure.

Quick visual inspections of the status of the LIGO 10-W Laser or any components mounted to the **IOO** / PSL optical table can be made through a series of see-through panels. The see-through portion of the panels will be made from an acrylic suitable for blocking 1064 nm light. During operation of the LIGO 10-W Laser, the see-through panels are covered by non-transparent covers to reduce the level of stray light.

On top of the enclosure, above the LIGO 10-W Laser, a HEPA filter and blower panel will be mounted. The panel, which is to be activated during major maintenance periods or any time that servicing of the LIGO 10-W Laser is required, provides a laminar air flow over the LIGO 10-W Laser. The top of the enclosure also has a series of hooks allowing the whole enclosure to be lifted by a crane. A schematic drawing of the enclosure is shown in Figure 5.

In addition the optical table enclosure will display the appropriate laser safety warning signs, which conform to Federal, State and LIGO safety requirements, on the outside. The outside of the enclosure will also display safety information including emergency shutdown procedures and a list of people to contact and their telephone numbers, in the case of an emergency.

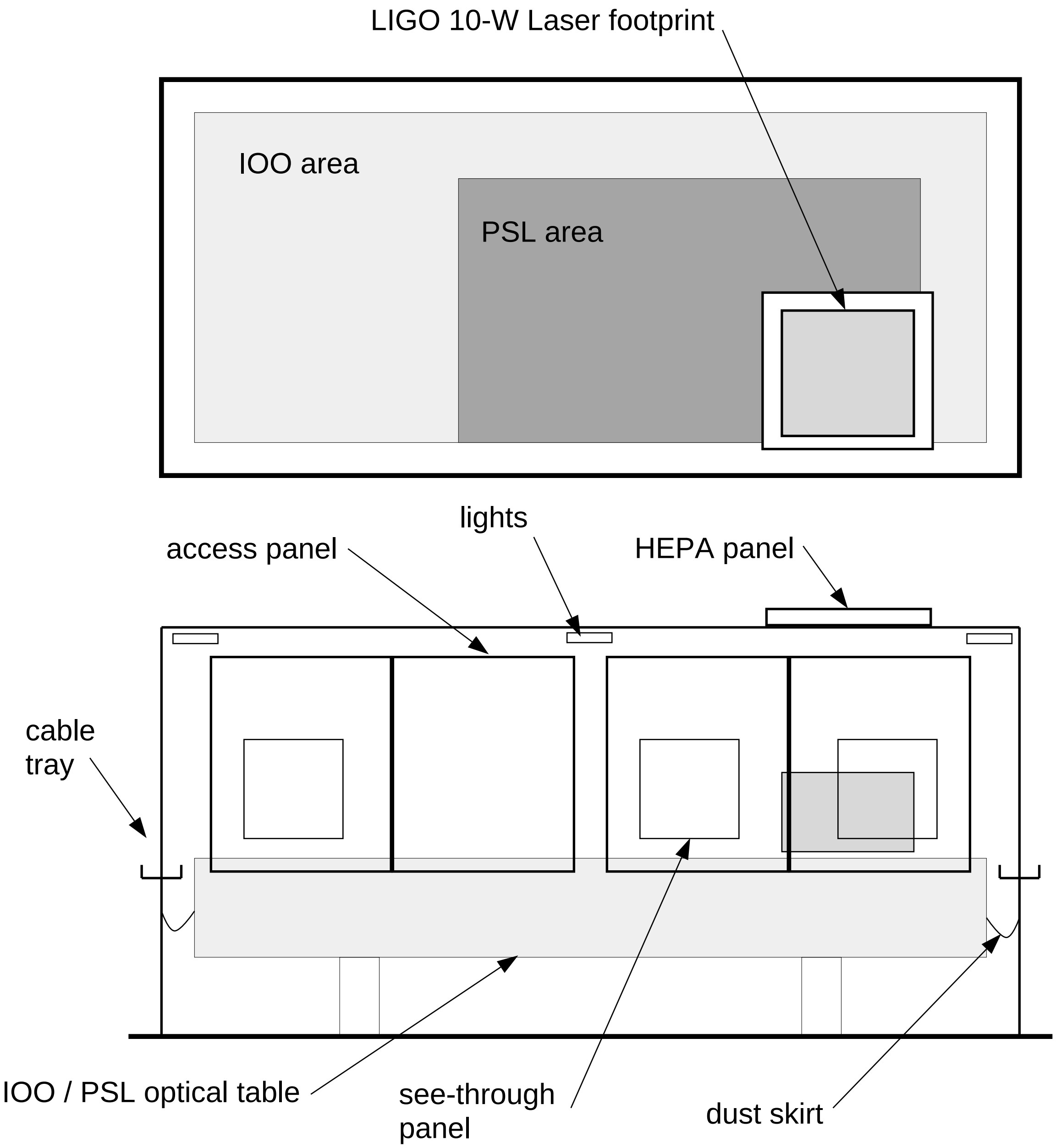

Figure 5: The IOO / PSL shared optical table.

## 3.3. Optical Table

The optical table will be similar to the Newport RS4000$^{\mathrm{TM}}$[1] series optical table of dimensions 16 ft. x 5 ft. x 24 in. mounted on vibration isolators (**TBD** by **IOO**).

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[1] RS4000 is a trademark of Newport Corporation, 1791 Deere Ave., Irvine CA, 92714.

## 3.4. Detailed Optical Layout

The PSL optical layout is given in Figure 6. The components of the optical layout are described in Table 1.

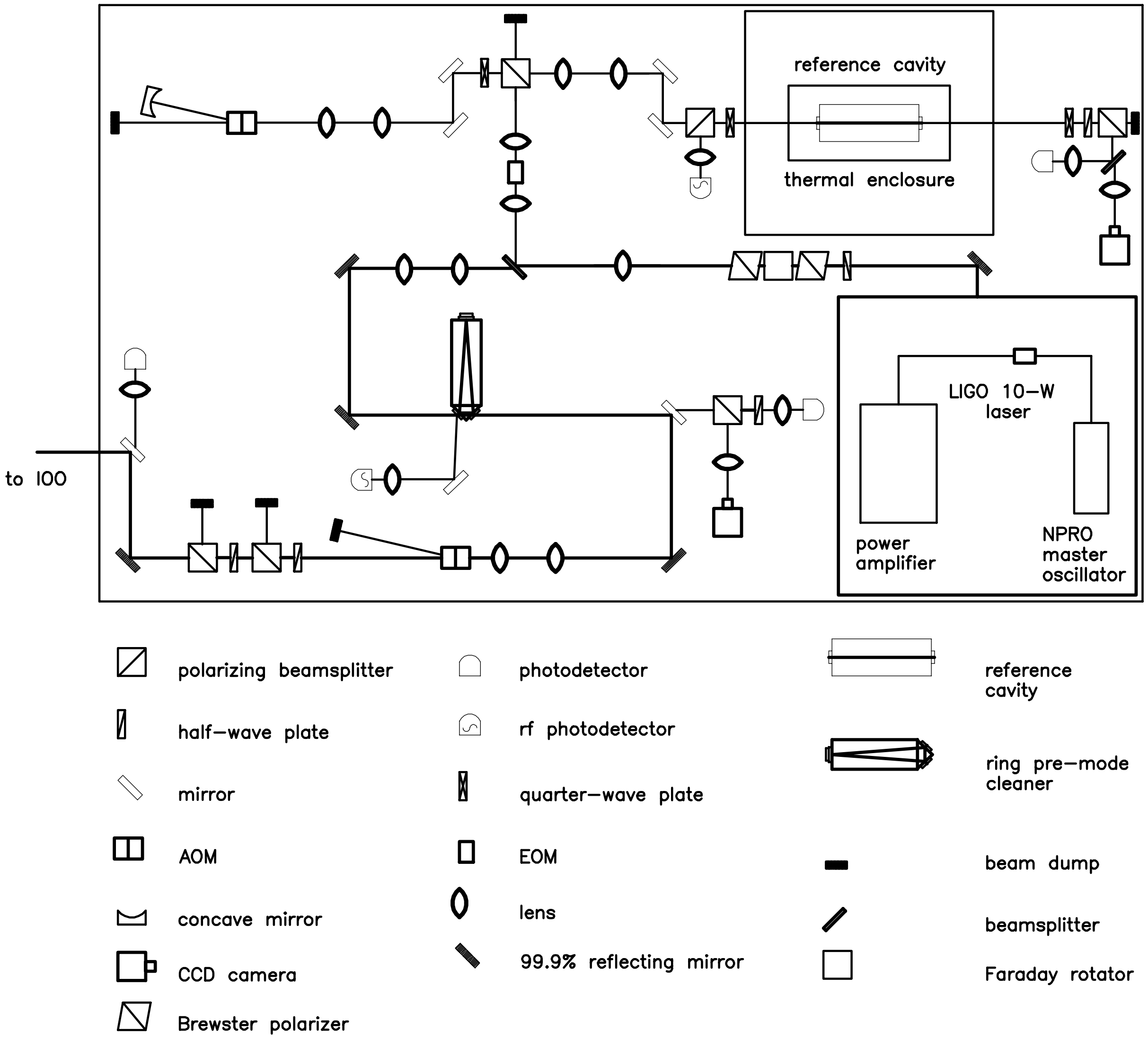

Figure 6: PSL optical layout.

The area shown is the 9 ft. x 4 ft. foot print on the **PSL** / **IOO** shared optical table. The *s* polarized output from the LIGO 10-W laser is allowed to expand and its polarization is rotated by a half-wave plate. The LIGO 10-W laser is optically isolated from feedback by a Faraday isolator, consisting of two calcite Brewster angle polarizers and a Faraday rotator. A lens then collimates the output beam. Two lenses are used for mode matching the beam into the pre-mode-cleaner. After being filtered by the pre-mode-cleaner the beam is coupled into an AOM which is used during diagnostics of the interferometer. Two half-wave plates mounted to motorized rotation stages and polarizing beamsplitters (only one set is required, the drawing will be updated) are used for

**Table 1: Optical layout components.**

| *Optical Component* | *Comments* | *Assumed Performance* |
|---|---|---|
| polarizing beamsplitter | *e.g.* CVI part PBSC-1064-050 | T = 99.5% |
| half-wave plate | zero order half-wave plate<br>*e.g.* CVI part QWPO-1064-10-2 | T = 99.5% |
| mirror | CVI high energy laser mirror<br>*e.g.* Y1-1025-45-S | R = 99.5% |
| AOM | *e.g.* IntraAction Corp. Model AFD-402 | T = 97.1% |
| concave mirror | AR coated on both sides | R = 99.5% |
| CCD camera | used for monitoring which mode the cavity is locked to | N / A |
| Brewster polarizer | calcite polarizer from Karl Lambrecht | T = 99.0% |
| photodetector | | N / A |
| RF photodetector | | N / A |
| quarter-wave plate | zero order quarter-wave plate<br>*e.g.* CVI part QWPO-1064-10-4 | T = 99.5% |
| EOM | *e.g*. New Focus Model 4004D | T = 97% |
| lens | AR coated on both sides | T = 99.5% |
| 99.9% reflecting mirror | super polished mirrors, HR coated by REO | R = 99.9% |
| reference cavity | same as one used with the NPRO-PSL, described in LIGO-T960089-00-D | N / A |
| ring pre-mode-cleaner | ring mode-cleaner similar to that used by Noboru Uehara | T = 97.0% |
| beam dump | *e.g*. Thorlabs LB1/M or similar | T = 0% |
| beamsplitter | *e.g*. CVI part W2-PW1-1012-UV-1064-45S | T = 99.5% |
| Faraday rotator | IsoLite Litton / Airtron rotator with terbium gallium garnet crystal | T = 98.9% |

coarse adjustment of the power delivered to **IOO** during CPR. Two steering mirrors are then used to direct the beam to the specified **IOO** delivery point.

The reflected signal from the pre-mode-cleaner is focused onto an RF photodetector for reflection locking the length of the pre-mode-cleaner. The output mode from the pre-mode-cleaner is monitored on a CCD camera and its power is monitored by a photodetector in transmission (this combined with the DC output of the RF photodetector enables selection of the $TEM_{00}$ mode). After power modulation hardware and before delivering the beam to **IOO**, the output power is again monitored by a photodetector.

A small fraction (~ 0.5%) of the main beam is picked off by a beamsplitter and is focused through the reference cavity EOM. The EOM adds the frequency sidebands for the PDH reflection locking stabilization scheme. The carrier and the sidebands are reflected by a polarizing beamsplitter cube to a quarter-wave plate which circularly polarizes the beam. The beam is then double passed through an AOM which shifts the frequency in proportion to a control signal from PSL-external cavities so that the frequency of the LIGO 10-W Laser can remain resonant in the PSL-external cavities whilst the frequency-shifted light resonates in the reference cavity. The beam is then converted back to linearly polarized light by the quarter-wave plate and transmitted by the polarizing beamsplitter cube and some mode matching optics into the reference cavity. The transmitted beam through the reference cavity is monitored by a CCD camera, which will allow visual confirmation of which mode the pre-mode-cleaner is locked onto. Mode selection is accomplished via a visibility monitor which utilizes transmitted and reflected power monitors. The reflected beam from the cavity is detected by an RF photodetector used in implementing the PDH reflection locking stabilization scheme.

# 4 THE LIGO 10-W LASER

## 4.1. System Overview

The LIGO 10-W Laser is being designed and developed under contract with Lightwave Electronics Inc., Mountain View CA. Lightwave Electronics Inc. is the manufacturer of the Model 126-1064-700 NPRO laser.

For this document the LIGO 10-W Laser is assumed to meet the performance requirements and as such is treated as a black box. The full specifications for the LIGO 10-W Laser[1] are included as Appendix 5 in this document.

The LIGO 10-W Laser is a master-oscillator-power-amplifier (MOPA) chain consisting of a Model 126-1064-700 NPRO-based, diode-pumped, narrow-linewidth, single-frequency laser as the master oscillator and a double-passed power amplifier. The amplifier chain consists of four Nd:YAG rods, each pumped by a pair of 20-W laser diodes. Specific details of the amplifier implementation will not be discussed in this document because of the proprietary nature of the design.

The LIGO 10-W Laser is mounted to a 2 ft. x 2 ft. optical breadboard with 1/4 in.-20 tapped holes on a 1 in. grid. The power amplifier is mounted to a copper baseplate which is cooled by a recirculating water chiller. A removable dust cover protects the power amplifier from contaminants and dust. A separate protective dust cover encloses the entire laser to protect the coupling and beam control optics. The total height of the LIGO 10-W Laser is to be less than 1 ft.

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[1] *Specifications: LIGO 10-W Laser*, LIGO-E970055-00-D.

The final design review for the LIGO 10-W Laser was held on June 20th, 1997 at Lightwave Electronics Inc. An engineering-prototype alpha unit is scheduled for delivery in early August, 1997 with delivery of the first LIGO 10-W Laser expected in early December, 1997.

### 4.1.1. LIGO 10-W Laser Optical Layout

Figure 7 shows the optical layout of the LIGO 10-W Laser (this drawing will be updated at a later date in response to the LIGO 10-W Laser final design review). The 1064 nm output from the NPRO master oscillator is passed through a half-wave plate, thin film polarizer and some beam shaping optics before being reflected into a Faraday rotator. The horizontally polarized beam is then transmitted through a thin film polarizer, passed through another Faraday rotator, a thin film polarizer and a half-wave plate before entering the power amplifier. The output from the power amplifier is passed back through the half-wave plate, thin film polarizer and Faraday rotator. The polarization of the beam is now such that it is reflected from the thin film polarizer and a pair of beam steering mirrors to become the output of the LIGO 10-W Laser.

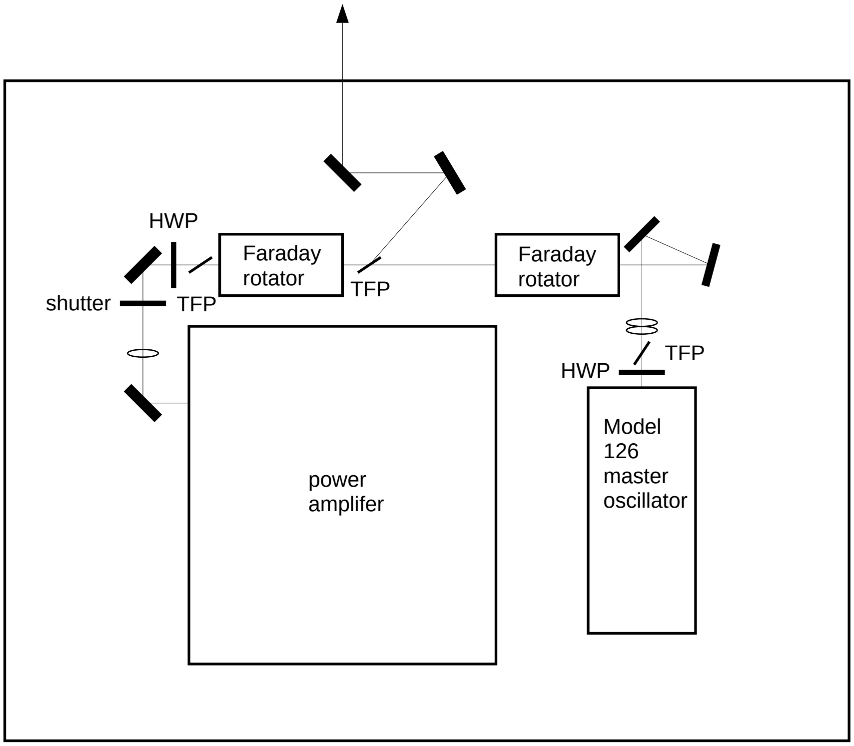

Figure 7: The optical layout of the LIGO 10-W Laser.

### 4.1.2. Features

The output wavelength of the LIGO 10-W Laser is 1064 nm. The output beam waist spot size of the LIGO 10-W Laser is $0.22\ \mathrm{mm} \pm 0.1\ \mathrm{mm}$ (TBD) at a location 55 mm from the output aperture, on the laser side. The output power of the LIGO 10-W Laser is specified to be greater than 10 W in a circular $TEM_{00}$ mode, with a total power in all non-$TEM_{00}$ modes to be less than 1 W. The polarization of the output is vertical, with an extinction ratio greater than 300:1.

It is expected that the frequency of the LIGO 10-W Laser will follow that of the NPRO master oscillator. As such the slow and fast actuators on the NPRO master oscillator are used for frequency tuning of the LIGO 10-W Laser. The slow actuator tunes the frequency of the NPRO master oscillator by heating or cooling the Nd:YAG crystal. The tuning coefficient for the slow actuator is approximately 4 GHz / V. Fast frequency tuning is accomplished via a piezo-electric translator (PZT) bonded to the Nd:YAG crystal. The tuning coefficient for the fast actuator is approximately 4 MHz / V. Power adjustments with the NPRO master oscillator are made only at low frequencies because of experience gained with the NPRO-PSL[1], where there was found to be a strong coupling between the power adjust input and the frequency of the NPRO laser. Stabilization of the output power of the LIGO 10-W Laser is via the AC and DC current adjust actuators on the power amplifier.

The LIGO 10-W Laser has two power monitors: one each for the NPRO master oscillator and the power amplifier. In addition there is a monitor for each of the 20-W pump laser diodes.

The LIGO 10-W Laser is to comply with CE mark, EN 55011 Class A for electromagnetic interference and Federal register 21 CFR 1040.10 and 1040.11 laser safety standards.

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[1] Refer to *NPRO-PSL Performance Data and System Documentation*, LIGO-T970052-00-D.

## 4.2. Specifications

A summary of the specifications of the LIGO 10-W Laser is provided in Table 2.

**Table 2: LIGO 10-W Laser specifications summary.**

| *Parameter* | *Specification* |
|---|---|
| 1. type of laser | $Nd^{3+}$:YAG |
| 2. wavelength | 1064 nm |
| 3. output beam waist spot size, $w_0$ | $0.25\ \text{mm} \pm 0.1\ \text{mm}$ |
| 4. output beam waist location | $55\ \text{mm}\ \pm 50\ \text{mm}$ from output aperture, on the laser side |
| 5. power in circular $TEM_{00}$ mode | > 10 W |
| 6. total power in all non-$TEM_{00}$ modes | < 1 W ($M_{\text{horizontal}} \times M_{\text{vertical}} < 1.1$) |
| 7. polarization extinction ratio | > 300:1 in the vertical plane |
| 8. electromagnetic interference (EMI) emissions | compliance with CE mark, EN 55011 Class A |
| 9. reliability:<br>*i*. mean time between failure (MTBF)<br>*ii*. minimum time between required beam alignment adjustment | <br>> 10 000 hours<br>> 2500 hours |

# 5 FREQUENCY STABILIZATION

## 5.1. Overview

One critical factor affecting the LIGO sensitivity to gravitational waves is the phase or frequency fluctuations of the laser used to read out differential length changes in the interferometer arms. This limit to the signal-to-noise ratio has two components, the fundamental shot-noise (the contribution of which can be decreased by going to higher light powers) and the laser's technical noise. Commercially available lasers, including the LIGO 10-W laser being developed by Lightwave Electronics Inc. are shot-noise limited only at frequencies well above the LIGO band of interest (40 Hz to 10 kHz). Inside the LIGO detection band the laser technical noise exceeds the required levels by up to nine orders of magnitude. The reduction of frequency noise is therefore a primary concern for PSL and other detector subsystems.

Practical issues such as frequency detector sensitivity, actuator ranges, loop stability, lock acquisition, parasitic feedback paths, etc. lead to a three-level approach to the suppression of laser frequency fluctuation. The frequency stabilization scheme adopted by LIGO[1] therefore employs nested loops utilizing the increasing frequency sensitivity of three reference cavities; the PSL reference cavity, the **IOO** 12-m mode-cleaner, and the interferometer's 4-km-long arm cavities using the **LSC** common-mode signal. A detailed description of this nested loop strategy is given in Appendix 4.

A schematic overview of the frequency stabilization elements in the PSL is given in Figure 4. Functionally, these elements can be grouped into three blocks:

- The first functional block is the PSL internal function of reducing the laser frequency noise from the free-running state (specified to be less than $500\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 100 Hz) to the levels required of the PSL[2] (less than $0.1\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 100 Hz). The PSL frequency stabilization control system employs a fixed reference cavity as the frequency fluctuation sensor, the PDH reflection locking scheme to derive the frequency error signal and three primary PSL frequency actuators, (SLOW, FAST and phase-correcting EOM), for stabilization of the laser frequency. The PSL frequency stabilization amplifier contains all the electronics necessary to condition and distribute the gain between the actuators. The PSL frequency fluctuation sensor, the primary PSL frequency actuators and the PSL internal frequency locking electronics are described in more detail in Section 5.2., Section 5.3., Section 5.4. respectively.

- The second functional block provides **IOO** with a wideband, frequency-control actuator. Together with the **IOO** frequency sensor, the 12-m mode-cleaner, the **LSC** common-mode error signal and the **IOO** mode-cleaner servo electronics, this actuator serves to stabilize the laser frequency beyond the sensitivity of the PSL frequency fluctuation sensor (to less than $10^{-4}\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 100 Hz). The response of the PSL wideband actuator is required to be flat within $\pm 2$ dB up to 100 kHz with a phase lag at 100 kHz of less than $20°$. As shown in

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[1] Refer to *Frequency Stabilization: Servo Configuration & Subsystem Interface Specification*, LIGO-T970088-00-D.

[2] *(Infrared) Pre-stabilized Laser Design Requirement*, LIGO-T970080-00-D.

Figure 8, below, this wideband actuator is realized by splitting the wideband input signal between an additive offset to the internal PSL frequency stabilization loop and the voltage-controlled oscillator (VCO) of the frequency shifter.

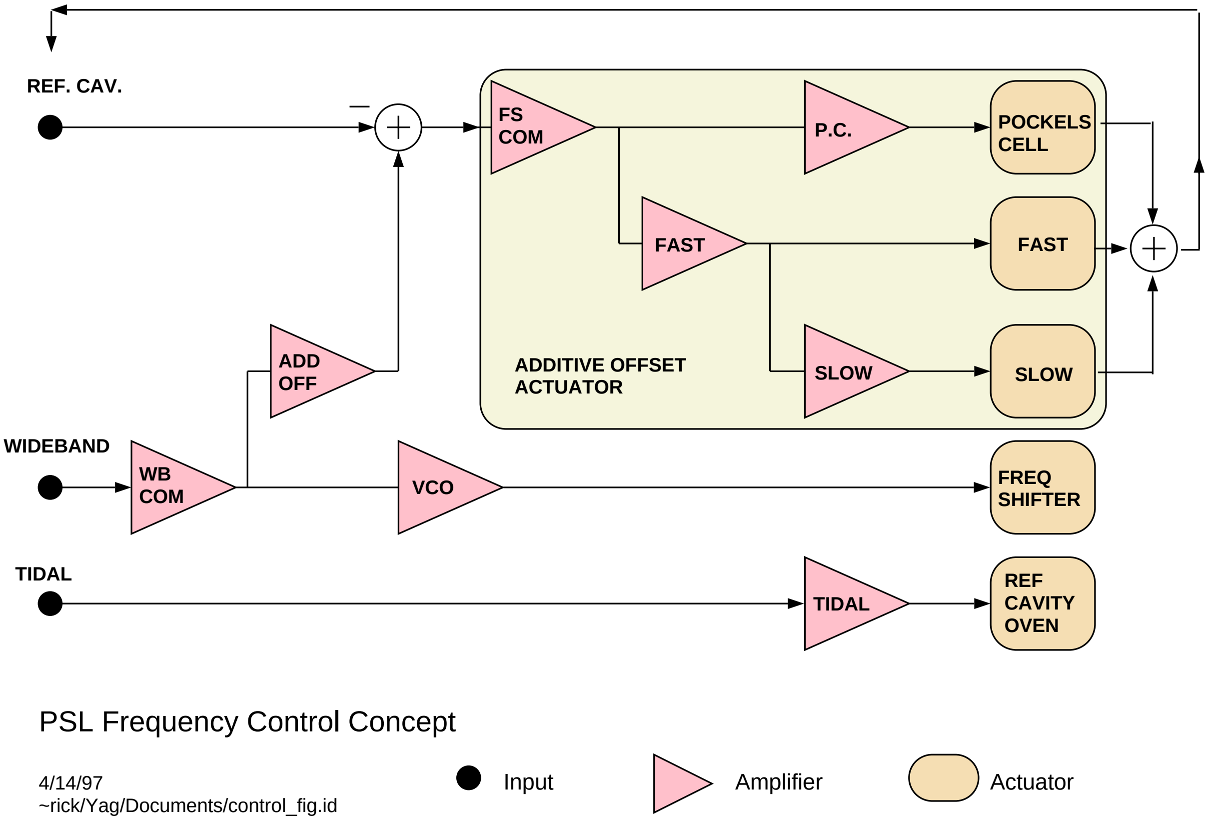

**Figure 8: PSL Frequency Control Concept.**

The frequency shifter offsets the frequency of the light used to interrogate the PSL reference cavity. This light, split from the main 10-W beam, double-passes an AOM[1] which shifts its frequency by 160 MHz, twice the nominal frequency of the AOM, with respect to the frequency of the main beam. Via the VCO, the frequency shifter gives the wideband actuator sufficient range at low frequencies to accommodate control signals from the wideband input. Because the laser frequency is locked to the resonance of the reference cavity an error signal is generated in response to frequency shifter offset. The PSL internal frequency locking electronics generate control signals for the PSL primary actuators which shift the frequency of the main 10-W beam to compensate for the offset introduced by the frequency shifter. Thus the PSL can remain locked to both the reference cavity and the cavity which generated the wideband frequency error signal.

At higher frequencies, where the wideband input frequency correction is within a fraction of the bandwidth of the reference cavity (approximately 10 kHz), it is fed to the primary actuators as an additive offset. The effect of the additive offset is to mimic a shifted line center of

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[1] See Figure 4.

the PSL reference cavity. The response of the frequency locking electronics is to compensate for this apparent shift in frequency by changing the actual frequency of the main 10-W beam, the desired effect. Details of the wideband actuator are given in Section 5.5.

- The third functional block of the PSL frequency stabilization elements concern the tidal input. Because of the long 4-km baseline LIGO will be sensitive to the tidal distortions of the Earth's crust[1]. These distortions cause relative motion between the suspended test masses and their ground-referenced suspension systems. Because the suspension actuators and the vibration isolation stack actuators have limited range, the common-mode interferometer length changes are compensated by changing the frequency of the light via the tidal input. This is accomplished by tuning the temperature (and therefore the resonant frequency) of the PSL reference cavity. The tidal input actuator is required to accommodate a frequency change of ±30 MHz within 1 hour. The tidal correction actuator is described in more detail in Section 5.6.

## 5.2. The PSL Frequency Fluctuation Sensor

### 5.2.1. Reference Cavity

The frequency fluctuation sensor utilizes a monolithic, fused silica spacer with mirrors optically contacted to each end. Optical contacting is a process by which two surfaces are adhered together through molecular attraction without the use of an epoxy. The reference cavity[2] is identical to that employed with the NPRO-PSL[3] and is shown in Figure 18 of Appendix 1. The reference cavity is suspended in vacuum with two loops of wire with their separation being roughly $1/\sqrt{3}$ times the length of spacer[4]. By analogy to the design of very sensitive electrical antenna circuits the majority of the frequency stabilization amplifier gain should be concentrated in the first stage, reducing the input-referred noise requirements on the following amplifier stages by the preceding gain factor. In the optical regime this corresponds to choosing an optical discriminator (reference cavity resonance) with high slope (high finesse) and high visibility (transmission losses much greater than absorption losses), as well as an optimum modulation depth[5] and mode-matching.

#### 5.2.1.1 Reference Cavity Parameters

- material: fused silica v-$SiO_2$
  - expansion coefficient: $5 \times 10^{-7}$ 1/K at room temperature (vendor specification)

- mirror characteristics at 1064 nm

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[1] Refer to *The Effect of Earth Tides on LIGO Interferometers*, LIGO-T970080-0.0-D.

[2] The reference cavity is described in more detail in Appendix 1

[3] Refer to LIGO-T960089-00-D, *NPRO-PSL Conceptual Design* and the current measurements at the MIT PNI.

[4] This gives enhanced dimensional stability of the length of the reference cavity against vertical accelerations in the two-wire suspension configuration.

[5] modulation index = maximum phase amplitude at modulation frequency in radians = 1.08 for maximum PDH signal-slope. For a thorough discussion of shot noise sensitivity as a function of modulation index, see P. Fritschel: *Shot noise sensitivity of the length control error signals*, section 4, T960042-01-D.

  - transmission: $300 \pm 30$ ppm
  - losses: < 30 ppm
  - diameter: 25.4 mm
  - thickness: 6.35 mm
  - wedge: 30 minutes
  - radius: 500 mm, concave

- reference cavity parameters
  - length: $203.2 \pm 0.3$ mm
  - free spectral range: 738 MHz
  - finesse: 10,000
  - bandwidth: 74 kHz

- temperature induced resonant frequency change: ~ 150 MHz / K

- shot-noise limited frequency sensitivity[1]: 0.2 mHz / $\sqrt{\mathrm{Hz}}$

### 5.2.2. Frequency Fluctuation Signal: Pound-Drever-Hall Scheme

The LIGO standard Pound-Drever-Hall reflection locking technique is utilized to compare the laser frequency with the cavity resonance and generate the error signal. The essential operating parameters are:

  - modulation frequency: 12.33 MHz
  - photodetector responsivity: 0.68 A/W (for silicon diodes)
  - modulation index: 1.08
  - total incident power onto the cavity: 10 mW
  - modematched fraction thereof: 90 %
  - photodetector transimpedance: 600 Ω **TBD** by **CDS** / PSL
  - cavity transmission on resonance[2]: 83 %

## 5.3. The Primary PSL Frequency Actuators

### 5.3.1. SLOW Input (Laser Temperature Actuator)

The SLOW input at the LIGO 10-W laser (via the Lightwave 126 NPRO master oscillator) will allow wide-range (10 GHz) frequency-tuning without mode hops using a thermo-electric cooler.

  - actuator coefficient: 4 GHz / V
  - bandwidth: DC to 0.2 Hz

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[1] The derivation of this value is given in Appendix 2.

[2] The derivation of this value is given in Appendix 1

- safe operating range ±1.25 V without mode-hopping
- corresponding frequency range: ±5 GHz
- poles: 3 poles @ 0.2 Hz

### 5.3.2. FAST Input (Laser PZT Actuator)

The FAST input at the LIGO 10-W Laser (via the NPRO master oscillator) allows fast frequency tuning using a PZT actuator glued onto the laser crystal.

- actuator coefficient: ~ 4 MHz / V
- bandwidth: flat within 1 dB up to 100 kHz
- safe operating range: ±50 V
- corresponding frequency range: ±200 MHz

### 5.3.3. High-Frequency Input (Phase Correcting EOM)

In order to achieve high gain at 10 kHz and stable loop operation (20 dB / decade gain slope at unity-gain frequency) the PSL will employ a phase-correcting EOM positioned between the NPRO master oscillator and the power amplifier inside the LIGO 10-W Laser.

- vendor: New Focus, Inc. in Santa Clara, CA
- type: 4004-D electro-optic modulator
- resonance bandwidth broadband, DC up to 100 MHz
- actuator coefficient: 15 mrad / Volt (phase amplitude) giving
  $f_{mod}$ * 1.5 x $10^{-2}$ / V (frequency amplitude)
- corresponds to: 450 Hz / V @ 30 kHz modulation frequency
- safe operating range: ±200 V
- corresponds to: ±90 kHz @ 30 kHz modulation frequency

## 5.4. PSL Internal Frequency Locking Electronics

The PSL internal frequency locking electronics establishes the feedback path that reduces the technical laser frequency noise from its free running state to the stability level specified in the PSL requirements[1] in the LIGO detection band from 40 Hz to 10 kHz. The input for this function is the frequency error signal derived from the PSL reference cavity and the output is the correction signal for the primary PSL frequency actuators (SLOW, FAST and phase correcting PC). Seen from the outside, *e.g.* the **IOO** wideband input, the PSL internal frequency locking electronics and the primary PSL frequency actuators constitute one single-frequency actuator unit used for stabilization beyond the sensitivity of the PSL reference cavity. This section will introduce the parameters (see Table 3) for the Matlab model (see Figure 9, Figure 10 and Figure 11) used to simulate and estimate the closed loop's performance as shown in Figure 12.

---

[1] The requirement is 1Hz / $\sqrt{\text{Hz}}$ @ 40 Hz, falling from there with $f^{-2.5}$ until 0.1 Hz / $\sqrt{\text{Hz}}$ @ 100 Hz, falling from there with $f^{-1}$ until it reaches a level of 0.01 Hz / $\sqrt{\text{Hz}}$ and maintaining this level until 10 kHz.

The PSL locking electronics design we present here has already been tested in most aspects in the NPRO-PSL[1]. Primary actuators are the SLOW control, the FAST PZT control and the phase-correcting EOM. SLOW control holds the laser frequency to the PSL reference cavity resonance for low frequencies up to 0.1 Hz. The FAST PZT takes over from there until around 12 kHz, where the EOM sets in and extends the high-gain region and finally rolls off the gain with a safe slope of roughly 20 dB / decade. The unity gain frequency is approximately 1 MHz. Shown in Figure 9 is the Matlab / Simulink schematic used to model the servo and predict its performance.

The actual parameters for the elements in the PSL locking electronics may deviate slightly from the values given here as **CDS** / PSL continues its design development.

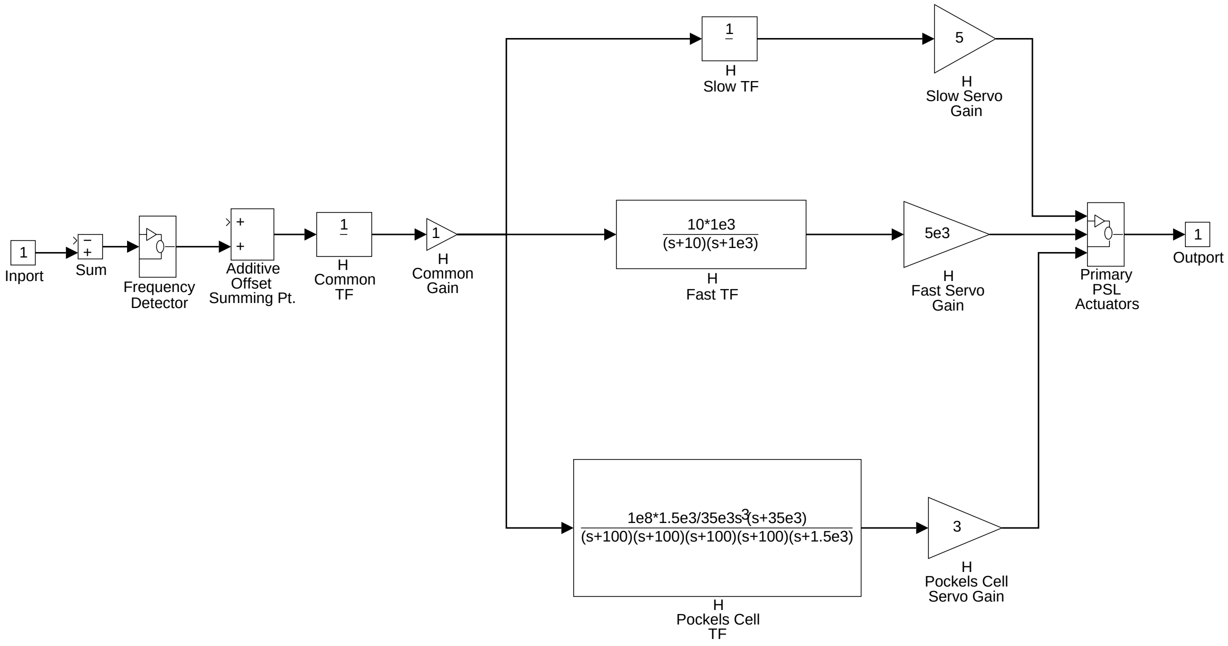

**Figure 9: Whole-servo Simulink schematic: Shown above is the Simulink schematic used to model the internal PSL frequency stabilization loop performance. The schematic for the frequency detector and the Primary PSL Actuators are described in detail in the following two figures.**

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[1] See e.g. *NPRO-PSL Performance Data and System Documentation* LIGO-T970052-00-D.

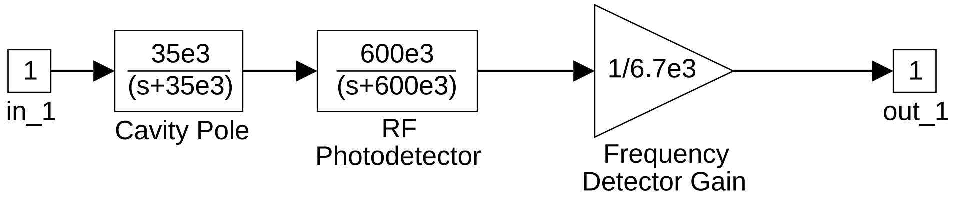

**Figure 10: Frequency detector - Simulink schematic: Shown above is the Simulink schematic for the frequency detector unit used to model the PSL frequency stabilization loop performance.**

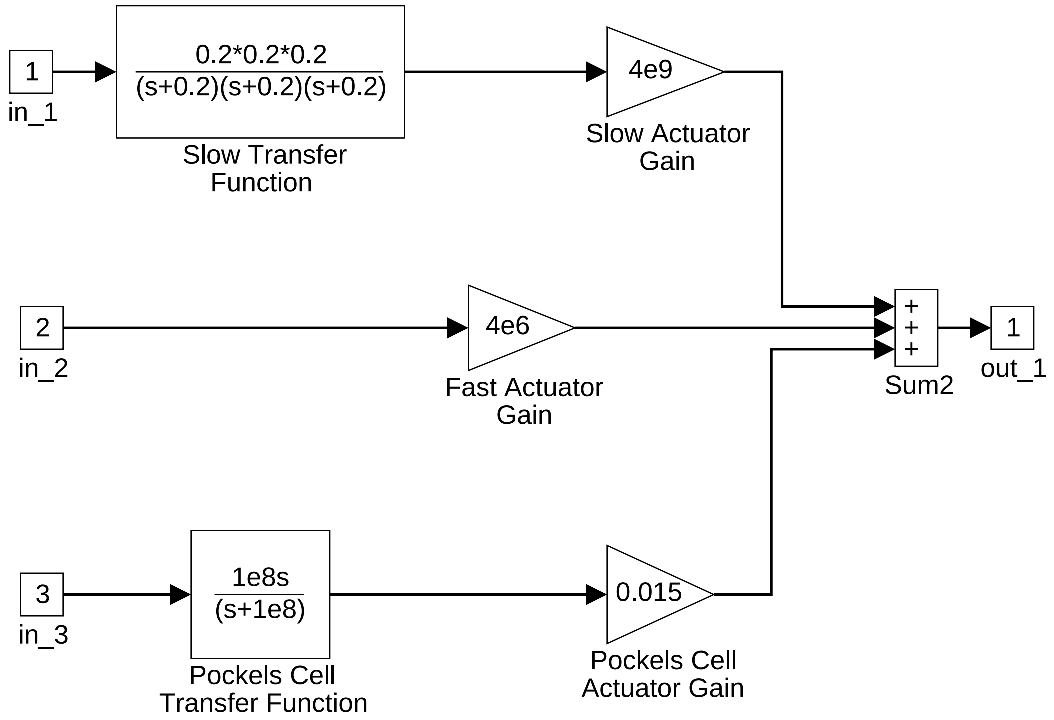

**Figure 11: Primary PSL frequency actuators - Simulink schematic. Shown above is the Simulink schematic used to model the internal PSL frequency stabilization loop performance.**

The essential parameters of this Simulink model are described in the table below. Unless otherwise noted, the transfer coefficient units are Volt / Volt.

**Table 3: PSL internal frequency servo electronics - parameters for Matlab model**

| *element* | *poles* | *zeros* | *transfer coefficient @ DC* | *transfer coefficient @ 10kHz* |
|---|---|---|---|---|
| cavity frequency transfer | 35 kHz | ------ | 1 | 0.78 |
| RF photodetector | 600 kHz | ------ | 1 | 1 |
| Frequency detector gain | ------ | ------ | $1 / 6.7\text{x}10^3$ V / Hz | $1 / 6.7\text{x}10^3$ V / Hz |
| H Slow Servo Gain | ------ | ------ | 5 | 5 |
| H Fast TF | 10 Hz, 1 kHz | ------ | 1 | $9\text{x}10^{-5}$ |
| H Fast Servo Gain | ------ | ------ | $5\text{x}10^3$ | $5\text{x}10^3$ |
| H Pockels Cell TF | 4 poles @ 100 Hz, and one @ 1.5 kHz | 3 zeros @ DC, and one @ 35 kHz | 0 | $1.2\text{x}10^4$ |
| H PC Servo Gain | ------ | ------ | 3 | 3 |
| Slow Transfer Function | 3 poles @ 0.2 Hz | ------ | 1 | $8\text{x}10^{-15}$ |
| Slow Actuator Gain | ------ | ------ | $4\text{x}10^9$ Hz / V | $4\text{x}10^9$ Hz / V |
| Fast Actuator Gain | ------ | ------ | $4\text{x}10^6$ Hz / V | $4\text{x}10^6$ Hz / V |
| Pockels Cell Transfer Function | $1\text{x}10^8$ | DC | 0 | $1\text{x}10^4$ |
| PC Actuator Gain[a] | ------ | ------ | 0.015 Hz / V | 0.015 Hz / V |

[a] the units are here Hz / Volt to keep Simulink model legend and the table overview simple. The actual EOM actuator gain is $f_{modulation}$ * 0.015 / V, refer to Section 5.3.3.

### 5.4.1. Overall Loop [1]

- unity-gain frequency: ~ 1 MHz
- gain @ 40 Hz: 120 dB
- gain @ 10 kHz: 50 dB
- SLOW-FAST crossover frequency: 0.1 Hz
- SlOW-FAST crossover gain: 130 dB
- FAST-PC crossover frequency: 12 kHz
- FAST-PC crossover gain: 30 dB

### 5.4.2. Performance Estimates

Shown below in Figure 12 is the Simulink Bode plot of the PSL frequency stabilization loop with the servo parameters set as described in Table 3, above.

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[1] Again, these values represent a first feasibility study and will be subject to changes during the further **CDS** / PSL development effort.

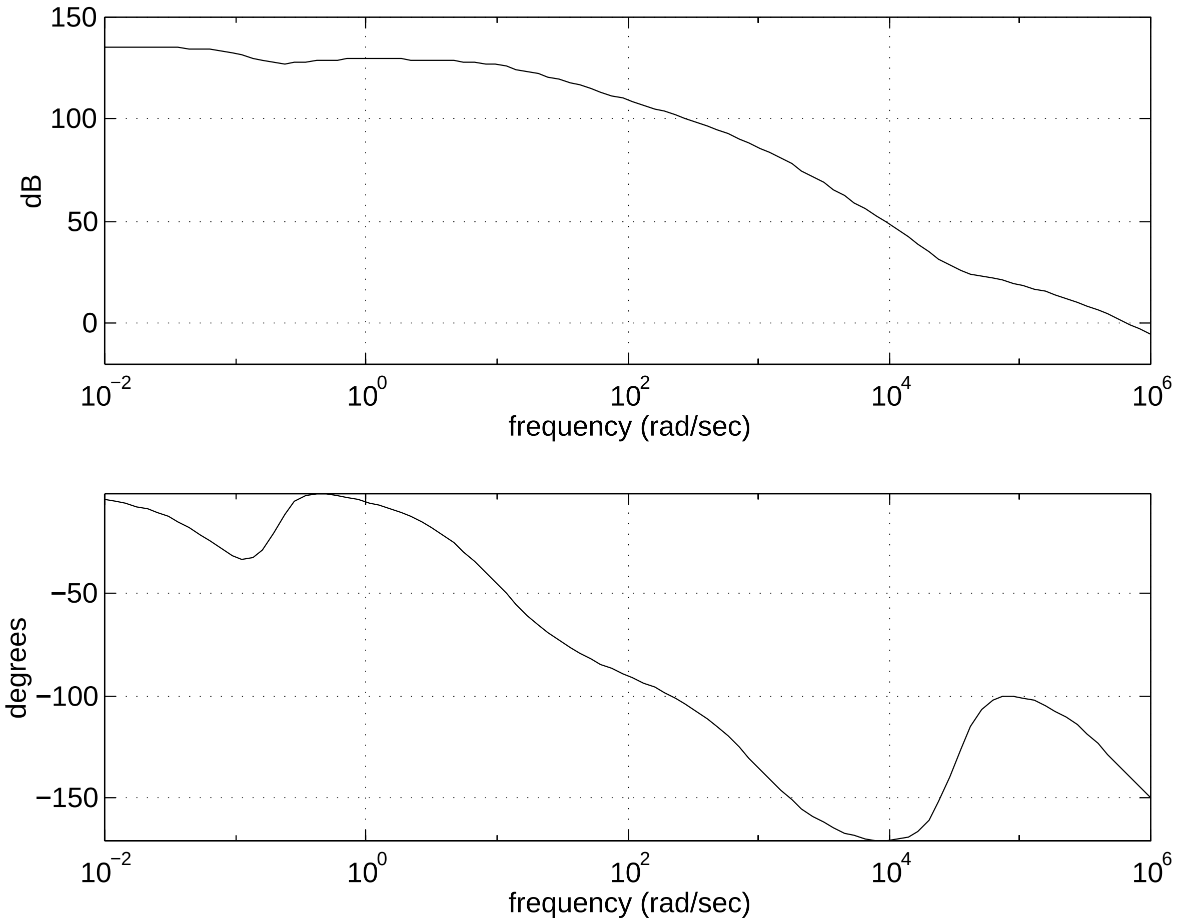

**Figure 12: Bode-plot PSL frequency servo. Shown is the magnitude and the phase of the open loop gain for the internal PSL frequency stabilization loop. The loop consists of the frequency fluctuation detector (cavity and PDH) the servo electronics and the three primary PSL frequency actuators.**

Work at Caltech[1] has shown that the free running frequency noise of the NPRO master oscillator has around 250 Hz / $\sqrt{\mathrm{Hz}}$ @ 100 Hz and falls off above 250 Hz with 1 / f to higher frequencies. Under the assumption that the LIGO 10-W Laser will have essentially the same performance, the Matlab / Simulink model used to model the free-running noise is shown below in Figure 13:

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[1] Refer to NPRO-PSL lab book of 4/2/96 16:05. The data are marked: NPRO Frequency noise upper limit (probably dominated by Tropel noise).

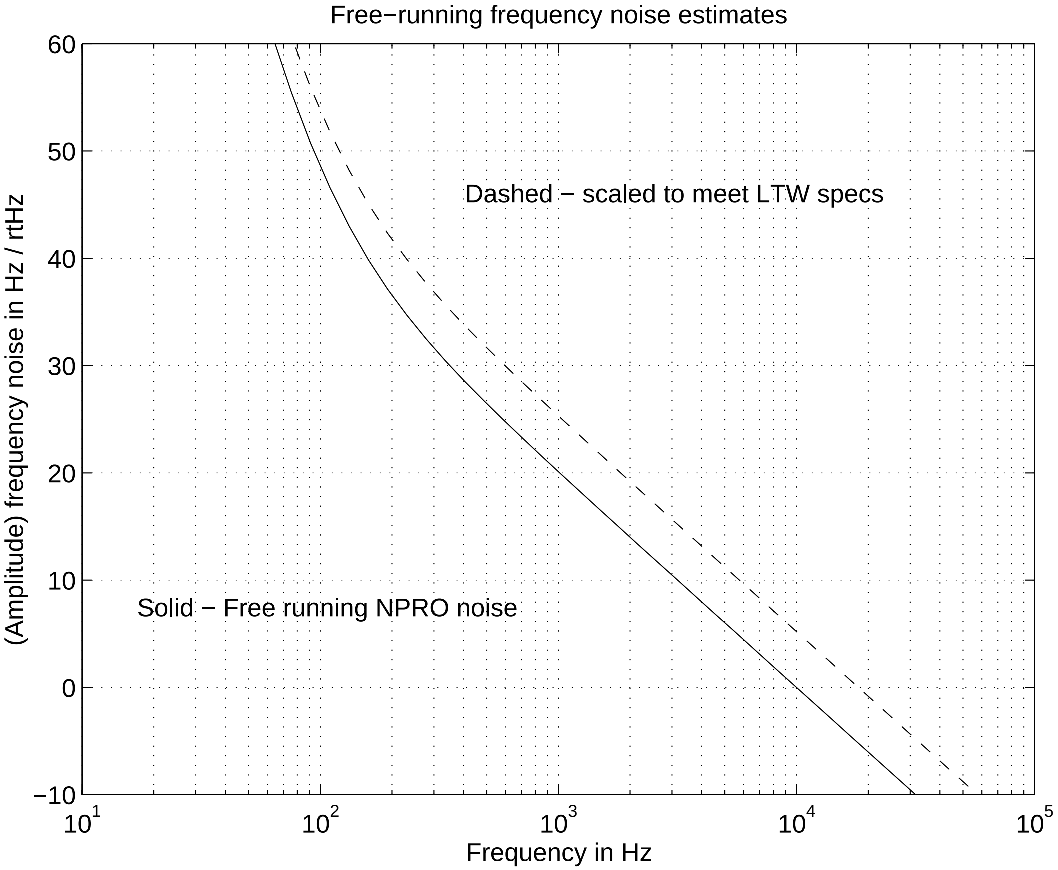

**Figure 13: Free-running frequency noise estimate. The solid curve represents a model for the data measured on the NPRO 126 laser[1]. We expect that the LIGO 10-Watt laser free-running noise will follow the shape of this curve. The dashed line combines the LIGO 10-W Laser specification points (500 Hz / $\sqrt{\mathrm{Hz}}$ @ 100 Hz and 50 Hz / $\sqrt{\mathrm{Hz}}$ @ 1 kHz) with the noise curve shape observed for the NPRO 126 at Caltech.**

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[1] Refer to NPRO-PSL lab book of 4/2/96 16:05. The data are marked: NPRO Frequency noise upper limit (probably dominated by Tropel noise).

Neglecting the frequency noise contribution of the PSL reference cavity itself, the Matlab / Simulink model predicts that we are able to meet the PSL requirements, as shown in Figure 14. The solid line corresponds to the residual noise assuming an input free-running noise as measured on the NPRO 126 at Caltech, the upper dashed curve represents the residual noise under the pessimistic assumption of the LIGO 10-Watt laser just meeting the specifications[1]. The figure below shows that the residual frequency noise requirements[2] can be met over the whole LIGO detection band of interest, that is from 40 Hz upward to 10 kHz, if the cavity would not contribute signifi-

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[1] Refer to Appendix 5.

cantly itself. However, work done at Caltech, MIT and at VIRGO indicate that cavity noise contributions are  indeed the dominating factor a low frequencies.  The best oscillator demonstrated so far (*F. Bondu et al.*, *Optics Letters* ***21***, *1996*) used a NPRO-laser as well and a football-shaped ULE[1] cavity carefully isolated against vibrations and temperature fluctuations. They achieved already a residual noise level alternating between 0.1 Hz / $\sqrt{\mathrm{Hz}}$ and 0.01 Hz / $\sqrt{\mathrm{Hz}}$ for noise frequencies below 200 Hz.

In absolute frequency stability, therefore, we expect excess noise (compared to the figure below: Figure 14) at frequencies below a few hundred Hertz due to vibrations limiting the sensitivity of the cavity in this frequency range.

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[2] Residual frequency noise requirements: 1 Hz / $\sqrt{\mathrm{Hz}}$ (or 0 dB Hz / $\sqrt{\mathrm{Hz}}$) @ 40 Hz, falling with $f^{-2.5}$ to 0.1 Hz / $\sqrt{\mathrm{Hz}}$ (or -20 dB Hz / $\sqrt{\mathrm{Hz}}$) @ 100 Hz, falling from there with 1/f to 0.01 Hz / $\sqrt{\mathrm{Hz}}$ (or -40 dB Hz / $\sqrt{\mathrm{Hz}}$) @ 1 kHz and maintaining this level up to 10 kHz.

[1] ULE is a ultra low expansion glass with an expansion coefficient of $1 \times 10^{-8}$ / K.

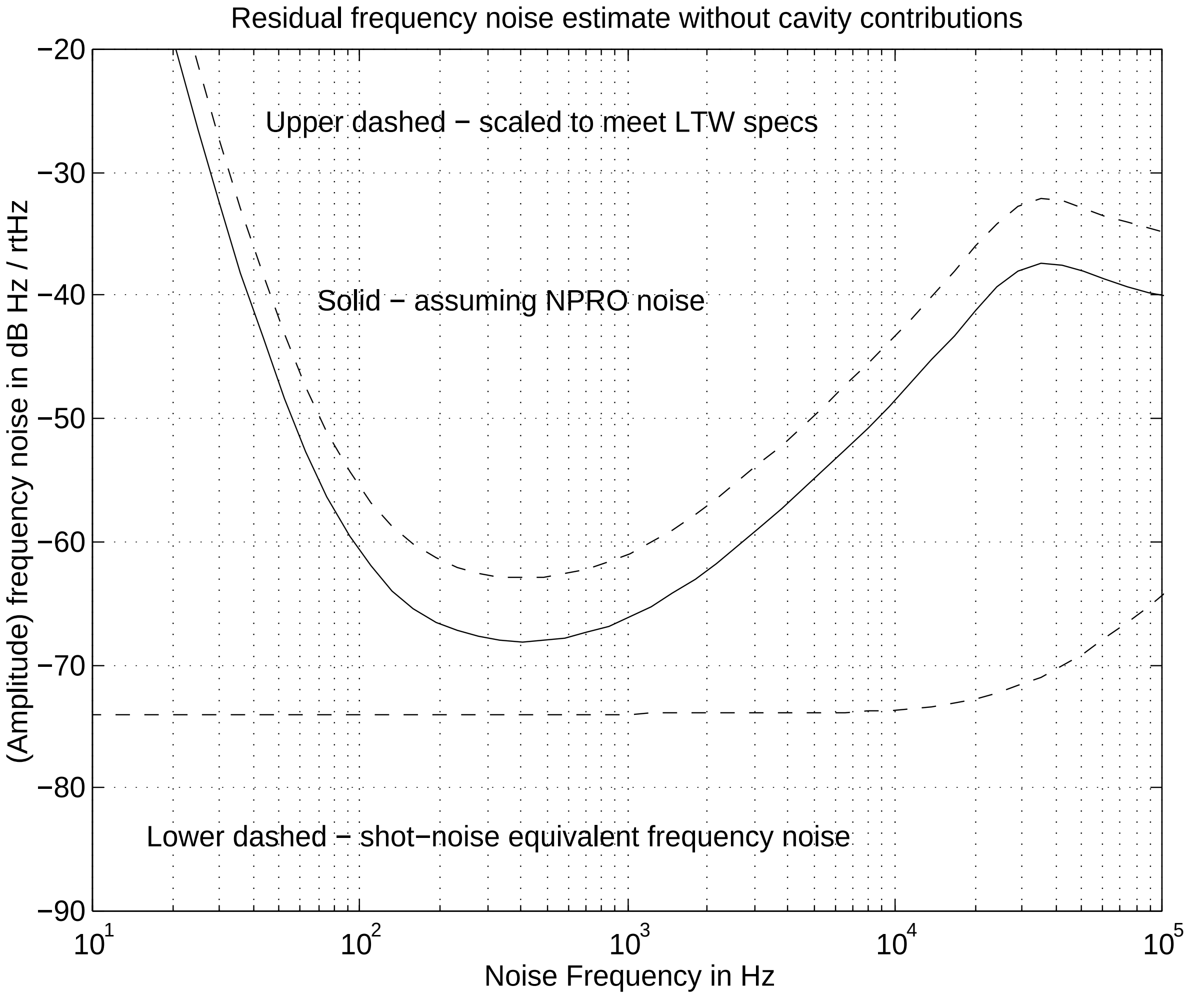

**Figure 14: Residual frequency noise estimate: Shown here is 1 / (1 + open loop gain) of the two free running noise models in the preceding figure. The lower dashed line represents the equivalent frequency noise to the (flat) photocurrent shot-noise associated with the detection scheme described in Section 5.2.2. The equivalent frequency noise rises proportional to f above the pole frequency of the PSL reference cavity at 35 kHz.**

## 5.4.3. Noise

The front end of the frequency stabilization system will be based on an existing module (LLSPA), previously used and tested with the Argon ion PSL. Its input-referred noise was ~4 nV / $\sqrt{\mathrm{Hz}}$, and we expect to achieve a similar level. Assuming a frequency fluctuation sensor slope of around 4 to 7 kHz / V (as demonstrated in the NPRO-PSL) the 0.01 Hz / $\sqrt{\mathrm{Hz}}$ frequency noise requirement for the internal PSL frequency stabilization corresponds to an electronic noise level of 2 µV / $\sqrt{\mathrm{Hz}}$ at the input of the amplifier. We therefore expect that electronic component noise will not be a limiting factor for the performance of the internal PSL frequency stabilization.

From the performance of other experiments aimed a minimizing laser frequency technical noise, we expect that below a few hundred Hz the residual noise spectrum will be dominated by the contribution of the PSL reference cavity. The first outside-the-loop measurements of an infrared PSL in May ‘97 at MIT[1] showed that the PSL requirements can be met using the approach discussed in the above sections.

## 5.5. Wideband Input - Actuator

The wideband-input signal is split into two paths. The low-frequency part with large frequency-pulling amplitudes is fed directly to the frequency shifter, the high-frequency part is accommodated by the additive offset actuator. This section introduces a design for the wideband-input actuator with a Simulink schematic (see Figure 15) and concludes with a performance estimate (open-loop Bode plot, see Figure 16) based on this Matlab / Simulink model.

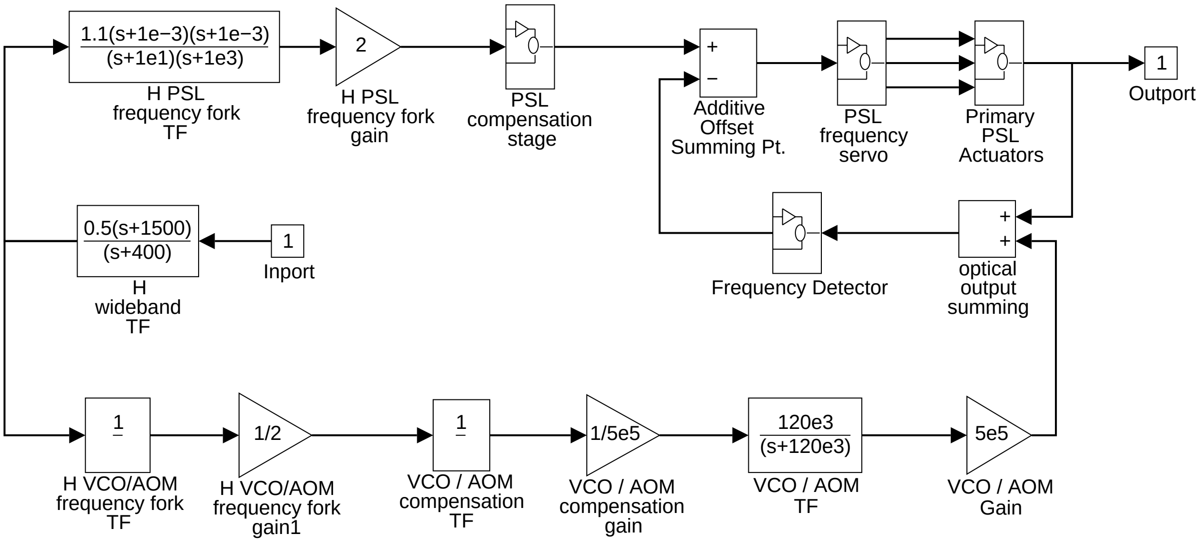

**Figure 15: Wideband-Input Actuator: Shown here is the Simulink / Matlab model for the wideband-input actuator design. Its main features are overall DC-coupling and a crossover between two actuators, one being an additive offset to the internal PSL frequency stabilization loop, and the other being the frequency shifter (VCO / AOM).**

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[1] They used a NPRO-PSL that was frequency-stabilized to a fixed reference cavity (same specifications as the one proposed in this section) and characterized its frequency stability against one arm of the PNI. The MIT optical table was equipped with a Stacis 2000 vibration isolation system and the vibration background differed from that at the Caltech lab and the actual LIGO-sites.

The first element in this model (H wideband TF) determines the overall transfer function shape of the wideband actuator. It serves for (at the moment) overall DC-coupling[1] and compensates the two-actuators crossover kink to some extent. The upper path represents the additive offset to the internal PSL frequency stabilization loop. This additive offset signal is first high-pass filtered and then passes a stage which compensates for the non-flat transfer function of the closed-loop system to follow. The lower path feeds the frequency-shifter consisting of the voltage-controlled oscillator (VCO) and the acousto-optic modulator (AOM). The time-delay of the AOM (due to finite speed of sound in the crystal) cannot be exactly represented in the linear model above. The approximation used here for the 40 degrees phase-shift at 100 kHz (measured at MIT) is an uncompensated single pole at 120 kHz. This model takes into account that the AOM frequency-shift doesn't directly affect the frequency of the main beam. This frequency-shift has to be transferred in the following step through the PSL frequency stabilization loop. The parameters for the model are summarized in the table below (Table 4):

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[1] c.f. Table 1 in P. Fritschel: *Frequency Stabilization: Servo Configuration & Subsystem Interface Specification*, LIGO-T970088-00-D

| *element* | *poles* | *zeros* | *transfer coefficient @ DC* | *transfer coefficient @ 10kHz* |
|---|---|---|---|---|
| H wideband TF | 400 Hz | 1.5 kHz | 1.9 | 0.55 |
| H PSL frequency fork TF | 10 Hz and<br>1 kHz | 2 zeroes @<br>1 mHz (DC) | 0 | 1 |
| H PSL frequency fork gain | ------ | ------ | 3 | 3 |
| PSL compensation stage | 35 kHz and<br>600 kHz | ------ | 1 / (6.7 x $10^3$) | 0.78 / (6.7 x $10^3$) |
| internal PSL frequency stabilization loop | closed-loop | closed-loop | 6.7 x $10^3$ | 6.7 x $10^3$ / 0.78 |
| H VCO / AOM frequency fork | ------ | ------ | 1 / 2 | 1/ 2 |
| VCO / AOM compensation stage | ------ | ------ | 1 / (5 x $10^5$) | 1 / (5 x $10^5$) |
| VCO / AOM TF | 120 kHz,<br>in reality a time-delay | ------ | 1 | 1 |

**Table 4: Wideband-input actuator parameters: Shown here are the Simulink / Matlab parameters used to model the wideband-input actuator as shown schematically Figure 16.**

### 5.5.1. Frequency Shifter Unit (VCO / AOM)

A small part (~ 0.5 %) of the LIGO 10-W Laser light power is split off the main beam and used to interrogate the PSL reference cavity. Before arriving at the cavity, the frequency of this light is decoupled from the frequency of the main beam. The reasons for this procedure are threefold:

- It provides a direct broadband input for the **IOO** frequency-servo which does not directly interfere with the PSL-internal lock to the PSL reference cavity fringe. This enables us to protect the dynamic range of the primary PSL frequency actuators (Fast-PZT and Phase-correcting EOM) and the PSL from losing fringe lock to its reference cavity in case of IOO-signal spikes or bursts on the wideband-input signal.

- It acts as an 70 dB[1] isolator for optical feedback for light going to the (linear) PSL reference cavity and being reflected back to the laser. While the reflected power is not diminished, the frequency of the reflected light is 4-pass AOM-shifted and the light’s ability to beat destructively with the laser mode is greatly reduced.
- It could accommodate and bridge a frequency-offset between the **IOO** mode-cleaner and the PSL reference cavity if need be. At this stage, though, it is planned to lock the **IOO** mode-cleaner to whatever wavelength the PSL delivers by adjusting its mirror separation.

#### 5.5.1.1 AOM

The acousto-optical modulator shifts the frequency of the first-order diffracted beam by the modulation frequency. Double-passing the AOM eliminates the frequency-dependent diffraction angle of the frequency-shifted beam to first order.

- aperture: **TBD** by PSL
- single pass transfer efficiency: 70% **TBD** by PSL
- single pass optical throughput: 98% **TBD** by PSL total (all orders together)
- single pass beam distortion: $\lambda$ / 10 (vendor-specs)
- damage threshold: 25 kW / cm$^2$
- acoustic time delay: 1.1 µs (MIT-value), some vendors could bring it down to 200 to 500 ns

#### 5.5.1.2 VCO

In order to function as a frequency-correcting element inside the frequency-control loop the AOM-frequency has to be continuously adjusted and shifted, nulling thereby the wideband AC-input signal from **IOO**. A low-noise, tunable VCO (voltage-controlled oscillator) provides this conversion from Volts to Hz frequency-shift and will drive the AOM. The VCO is being developed by the CDS group.

- actuator coefficient: 500 kHz / V
- nominal output frequency: 80 MHz
- signal to noise ratio for the VCO **TBD** by **CDS /** PSL
- actuation range: ±3 MHz **TBD** by **CDS /** PSL
- maximum input referred noise: **TBD** by **CDS /** PSL

### 5.5.2. Additive Offset Actuator

The additive offset shifts the set-point for the internal PSL frequency stabilization loop. The actuator representation in the Simulink model has to take into account that the actuation range is limited to a fraction of the PSL reference cavity linewidth. Otherwise, the internal PSL frequency stabilization loop gain parameters change significantly or, in the extreme case, the PSL frequency stabilization loop loses fringe-lock. In the Simulink model, this point is accommodated by placing a 1 kHz high-pass (labeled frequency fork) in front of the (closed-loop) internal PSL actuator that cuts off the low-frequency input signal with its large amplitudes. Flat response of the internal PSL

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[1] Refer to C. Salomon, D. Hils and J.L. Hall: *Laser stabilization at the millihertz level*, JOSA B 5, 1576-87 (1988), on page 1580

actuator is achieved by a compensation stage that mimics the behavior of the frequency fluctuation sensor in this loop.

### 5.5.3. Wideband Input Actuator performance estimate

Based on the Simulink / Matlab model discussed above (Figure 15) the predicted Bode-plot response (Figure 16) meets the requirements[1] for the wideband input actuator. In order to get a flat magnitude response without a kink from the crossover between two actuators, their relative phase has to be kept equal to or smaller than 90 degrees at crossover. This is the case for the model described above. Some residual magnitude response hump is compensated by the lag-lead stage immediately following the inport in Figure 16. Another possibility would be to use only one actuator, thereby canceling the crossover problem completely.

The phase-lag requirement (20 degrees) at 100 kHz is met in this simulation (around 0 degrees at 100 kHz). This is largely due to giving the majority of the high-frequency gain to the PSL-actuator, which is basically without phase-lag. If one would use the frequency-shifter alone in a one-actuator approach, the time-delay in the AOM (as measured for the current type used at the MIT) of 40 degrees would already violate the phase-lag requirement without taking into account further phase-lags due to the rest of the electronics. AOM-vendors are able to sell units with less time-delay and it may be possible to reduce that effect, if we were to choose a one-actuator design.

The tunability of the frequency-shifter is expected to be $\pm 3$ MHz instead of $\pm 5$ MHz as required. The limitation here is a conflict of design aims; *e.g.* it is quite hard to build a widely-tunable VCO with at the same time outstanding frequency-stability.

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[1] Flat within 2 dB up to 100 kHz, and above 100 kHz staying below (f / 100 kHz) x (average response below 100 kHz). Phase lag at 100 kHz should be smaller than 20 degrees.

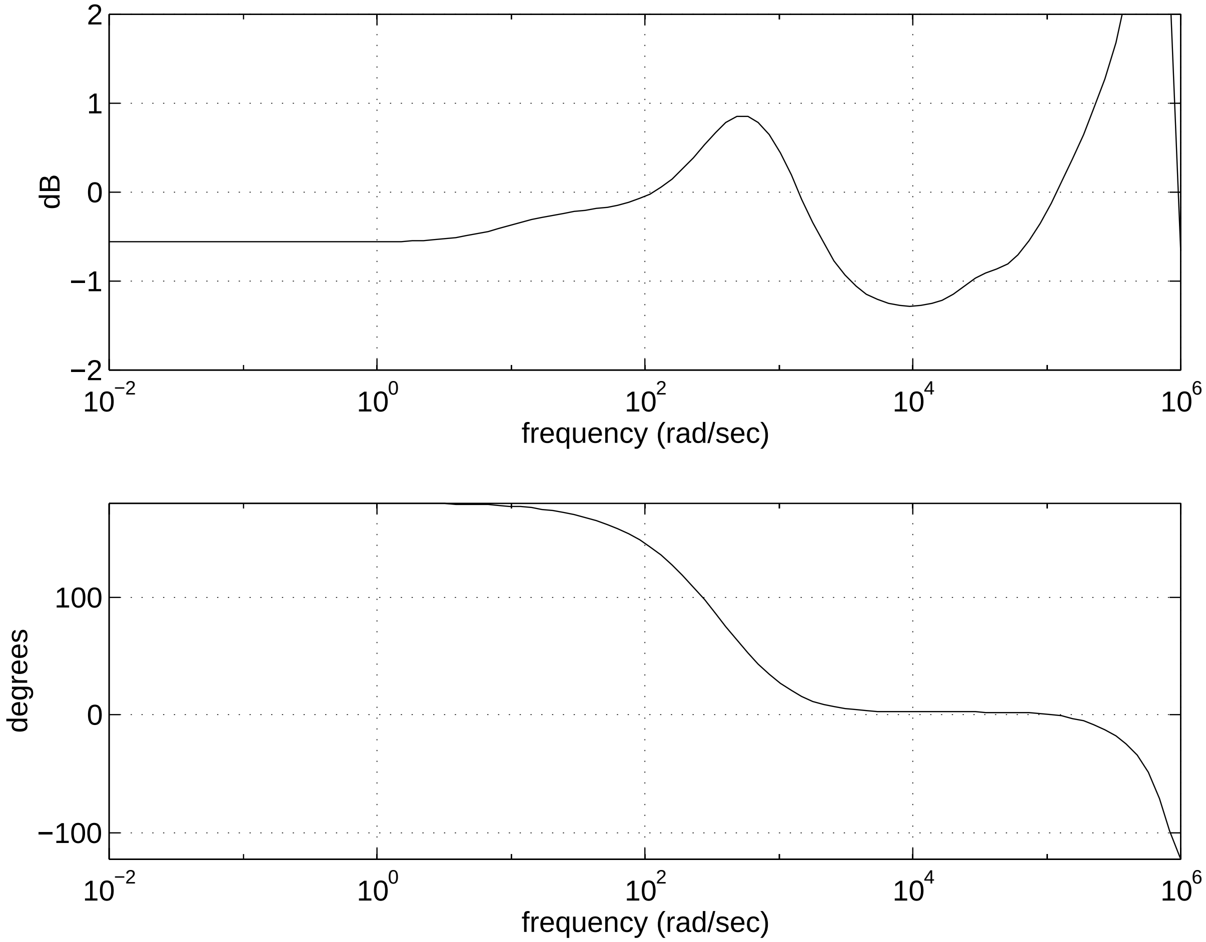

**Figure 16: Wideband input Bode plot: Shown here is the frequency-response of the wideband-input model as predicted by the Simulink / Matlab model discussed above.**

### 5.5.4. Wideband Input Actuator Noise

The allowed input referred noise level for the wideband actuator (as seen from **IOO**) has to be determined by **IOO TBD**. Our estimates show that this requirement should be less stringent than in the case of the PSL internal frequency stabilization loop.

## 5.6. Tidal Correction Actuator

Differential tidal stretching of Earth’s crust may extend beyond the dynamic range limits of the SEI stack-actuators on the 4 km Interferometer controlling the test-masses positions. On tidal timescales of over 1 hour the PSL wavelength itself has to be adjusted to compensate this effect, else the LIGO-interferometer loses lock. LIGO-estimates require the PSL to be able to shift its frequency by up to 30 MHz within 1 hour[1].

PSL will achieve this end by controlling the temperature of the PSL-reference cavity and its resonance frequency. The temperature of the reference cavity will be controlled by passive and active means, as shown in the figure below. The main elements are:

- The cavity's temperature will be actively controlled by heater-tapes on the outside of the vacuum vessel. For active control during acquiring mode, temperature sensors will be placed on the outside of the vacuum vessel. In normal operation mode the temperature control-loop error input will be switched to the tidal error signal from SEI, which will act as an offset to the temperature control system for the PSL reference cavity.
- Inside the vacuum vessel the temperature of the reference cavity will be decoupled from ambient temperature changes. Passive isolation is provided by the UHV vacuum excluding gas heat-transfer and the thin suspension wires with their low heat conduction.

### 5.6.1. Reference Cavity Temperature Control

Based on experience with time-constants of vacuum-isolated reference cavities the required range and dynamics of frequency-adjustment by temperature control seem to be achievable[1]. The following list summarizes relevant parameters for the active temperature control of the PSL reference-cavity (heating the vacuum vessel):

- required frequency tuning range: ±30 MHz
- required time constant: 1 hour
- time constant of the loop T --> Hz 0.5 hours **TBD** by **PSL (experimentally)**
- v-$SiO_2$ cavity expansion coefficient: $\alpha = 5 \times 10^{-7}$ 1 / K
- equivalent temperature range: ±0.2 K for $\alpha = 5 \times 10^{-7}$ 1 / K

- environment temperature fluctuation: ±3.5° Fahrenheit (±2° Celsius)
- mean working temperature: 10 K above local ambient temperature
  local can be chilled water temperature
- heater voltage supply: 110 V AC @ 1 A **TBD** by **PSL**
  galvanically decoupled **TBD** by **PSL**
- heat actuator range room temperature to 200° Celsius in 4 to 8 hrs
  at least ±10° Celsius for environmental control.
- exterior temperature sensor: *e.g.* Analog Devices AD 590

# 6 POWER STABILIZATION

There are three related but distinct categories of requirements for PSL power stability. First there is a requirement on low-frequency variations in the PSL output power. Second, allowed relative power fluctuations in the GW band are severely constrained, and third, there is a stringent require-

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[1] *The Effect of Earth Tides on LIGO Interferometers*:, LIGO-T970080-0.0-D, and *Frequency Stabilization: Servo Configuration & Subsystem Interface Specification*, LIGO-T970088-00-D.

[1] Private communication from Stefan Seel.

ment on the shot-noise-limited power fluctuations at the modulation frequency for the sidebands used for GW detection. Each of the three categories of requirements is satisfied by a different control strategy as described below.

## 6.1. Low Frequency Power Variations

The requirement for low-frequency variations in PSL output power is: “The low-frequency variations in the PSL output power shall be less than 1% peak-to-peak over any 24-hour period”. The specification for the LIGO 10-W laser being developed by Lightwave is: “Relative power fluctuations: Drift over 24 hours < 1% peak to peak.”

Even if the LIGO 10-W laser meets this requirements, other factors may cause the output power of the PSL to drift by more than 1%. The LIGO 10-W Laser will have monitors for the output power of both the master oscillator and the amplified output. The power will also be monitored at the output of the PSL and at the input to the **COC**. At low frequencies (DC), the LIGO 10-W Laser output power can be adjusted via two independent actuators. First, the MO power can be adjusted via voltages applied to the MO Power Adjust actuator which varies the current to the pump laser diode. The MO output varies by approximately $\pm 10\,\%$ for a $\pm 10\ \mathrm{V}$ input[1]. Second, the current to the pump laser diodes in the power amplifier can be adjusted via the DC current adjust actuator for the LIGO 10-W Laser power supply. This actuator path has two poles at approximately 1 Hz. The laser output varies by approximately $\pm 2.5\ \mathrm{W}$ for a $\pm 10\ \mathrm{V}$ input[2].

The concept for control of low frequency power variations is to monitor the output powers of both the oscillator and the amplifier and to made periodic corrections as required. This amounts to a low bandwidth digital control loop utilizing the computer monitoring and control interface provided by **CDS**.

## 6.2. Fractional Light Power Fluctuations in the GW Band

PSL is required to provide power-stabilized light to both the **IOO** and the **COC**. The requirement at the input to the **IOO** is: “The amplitude spectral density of the fractional light power fluctuations at the input to the **IOO** shall be $\delta P(f)/P < 10^{-6}\ 1/\sqrt{\mathrm{Hz}}$ for $100\ \mathrm{Hz} < f < 10\ \mathrm{kHz}$ and rising as $f^{-3/2}$ for $40\ \mathrm{Hz} < f < 100\ \mathrm{Hz}$”. The requirement at the input to the **COC** is: “The amplitude spectral density of the fractional light power fluctuations at the input to the **COC** (recycling mirror) shall be $\delta P(f)/P < 10^{-8}\ 1/\sqrt{\mathrm{Hz}}$ for $100\ \mathrm{Hz} < f < 10\ \mathrm{kHz}$ and rising as $f^{-3/2}$ for $40\ \mathrm{Hz} < f < 100\ \mathrm{Hz}$ for both the carrier and for the sidebands used for GW detection”. **IOO** will provide a sample of the mode-cleaner output beam to PSL for power stabilization.

For the NPRO-PSL development work[3] conducted at Caltech, the power adjust actuator of the MO was utilized to stabilize power fluctuations in the GW band. This was found to be unsatisfactory for two reasons; first, the 126-internal relaxation oscillation suppression loop (noise eater) conflicted with the power stabilization loop (they both use the same actuator, the current to the

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1. Refer to *Series 126 Diode-pumped Non-planar Ring Laser Users Manual*, Lightwave Electronics, Inc.
2. Refer to *LIGO 10-W Laser Specifications*, LIGO-E970055-00-D
3. Refer to *NPRO-PSL Performance Data and System Documentation*, LIGO-T970052-00-D

pump laser diode), and second, a significant level of cross-coupling between the power stabilization loop and the frequency stabilization loop was observed. This is thought to be due to changes in the pump laser light level causing thermal-induced changes in the optical path length of the oscillator resulting in frequency changes. This effect is not expected if the actuator utilized to stabilize power fluctuations is the current to the laser diodes in the power amplifier.

The location of the power stabilization photodetector (PSPD) after the **IOO** mode-cleaner, implies that variations in various beam parameters such as pointing, diameter, mode quality, as well as parameters not related to the LIGO 10-W Laser such as mode-cleaner length or alignment variations, will result in power variations sensed by the PSPD. Changes in the laser power introduced via changes in the amplifier pump diode current will be used to counteract power fluctuations caused by all such variations.

### 6.2.1. Free-running Relative Power Fluctuations

The specifications for relative power fluctuations for the LIGO 10-W Laser are reproduced in Table 5, below.

| | |
|---|---|
| 1. 1-100 Hz | < [-100 + 40 log(100 Hz / f)] dB / Hz |
| 2. 100 Hz - 10 kHz | < -100 dB / Hz |
| 3. 10 kHz - 3 MHz | < -120 dB / Hz |

**Table 5: Relative power fluctuations specifications for the LIGO 10-W Laser**[a]

[a] From *LIGO 10-W Laser Specifications*, LIGO-E970055-00-D

Measurements of the relative power fluctuations (often referred to as relative intensity noise or RIN) of the output of the Brassboard laser used for development of the LIGO 10-W Laser at Lightwave[1] indicate that these requirements can easily be met over all frequencies of interest. This may not be the case when fluctuations in other parameters are converted to power fluctuations at the PSPD as described above.

### 6.2.2. Feedback Control Loop Design

The power stabilization control loop design will not be described in detail here because it is similar to the design utilized for the NPRO-PSL.[2] The NPRO-PSL relative output power fluctuations were stabilized to below $1\times10^{-7}\ 1/\sqrt{\mathrm{Hz}}$ from 300 Hz to 10 kHz.[3] The PSL power stabilization control loop will not operate in conflict with the noise eater of the NPRO because it actuates on the amplifier current; this should improve performance. However, other factors which are thought to have limited the performance of the NPRO-PSL power stabilization, factors such as air currents, vibration-induced movement of optical components, spatial variations in photodetector sensitivity, etc., must be addressed. The beam path between optical components may require

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[1] Refer to *Lightwave Preliminary Design Review Documentation Package*, LIGO-C970712-00-R

[2] Refer to *NPRO-PSL Conceptual Design*, LIGO-T960089-00-D

[3] Refer to *NPRO-PSL Performance Data and System Documentation*, LIGO-T970052-00-D

enclosure in beam pipes (the optical table enclosure is expected to reduce air currents as well) and extremely rigid optical mounts and support posts will be utilized (the LIGO sites are also expected to be much quieter than the optics lab at Caltech where the NPRO-PSL development work took place).

## 6.3. Shot-noise-limited Power Fluctuations

The requirement for this category of fluctuations is: “The amplitude spectral density of relative power fluctuations in the output beam of the PSL, measured at the input to the **IOO**, at frequencies above 24.5 MHz and 29.5 MHz (the modulation frequencies of the sidebands used for gravity wave detection for the 4-km and 2-km interferometers, respectively[1]), shall be less than 1.005 times the shot noise limit for 600 mW of laser light. (This is the expected power level at the dark port of the interferometer).”

### 6.3.1. Pre-mode-cleaner Requirement

Because the LIGO 10-W laser will utilize a Master-Oscillator-Power-Amplifier (MOPA) configuration in which the master oscillator power is comparable to the expected power level at the dark port of the interferometer (600 mW), relative power fluctuations in the output beam of the LIGO 10-W laser at 24.5 MHz and above will have to be attenuated in order to meet his requirement. Thus PSL will utilize a Fabry-Perot cavity with a bandwidth designed to give the required attenuation, a pre-mode-cleaner (PMC). A derivation of the predicted noise in MOPA systems and the required bandwidth of a PMC in order to obtain a given noise attenuation factor is given in Appendix 3. The amplitude spectral density (ASD) of the fluctuations in the sampled beam is required to be below 1.005 times the shot noise limit which, following the formalism of Appendix 3, translates to the requirement, $V_{SAMP} < 1.01$. Using this value for $V_{SAMP}$, a value of 20 for $H$, 0.6/10 for $\eta$, 24.5 MHz for $f$, and assuming that the master oscillator is shot-noise-limited at 24.5 MHz ($V_{MO} = 1$) results in the requirement

$$f_c < 1.63 \text{ MHz}$$

Thus, if the MO is shot-noise-limited, we require that the bandwidth, $2f_c$, of the PMC be less than 3.3 MHz in order to filter the PSD of relative power fluctuations to the required level at 24.5 MHz and above.

### 6.3.2. Expected Performance of the LIGO 10-W Laser

Measurements of free-running relative power fluctuations (the NPRO relaxation oscillation suppression control loop was active) performed on the Brassboard laser used for development of the LIGO 10-W Laser at Lightwave[2] indicate that the LIGO 10-W laser will be very close to shot-

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[1] Refer to *Recycling Cavity and Mode Cleaner Cavity Baseline Dimensions*, LIGO-T970068-00-D.

noise-limited for 400 mA of photodetected current (600 mW optical power). This conclusion is based on the rate of the decrease in the ASD of the relative power fluctuations extrapolated to 24.5 MHz. Of course, if there is an anomalous noise source hidden in the noise of the measurements made with only about 10 mW of sampled light, the laser will not meet the shot noise requirement. This will be investigated by measuring the noise at up to 100 mW using the InGaAs photodetector being developed at MIT, but not at 600 mW until the LIGO detector or detector array is available.

### 6.3.3. Pre-mode-cleaner Design

During the past 10 months, LIGO has collaborated with E. Gustafson, N. Uehara, and B. Willke from Stanford University to develop a PMC capable of satisfying LIGO's requirements. One of the main goals of the project was to determine if a PMC similar to what might be required by LIGO could withstand the high levels of circulating optical power without degrading the spatial quality of the beam. N. Uehara, *et al.* designed, fabricated and tested a PMC that appears to satisfy PSL's requirements. Coincidentally, although our requirements were not well understood at the time his PMC was designed, N. Uehara measured the cavity bandwidth to be 3.3 MHz.

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2. Refer to *Lightwave Preliminary Design Review Documentation Package*, LIGO-C970712-00-R

Figure 17 is a mechanical drawing of the Stanford PMC. The ring PMC consists of two flat, fused silica mirrors and a 1 m radius of curvature, fused silica, concave mirror. The mirrors were glued to the fused silica spacer with epoxy. A PZT was glued between the spacer and the curved mirror. N. Uehara operated this cavity, and has extensive experience operating similar cavities, at high circulating powers in air, rather than in vacuum as is common practice at LIGO.

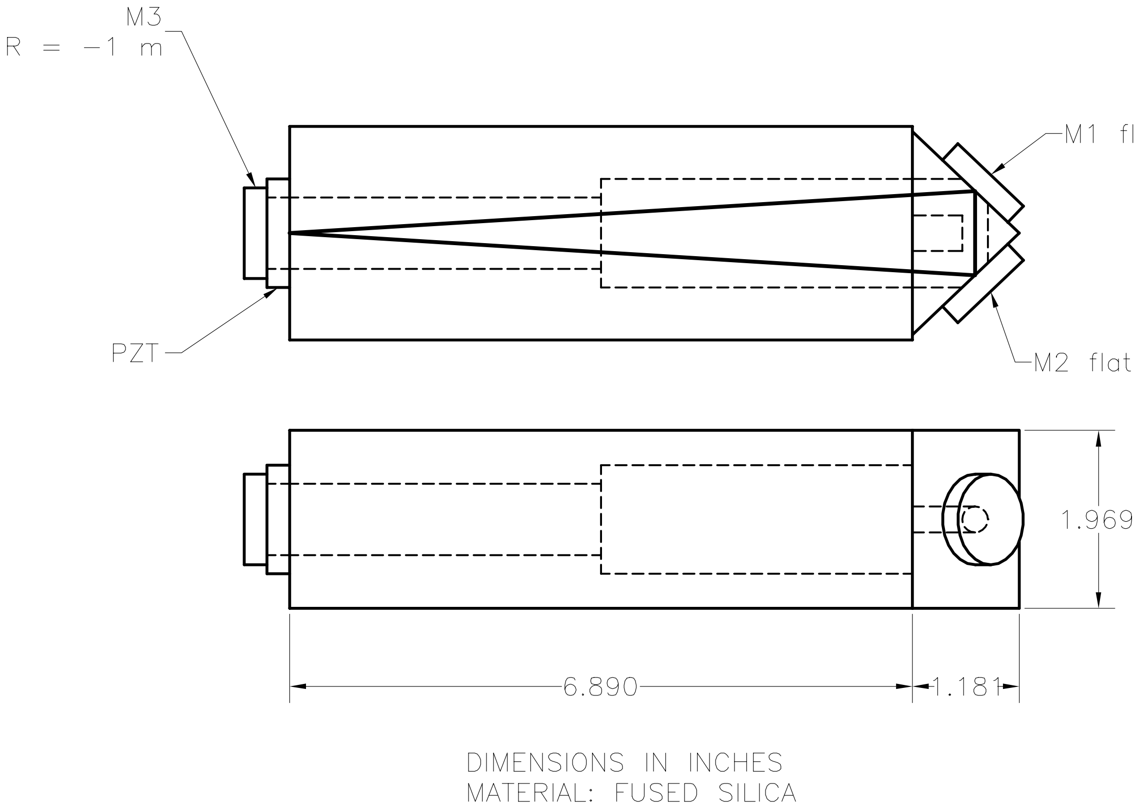

**Figure 17: Mechanical drawing of the Stanford PMC**

The PSL will utilize a ring PMC similar to the Stanford PMC. The flat mirrors will be optically contacted to the spacer and the PZT and curved mirror will be glued with epoxy. The PMC will be fabricated according to standard LIGO procedures for vacuum compatibility. The design reflectivity of the flat mirrors will be adjusted to yield a cavity bandwidth of approximately 2 MHz (a safety factor of 3.3/2)) for *s*-polarized light.

N. Uehara experienced that alignment into the ring PMC is extremely sensitive. PSL will employ manual alignment techniques similar to those developed at Stanford. The alignment into the PMC will not be actively controlled. The PMC will be operated in air unless seismic- or acoustic-induced vibrations are found to be excessive or degradation of the cavity storage time is found to be greater than that expected if the cavity were suspended in vacuum.

### 6.3.4. PMC Length Control

The length of the PMC must be controlled in order to maintain resonance with the laser light. The PMC length will be controlled using the Pound-Drever-Hall reflection locking technique. In order to avoid introducing an additional EOM in the main PSL beam, the modulation sidebands will be introduced by summing into the phase-correcting EOM signal. This technique has not yet been tested by the PSL group. The modulation depth will be very low in order to not use more than 1% of the 10-W beam (100 mW) for PMC locking. The modulation frequency will be a high as practicable in order to reduce sideband power transmitted to **IOO**. The strawman modulation frequency is 50 MHz. Quality of lock will be degraded by the non-$TEM_{00}$ light reflected by the PMC; this could be as much as 1 W. Preliminary calculations using expected parameters indicate that the shot-noise-limited locking accuracy of the PMC will be approximately 7 $\mathrm{mHz}/\sqrt{\mathrm{Hz}}$. We expect that this will be degraded by acoustics and vibrations. Experience with the PSL prototype will determine whether or not measures such as vibration isolation or mounting in vacuum will be required.

# 7 POWER BUDGET

Assuming the performance parameters tabulated in Table 1 of Chapter 3 for the various optical components shown in the detailed optical layout and that the output power of the LIGO 10-W Laser is 10 W in a circular $TEM_{00}$ mode, the power delivered to **IOO** is calculated to be 8.5 W. This represents a conservative estimate since where ever mode matching is required two lenses are used when in practice it might be possible to mode match using a single lens. Also included in the detailed optical layout are components that formed a Faraday isolator to isolate the LIGO 10-W Laser from optical feedback. The calculation did not take into account the effect of the quality of the optical surfaces on the optical wavefront which reduces the output power of the $TEM_{00}$ mode. Meeting the requirement that the PSL deliver 8.5 W to IOO is expected to be one of the challenges in the PSL task.

# 8 LOCK ACQUISITION

## 8.1. Interferometer Global Lock Acquisition Sequence

Although it has not yet been defined, we assume that the PSL will participate in a global lock acquisition sequence. In order to help us understand to what conditions the PSL will be subjected to as it steps through the global lock acquisition sequence, a guess of what the global lock acquisition scenario might be is sketched below.

1. Initial condition: all loops open. PSL frequency shifter AOM running at its nominal operating frequency of 80 MHz. PSL Model 126 master oscillator adjusted so that its frequency is in the middle of a mode-hop-free region. Wideband input active at a greatly reduced gain.
2. PSL initiates the lock acquisition sequence for the pre-mode-cleaner. Once the pre-mode-cleaner length stabilization loop is locked and stabilized, the *Pre-Mode-Cleaner Lock* (PML) flag is set.
3. PSL senses the PML flag is set and closes the DC power stabilization loop. Once the loop is

locked and settled, the *DC Power Stabilization Lock* (DCP) flag is set.

4. PSL senses that the DCP flag is set and initiates the PSL frequency stabilization loop locking sequence (described in Section 8.2.). Once the frequency stabilization loop is locked in acquisition mode, the *Frequency Lock in Acquisition Mode* (FLA) flag is set.
5. **IOO** senses the FLA flag is set and initiates the lock acquisition sequence for the 12-m mode-cleaner. Once the 12-m mode-cleaner is locked in acquisition mode, the *Mode-Cleaner Lock in Acquisition Mode* (MCA) flag is set[1].
6. PSL senses that the MCA flag is set and initiates the transition of the frequency stabilization loop from acquisition mode to run mode. Once the loop has transitioned to the run mode, the *Frequency Lock in Run Mode* (FLR) flag is set.
7. PSL senses that the FLR flag is set and closes the AC power stabilization loop. Once the loop is locked and settled, the *AC Power Stabilization Lock* (ACP) flag is set.
8. **LSC** senses that the ACP flag is set and initiates the interferometer locking sequence. Once the interferometer is locked and settled, the *Interferometer Locked* (IFL) flag is set.
9. **IOO** senses that the IFL flag is set and transitions the 12-m mode-cleaner control loop from acquisition mode to run mode. Once the loop is locked in run mode, the *Mode-Cleaner Lock in Run Mode* (MCR) flag is set.
10. PSL closes the tidal frequency stabilization control loop. Once the loop is locked and settled, the Tidal Stabilization Lock (TSL) flag is set.

## 8.2. PSL Frequency Stabilization Loop Lock Acquisition

The PSL Model 126 MO is adjusted so that its frequency is in the middle of a mode-hop-free region. The slow actuator voltage offset is scanned to bring the laser frequency within range of the fast actuator, at which point error signal is established and the loop acquires lock. The slow voltage offset is then adjusted to null the fast actuator voltage. The correct mode to lock onto is identified using the standard LIGO visibility monitoring technique, which compares the transmitted light level with the reflected light level. The $TEM_{00}$ mode gives the highest level. The threshold level is set to reject the non-$TEM_{00}$ mode. This technique was implemented manually during development of the NPRO-PSL and will be automated via the CDS interface.

We will also communicate with the VIRGO laser group who reported “an automatic locking system was implemented that always relocks the system in a few seconds[2].”

## 8.3. Power Stabilization Loop Lock Acquisition

Acquisition of the power lock for the power stabilization loop is relatively simple compared to the frequency stabilization case because the error signal is always present. However, because the run-state power stabilization photodetector (PSPD) is after the **IOO** 12-m mode-cleaner, which may

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[1] The acquisition mode for the 12-m mode-cleaner allows for different gains in the wide-band signal combining electronics than those utilized in the normal run mode. This ensures that other dependent loops are not pushed out of lock by interferometer locking transients.

[2] *Ultrahigh-spectral purity laser for the VIRGO experiment*, F. Bondu, P. Fritschel, C. N. Mann and A. Brillet, Optics Lett, **21**, 582 (1996).

or may not be locked, the photodetector immediately after the pre-mode-cleaner will be used to stabilize the power when the **IOO** 12-m mode-cleaner is not locked. Once the **IOO** 12-m mode-cleaner is locked and stable, the power stabilization control loop will transition to the PSPD. The ability to make this transition without upsetting the three cavities locked to the laser frequency using the PDH reflection-locking technique (the reference cavity, the PMC, and the **IOO** 12-m mode-cleaner) has not been tested and may prove to be a challenge. However, even without power stabilization, the power fluctuations of the LIGO 10-W Laser are expected to be quite small[1].

# 9 DIAGNOSTIC MODES

For initial interferometer alignment and performance diagnostics as described in the subsystems maintenance schedules, the PSL will offer external and internal diagnostic modes in addition to the steady-state, normal PSL operation mode.

## 9.0.1. PSL-External Diagnostic Modes

In order to enable diagnostics of subsystems other than the PSL subsystem, the PSL operates in various external diagnostic modes. They are called external operation modes, because their purpose is to diagnose external subsystems (not the PSL).

### 9.0.1.1 PSL Beam Finding (BF) Mode

In order to enable locating interferometer optical beams prior to fine alignment, the output power of the PSL can be square-wave modulated by remote command by up to 50% at a frequency of 2 Hz.

During operation in this mode, the power stabilization and frequency stabilization control loops remain locked and active, but with reduced performance.

The output power modulation in BF mode will be facilitated by an AOM after the pre-mode-cleaner (see Figure 4). The details of the AOM and its driver have not yet been investigated.

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[1] Refer to *LIGO 10-W Laser Specifications*, LIGO-E970055-00-D.

### 9.0.1.2 PSL Cavity Ringdown (CR) Mode

In order to measure ringdown times of the various optical cavities in the interferometers, the PSL allows output power modulation by remote command. The modulation parameters are as specified in Table 6, below.

| *Parameter* | *Specification* |
|---|---|
| 1. Modulation Waveform | Square wave and Sine wave |
| 2. Modulation Depth | Variable between 1% and 10% in steps no coarser than 1%. |
| 3. Modulation Frequency | Square wave: variable between 0.01 Hz and 100 Hz in steps no larger than ten per decade. **TBD** by **COC** / **SYS**.<br>Sine wave: variable between 0.01 Hz and 10 kHz in steps no larger than ten per decade. **TBD** by **COC** / **SYS**. |
| 3. Slew Time | The Min-to-Max and Max-to-Min slew times shall be less than 0.05 s **TBD** by **COC / SYS**. |

**Table 6: PSL CR Mode Parameters**

During operation in this mode, the power stabilization and frequency stabilization control loops remain locked and active, but with reduced performance requirements.PSL CR Mode Implementation

The output power modulation in CR mode is facilitated by an AOM after the pre-mode-cleaner.

### 9.0.1.3 PSL System Diagnostics (SD) Mode

In order to perform system-level signal diagnostics, the PSL allows output power modulation and output frequency modulation by remote command. The relative power modulation parameters are as specified in Table 7, below.

| *Parameter* | *Specification* |
|---|---|
| 1a. Modulation Waveform | Sine wave. |
| 1b. Modulation Amplitude | Variable between $10^{-8}$ and $10^{-3}$ rms in steps no coarser than ten per decade. |
| 1c. Modulation Frequency | Variable from 1 Hz to 10 kHz in steps no coarser than ten per decade. |
| 2a. Modulation Waveform | Pseudo-random (noise-like). |
| 2b. Modulation Amplitude Spectral Density | Variable between $10^{-8}$ and $10^{-3}$ $1/\sqrt{\mathrm{Hz}}$ in steps no coarser than ten per decade. |
| 2c. Modulation Bandwidth | > 10 kHz |

**Table 7: PSL SD Mode Power Modulation Parameters**

The frequency modulation parameters are as specified in Table 8, below.

**Table 8: PSL SD Mode Frequency Modulation Parameters**

| *Parameter* | *Specification* |
|---|---|
| 1a. Modulation Waveform | Sine wave. |
| 1b. Modulation Amplitude | Variable between $10^{-7}$ and $10^{-2}$ Hz rms in steps no coarser than ten per decade. |
| 1c. Modulation Frequency | Variable from 1 Hz to 10 kHz in steps no coarser than ten per decade. |
| 2a. Modulation Waveform | Pseudo-random (noise-like). |
| 2b. Modulation Amplitude Spectral Density | Variable between $10^{-7}$ and $10^{-2}$ Hz / $\sqrt{\mathrm{Hz}}$ rms in steps no coarser than ten per decade. |
| 2c. Modulation Bandwidth | > 10 kHz |

During operation in this mode, the power stabilization and frequency stabilization control loops (either or both) remain locked and active with reduced performance requirements or unlocked (inactive) at the user’s discretion. In the ‘inactive mode’, both the frequency and power modulation inputs are held at their last operational value by offset voltages no more noisy than the operational mode inputs.

The output power modulation in SD mode is facilitated by an AOM after the pre-mode-cleaner. The technique for implementing the output frequency modulation in SD mode has not yet been determined.

#### 9.0.1.4 PSL Calibrated Power Reduction (CPR) Mode

The PSL allows a calibrated output power reduction from full power (8.5 W) to 10 mW by remote command.

During operation in this mode, the power stabilization and frequency stabilization control loops remain locked and active, but with reduced performance.

The output power reduction in CPR mode is facilitated by a combination of the AOM, which can reduce the output power by ~ 90%, and a motorized rotatable half-wave plate and polarizing beamsplitter combination.

### 9.0.2. PSL-Internal Diagnostics Mode

(This topic has not yet been adequately addressed. The internal diagnostics will be based on experience gained with the 40-m prototype argon ion pre-stabilized laser, the NPRO-PSL).

The PSL incorporates all diagnostic sequences necessary to verify conformance with performance requirements. All power and frequency stabilization control loops contain test inputs and monitoring points for open and closed loop performance analysis. Separate photodetectors are provided for making “outside the loop” power fluctuation measurements. Measurement of frequency fluctuations and beam pointing fluctuations require diagnostic signals from the **IOO** 12-m mode-cleaner, the details of which have not been resolved.

On-line, diagnostic data will be available during all operational modes. The sampling rate of the data has not yet been determined. As a rule, the data immediately before a interferometer loss of lock is more important than those during normal steady-state operation.

Possible on-line measurements (to be continuously updated) are:

- VCO/AOM error / correction point signal
- primary PSL frequency actuator error / correction point signal
- PSL reference cavity transmission on a quadrant diode (tilt)
- NPRO internal temperature
- NPRO output power
- the power from each pump diode monitor in the LIGO 10-W Laser power amplifier, this will help identify which pump diode is degrading and will give valuable maintenance data
- outcoupled light power in the amplifier-internal Faraday isolator, giving information about thermal depolarization inside the amplifier.
- sampling the amplifier 10-W output power
- temperature signal from the PSL reference cavity quiet enclosure
- heater signal from the PSL reference cavity quiet enclosure
- duty hours of the PSL systems
- PSL reference cavity vacuum system pressure

# 10 COMPUTER CONTROL INTERFACE

All operational and diagnostic modes of the PSL are accessible via CDS. The user will be able to perform the following functions:

- power up the PSL
- power down the PSL
- close the mechanical shutter of the LIGO 10-W Laser
- enable an emergency shutdown of the LIGO 10-W Laser
- place the PSL in stand-by mode, where there is no actual lasing taking place but the pump diodes are kept at operating temperature
- obtain the present status of the PSL
- initiate lock acquisition mode
- initiate beam finding mode
- initiate cavity ringdown mode
- initiate strain diagnostics mode
- initiate calibrated power reduction mode
- monitor the temperature of the YAG crystal
- monitor the temperature of the laser diodes
- monitor the output of each of the pump diodes in the power amplifier
- adjust the slow actuator of the PSL
- adjust the fast actuator of the PSL
- make small adjustments to the laser current

- turn off or on the noise reduction electronics
- log the performance of the PSL and set the sampling rate
- recall previous logs of the PSL performance for comparison with current performance levels
- keep track of the number of operational hours the LIGO 10-W Laser has accumulated
- initiate the internal diagnostic modes of the PSL
- initiate the external diagnostic modes of the PSL
- adjust the gain and servo settings

The PSL will pass various flags, concerning the current status of the PSL, to **CDS** for control. Flags to be passed include:

- on-line / off-line status
- lasing status
- lock acquisition status
- fault indicator status
- diagnostic mode status
- maintenance indicator status

# 11 RELIABILITY AND MAINTENANCE

## 11.1. 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)[1].

## 11.2. Spares Policy

Spare optical components such as polarizing beamsplitters, half-wave and quarter-wave plates, mirrors and lenses shall be kept at all times. Spares of other components such as the EOMs, AOMs, CCD cameras, photodetectors and RF photodetectors will also be maintained. A log of the number of spares components shall be maintained next to the stockpile of spare components and the optical table enclosure. Records of the type, quantity, date of replacement and the date of testing shall be kept.

In addition to keeping a stockpile of optical components, spare amplifier pump laser diodes shall also be kept. The spare pump laser diodes will be chosen to have the same wavelength versus temperature characteristics and similar output ($\pm 5\%$ TBD for the same operating current). The spare diodes may be run continuously to ensure that they are the same age as those used for the LIGO 10-W Laser deployed in the LIGO interferometer. This ensures that a similarly aged 20-W pump diode is available if the power amplifier requires replacement of a 20-W pump diode. At least two spare complete power amplifier modules and NPRO lasers will also be kept on hand. When it is necessary to install the spare components, the failed components should be returned for servicing, either by Lightwave Electronics or a suitably qualified person.

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[1] Refer to *(Infrared) Pre-stabilized Laser (PSL) Design Requirements*, LIGO-T970080-00-D.

Spare optical mounting hardware and associated assembly hardware shall also be kept. Vacuum components like vacuum windows, copper gaskets, screws and nuts, ion pumps, ion pump controllers and vacuum gauges shall be kept.

## 11.3. Maintenance

A maintenance strategy and procedure needs to be devised in order to keep the PSL in good operating condition. The minimum time between required beam alignment adjustments for the LIGO 10-W Laser is specified to be greater than 2500 hours[1]. Thus every 2500 hours there should be a maintenance inspection. This inspection should check the condition of the LIGO 10-W Laser as well as other components on the **IOO** / PSL optical table, such as the condition of the Faraday isolators and the performance of the EOM and AOM. The output power and beam quality of the LIGO 10-W Laser should also be checked.

### 11.3.1. Maintenance Procedure

It is expected that the performance of all the 20-W pump laser diodes will degrade over time in the same manner. However, in the event that one of the 20-W diode power monitors shows the output of the pump diode beginning to deteriorate faster than the others, then maintenance on the power amplifier module will be necessary.

The following preparatory procedure shall be followed prior to performing any maintenance on the LIGO 10-W Laser.

The LIGO 10-W Laser should be shutdown and turned off via remote control. Prior to removing any panels of the optical table enclosure, a quick visual inspection of the operational status should be made to confirm that the laser is not operating. The access panels in the enclosure should then be removed and the HEPA panel turned on. The HEPA filter should be on for at least a period of time (TBD) that establishes Class 100 clean room conditions prior to the removal or disassembly of any components. All tools used should be grounded to the metal cover of the LIGO 10-W Laser to guard against static electricity. Once clean room conditions have been established then the protective metal dust cover can be removed. The faulty pump laser diode can then be removed and replaced. No alignment of the pump laser diode should be necessary as kinematic mounting should allow for reproducible positioning. The protective metal dust cover should then be replaced over the power amplifier followed by the protective metal cover over the LIGO 10-W Laser. The laser should then be operated and checks of the beam quality and output power performed. The spare LIGO 10-W Laser should then be switched back on to ensure that it accumulates the same number of operating hours as the laser deployed in the LIGO interferometer. Entries into the maintenance log should then be made, noting the time, date and nature of the maintenance performed, including replacement part serial numbers and manufacturers. The HEPA filter can then be switched off and the optical table enclosure closed.

For maintenance of other components such as the AOM, EOM and Faraday isolator, these components should be simply replaced if they are diagnosed to be faulty. When replacing these items, it will be necessary to perform an alignment check of the laser beam to check that the desired

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[1] Refer to *LIGO 10-W Laser Specifications*, LIGO-E970055-00-D.

throughput level has been achieved. Optical components such as mirrors and polarizing beamsplitters should be replaced if found to be damaged.

# APPENDIX 1 THE REFERENCE CAVITY

The reference cavity is shown in Figure 18. The reference cavity is formed by two identical concave mirrors with $T = 300 \pm 30\ \mathrm{ppm}$, $L < 30\ \mathrm{ppm}$, with a radius of curvature of 500 mm. The mirrors are separated by a 203 mm long fused silica spacer.

The peak transmission $\tau$ of the cavity is given by

$$\tau = \left(1 - \frac{L}{1-R}\right)^2$$

where $R = 1 - (T + L)$. Therefore, the reference cavity has a peak transmission of 83%.

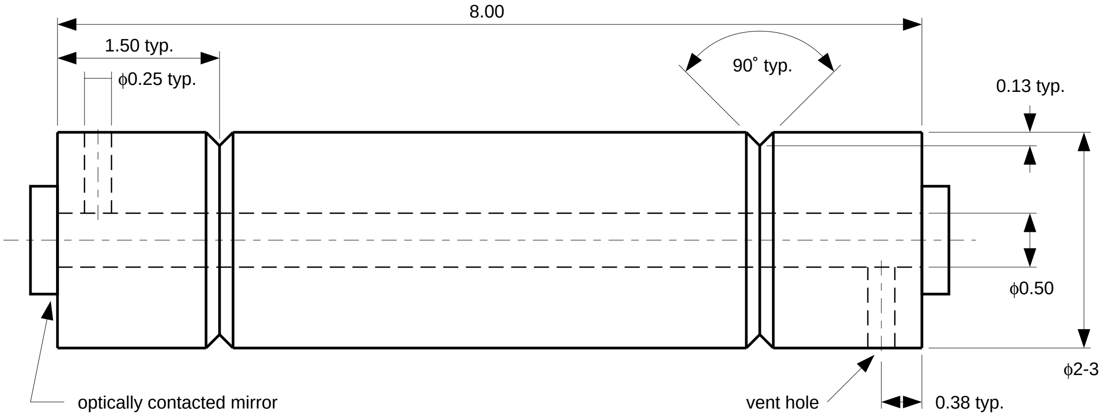

Figure 18: The reference cavity.

# APPENDIX 2 POUND-DREVER-HALL DISCRIMINATOR SLOPE AND SHOT NOISE CALCULATIONS

The expression for the magnitude of the Pound-Drever-Hall discriminant $D_{\mathrm{V,\ disc}}[\mathrm{V/Hz}]$ has been shown by Day[1] to be given by

where $F$ and $\delta\nu_{\mathrm{c}}$ are the finesse and linewidth of the reference cavity respectively, $\beta$ is the modulation index of the phase modulator, $R$ is the RF photodetector responsivity, $P_i$ is the power

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[1] *Sub-Hertz Relative Frequency Stabilization of Two-Diode Laser-Pumped Nd:YAG Lasers Locked to a Fabry-Perot Interferometer*, Timothy Day, Eric K. Gustafson, and Robert L. Byer, IEEE Journal of Quantum Electronics, **QE-28**, pp1106-1117 (1992).

$$D_{\text{V, disc}}[\text{V / Hz}] \;=\; 8\frac{J_0(\beta)J_1(\beta)}{\delta v_{\text{c}}}\sqrt{\frac{\text{sinc}^2(\omega/(2F\delta v_{\text{c}}))}{1+\dfrac{4F^2}{\pi^2}\sin^2(\omega/(2F\delta v_{\text{c}}))}}RP_i$$

incident on the photodetector, $J_0$ and $J_1$ are the zeroth and first order Bessel functions and $\omega$ is the difference between the angular frequency of the first sideband and the angular frequency of the carrier. This slope is maximized for $\beta \sim 1.08$ leading to the approximation

$$D_{\text{V, disc}}[\text{V / Hz}] \sim \frac{2.71}{\delta v_c}RP_i.$$

Assuming a quantum efficiency of 0.8, the RF photodetector responsivity is calculated to be $0.68\ \text{A / W}$. Assuming the RF photodetector transimpedance to be 600 Ω, $R$ is calculated to be $410\ \text{V / W}$. With 10 mW of power incident on the reference cavity and a reference cavity linewidth of 75 kHz, the maximum discriminator slope is calculated to be approximately $150\ \text{V / MHz}$.

Assuming an impedance matched cavity, the discriminator shot noise spectral density of current, $S_{\text{A, disc}}(\text{A}/\sqrt{\text{Hz}})$ is given by

$$S_{\text{A, disc}}(\text{A} / \sqrt{\text{Hz}}) \;=\; \sqrt{2}\sqrt{2e\left(2J_1^{\;2}(\beta)\frac{e\eta P_i}{h\nu}\right)}$$

where $\eta$ is the quantum efficiency of the photodetector and $h\nu$ is the energy of the detected photons. With the above assumptions the shot noise spectral density of current is calculated to be $4.4\times10^{-11}\ \text{A} / \sqrt{\text{Hz}}$. Multiplying $S_{\text{A, disc}}(\text{A}/\sqrt{\text{Hz}})$ by the transimpedance of the RF photodetector and dividing by the maximum slope of the Pound-Drever-Hall discriminator gives the shot noise limited frequency sensitivity of the reference cavity to be $0.2\ \text{mHz} / \sqrt{\text{Hz}}$.

## Appendix 3 Noise Propagation in MOPA Systems

*The following derivation resulted from a discussion of noise in amplifiers organized by E. Gustafson of Stanford University that included T. Ralph from ANU, M. Fejer, B. Tulloch, and B. Willke from Stanford and R. Savage from Caltech.*

Because the LIGO 10-W laser will utilize a Master Oscillator Power Amplifier (MOPA) configuration in which the master oscillator power is comparable to the expected power level at the dark port of the interferometer (600 mW), relative power fluctuations in the output beam of the LIGO 10-W laser at 24.5 MHz and above will have to be attenuated in order to meet this requirement.

The justification for this statement begins with the following expression which relates the relative power fluctuations in the output of a MOPA system to those of the maser oscillator.[1]

$$V_{MOPA} = H(V_{MO} + 1) - 1$$

Here $V_{PA}$ is the ratio of the power spectral density (PSD) of the relative power fluctuations in the power amplifier output relative to the shot noise limit for a beam of that power, *H* is the power amplification factor, and $V_{MO}$ is the ratio of the PSD of the relative power fluctuations in the master oscillator output relative to the shot noise limit for a beam of that power. If one samples a fraction of the output of the MOPA, the PSD of relative power fluctuations in the sampled beam is given by[2]

$$V_{SAMP} = 1 + \eta(V_{MOPA} - 1)$$

Here $\eta$ is the ratio of the sampled power to the MOPA output power. Combining the two expressions above gives

$$V_{SAMP} = 1 + \eta[H(V_{MO} + 1) - 2]$$

For the LIGO 10-W laser, where the master oscillator power is approximately 500 mW, and in the case where the sampled power is approximately 600 mW (the expected power at the dark port of the interferometer), $V_{SAMP} \approx V_{MO} + 2$. Thus, even if the PSD of relative power fluctuations of the master oscillator is at the shot noise limit ($V_{MO} = 1$), the PSD of the relative power fluctuations in the sampled beam will be approximately three times the shot noise limit. In order to reduce the relative power fluctuations to the required level, a passive optical filter, a pre-mode-cleaner (PMC), will be employed.

Using the vocabulary introduced by T. Ralph, the filtering of the PSD of relative power fluctuations as a function of frequency by a Fabry-Perot cavity is given by

$$V_{TRANS}(f) = \left(\frac{1}{1 + (f/f_c)^2}\right)(V_{INPUT} - 1) + 1$$

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[1] Private conversation with T. Ralph of Australian National University, Canberra, Australia.

[2] *ibid*.

where $f_c$ is half the resonance bandwidth (FWHM) of the cavity. Combining the above equations according to the flow diagram in Figure 19, and solving for the cavity half-width yields

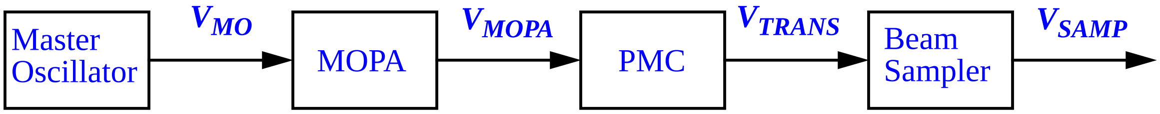

**Figure 19: Flow diagram for shot noise calculation.**

$$f_c = f\left\{\frac{\eta[H(V_{MO}+1)-2]}{V_{SAMP}(f)-1}-1\right\}^{-1/2}$$

This expression gives the half-bandwidth of the optical cavity required to obtain a noise level of $V_{SAMP}(f)$ given the master oscillator noise, $V_{MO}$, the power amplifier gain, *H*, and the sampled power ratio, $\eta$.

# APPENDIX 4 GLOBAL FREQUENCY STABILIZATION STRATEGY - NESTED LOOPS

This section is being worked upon. It will follow along the lines of J. Camp: *Frequency-stabilization in LIGO*, LIGO-T960164-00-D and P. Fritschel: *Frequency Stabilization: Servo Configuration & Subsystem Interface Specification*, LIGO-T970088-00-D.

It will contain an estimate of essential loop-parameters for the IOO frequency-stabilization loop that utilizes the PSL-wideband actuator described in this document.

# APPENDIX 5 LIGO 10-W LASER SPECIFICATIONS

## Performance Specifications

| *Parameter* | *Specification* |
|---|---|
| 11. Power in circular $TEM_{00}$ mode | > 10 W |
| 12. Total power in all non-$TEM_{00}$ modes | $< 1\ \mathrm{W}\ (M_{\mathrm{horizontal}} \times M_{\mathrm{vertical}} < 1.1)$ |
| 13. Relative spot size fluctuations, $\delta w/w$ | < 2% peak-to-peak |

| *Parameter* | *Specification* |
|---|---|
| Relative Power Fluctuations, $\delta P(f)/P$ : | |
| 14. Drift over 24 hours | < 1% peak-to-peak |
| 15. Drift over 500 hours | < 3% peak-to-peak |
| 16. 1-100 Hz | < [-100 + 40 log(100 Hz / f)] dB / Hz |
| 17. 100 Hz - 10 kHz | < -100 dB / Hz |
| 18. 10 kHz - 3 MHz | < -120 dB / Hz |
| 19. 10 MHz | < - 163 dB / Hz (within 2 dB of the shot noise limit for 10 mA photodetected current) |
| Relative Power Fluctuations, $\delta P(f)/P$, at 60 Hz Line Frequency and Harmonics: | |
| 20. 60 Hz and 120 Hz | $< 1 \times 10^{-5}$ rms |
| 21. Between 150 Hz and 10 kHz | $< 1 \times 10^{-5}$ rms |
| 22. Between 10 kHz and 3 MHz | $< 2.4 \times 10^{-6}$ rms |
| 23. Relative power fluctuations, $\delta P(f)/P$, at Model 126 power supply switching frequency (~80 kHz) | $< 2 \times 10^{-5}$ rms |
| Frequency Fluctuations: | |
| 24. Between 40 Hz and 100 Hz | $< [54 + 50\ \log(100\ \mathrm{Hz}/f)]$ dB $\mathrm{Hz}^2$ /Hz |
| 25. Between 100 Hz and 10 kHz | $< [54 + 20\ \log(100\ \mathrm{Hz}/f)]$ dB $\mathrm{Hz}^2$ /Hz |
| Frequency Drift: | |
| 26. At constant ambient temperature | < 50 MHz / hour |
| 27. At constant ambient temperature | < 1 GHz / month |
| 28. Per degree ambient temperature change | < 30 MHz |

| *Parameter* | *Specification* |
|---|---|
| Frequency-to-Intensity Conversion: | |
| 29. Fractional power change (W/W) per Hz of frequency change | $< 2 \times 10^{-10}$ |
| Relative Pointing Angle Fluctuations, $\delta\theta/(\theta_d/2)$, (divergence half angle, $\theta_d/2 = \lambda/(\pi \times w_0)$): | |
| 30. Drift over 24 hours | $< 2.5 \times 10^{-2}$ peak-to-peak |
| 31. 40 Hz to 150 Hz | < [-110 + 40 log(150 Hz / f)] dB / Hz |
| 32. > 150 Hz | < -110 dB / Hz |
| Relative Transverse Position Fluctuations, $\delta x/w$, (w is the spot size): | |
| 33. Drift over 24 hours | $< 2.5 \times 10^{-2}$ peak-to-peak |
| 34. 40 Hz to 150 Hz | < [-110 + 40 log(150 Hz / f)] dB / Hz |
| 35. > 150 Hz | < -110 dB / Hz |
| 36. Polarization extinction ratio | > 300:1 |
| 37. Electromagnetic interference (EMI) emissions | In compliance with CE mark, EN 55011 Class A |
| Reliability: | |
| 38. Mean time between failure (MTBF) | > 10,000 hours |
| 39. Minimum time between required beam alignment adjustments | > 2,500 hours |

# Configuration Specifications

| *Parameter* | *Specification* |
|---|---|
| 40. Type of laser | $Nd^{3+}$:YAG |
| 41. Wavelength | 1064 nm |
| 42. Optical scheme | Master Oscillator Power Amplifier, double-pass |
| 43. Amplifier pumping | 8 x 20-W diode bar, direct-coupled, side-pumped |
| Frequency Control: | |
| 44. Thermal tuning range, continuous | 10 GHz |
| 45. Thermal tuning range, total | 30 GHz |
| 46. Thermal tuning rate | 1 GHz/sec |
| 47. Piezo tuning range, ±15 V | 30 MHz |
| 48. Piezo response bandwidth, small-signal | > 30 kHz |
| 49. Warm-up time | < 1 hour |
| Laser head, mechanical: | |
| 50. Support structure | 2 ft. x 2 ft., 1/4 in.-20 tapped holes on 1 in. square grid |
| 51. Modules/components | a. Model 126-1064-700 master oscillator<br>b. Power amplifier, sealed<br>c. Coupling and beam control optics |
| 52. Beam height above support structure | **TBD** ±0.05 in. |
| 53. Cover | Removable dust protective cover, metal |
| 54. Total laser height | < 1 ft. |
| 55. Distance from laser head to power supplies | Up to 50 ft. |

| *Parameter* | *Specification* |
|---|---|
| Laser head, optical: | |
| 56. Output beam waist spot size, $w_0$ | 0.22 mm ±0.1 mm |
| 57. Output beam waist location | 55 ±50 mm mm from output aperture, inside the laser |
| Laser chiller: | |
| 58. Type | Low-temperature, bath circulator |
| 59. Manufacturer, Model | Neslab, RTE-140M |
| 60. Cooling capacity | 600 W at 10 °C, at ambient temp. of 20 °C |
| 61. Pumping capacity | 0.9 gpm through 100 ft. length of 3/8 in. ID hose |
| 62. Dimensions (h x w x d) | 66.0 cm x 31.4 cm x 48.3 cm (> 12 in. clearance at front and rear for ventilation) |
| 63. Distance from laser head to chiller | Up to 50 ft. |
| 64. Distance from chiller microprocessor controller to chiller | Up to 50 ft. |
| 65. Laser safety | In compliance with federal register 21 CFR 1040.10 & 1040.11 laser safety standard |
| 66. Transportability | Transportable by commercial carrier without performance degradation |

# Electronics Specifications

Refer to *Specification for LIGO 10W Laser Amplifier Electronics,* Lightwave Electronics document number D-0226X2.DOC, attached.