LIGO-P980002-00-D

# A Highly-Stabilized 10-Watt Nd:YAG Laser for the Laser Interferometer Gravitational-Wave Observatory (LIGO)[1]

R. L. Savage, Jr., P. J. King, and S. U. Seel

LIGO Project
California Institute of Technology
Mail Code 18–34
Pasadena, CA 91125

## 1 Introduction

Einstein's General Theory of Relativity describes gravity as being the result of the curvature of space-time. When the curvature is small, the result is Newtonian gravity, which governs the mechanics of the solar system. As the curvature of space-time increases, gravity departs from the more familiar classical behavior and becomes increasingly non-linear. A consequence of this non-linearity is the creation of black holes. If a body were to make violent, non-axisymmetric motions, it would create ripples in the fabric of space-time that propagate at the speed of light. These ripples are gravitational waves.

To date gravitational waves have not been directly observed, although their existence has been inferred from measurements of the orbital decay of the neutron stars PSR $1913+16$ [1]. Possible sources of gravitational waves include supernovae and binary systems comprised of black holes or neutron stars. Figure 1 is an artist's depiction of the ripples in space-time generated by two coalescing black holes.

Figure 1: Two coalescing black holes emit gravitational waves.

The principal goal of the LIGO Project is the direct detection of cosmic gravitational

---

[1] The LIGO Project is supported by the National Science Foundation under cooperative agreement PHY-9210038.

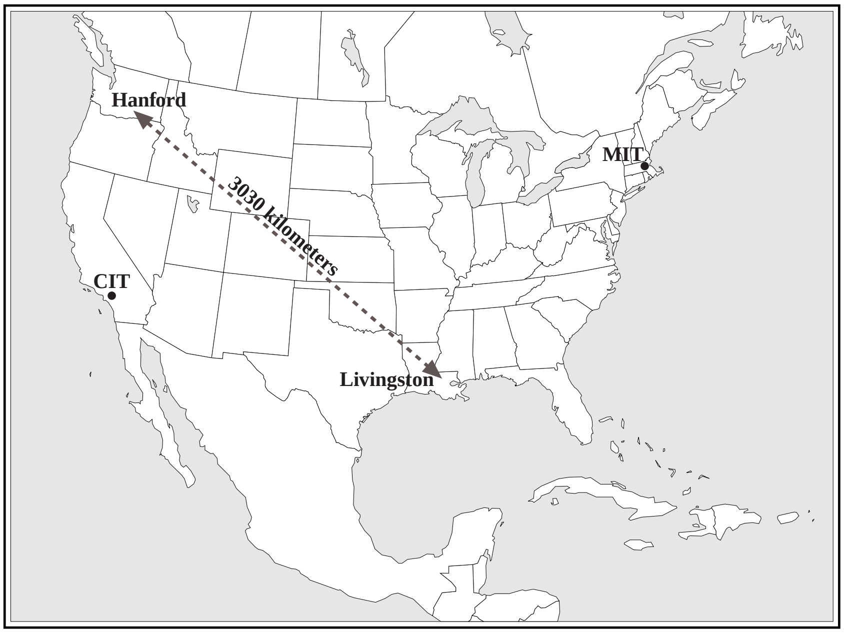

Figure 2: The location of the two LIGO observatories, the sites are separated by a distance of 3030 km, corresponding to a time of arrival difference of ± 10 ms.

waves. State-of-the-art laser interferometers located at the LIGO observatories in Hanford, WA and Livingston Parish, LA (see Figures 2 and 3), will measure the infinitesimal oscillating displacements of isolated test masses that indicate the presence of a gravitational wave. Theory predicts that in order to detect candidate sources with reasonable event rates, LIGO must achieve a strain sensitivity spectral density of better than $10^{-22}\,1/\sqrt{\mathrm{Hz}}$ at $\sim 100$ Hz which translates to a displacement sensitivity on the order of $10^{-19}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ or a phase sensitivity on the order of $10^{-10}\,\mathrm{radians}/\sqrt{\mathrm{Hz}}$. Operation at these sensitivity levels requires high-power laser beams with very low frequency fluctuations and power fluctuations.

## 2 The LIGO Pre-stabilized Laser

The Pre-stabilized Laser (PSL) subsystem of the LIGO detectors, presently in the preliminary design phase, includes the high-power source and the feedback control loops necessary to reduce power and frequency fluctuations to the required levels. The allowed levels of power fluctuations are shown in Figure 4 and frequency fluctuations are shown in Figure 5. Additional PSL performance requirements are given in Table 1.

A schematic diagram of the PSL is shown in Figure 6. The three main functional blocks are the power stabilization control loop, the frequency stabilization loop and the pre-mode-cleaner. The power stabilization loop utilizes a photodetector which receives a fraction of the output beam and a power adjust actuator which varies the current to the laser diodes that excite the amplifier stages. LIGO requires reduction of the amplitude spectral density of relative power fluctuations in the gravitational-wave band, 40 to 10 000 Hz, to

Figure 3: An aerial view of the LIGO Hanford, WA facility.

| | |
|---|---|
| output power | $> 8.5\,\mathrm{W}$ in a circular $\mathrm{TEM}_{00}$ mode |
| beam quality | $< 100\,\mathrm{mW}$ total in all non-$\mathrm{TEM}_{00}$ modes |
| relative power fluctuations above 24.5 MHz | $< 3 \times 10^{-9} 1/\sqrt{\mathrm{Hz}}$ |
| beam relative pointing angle fluctuations | $< 2 \times 10^{-6}\, 1\,/\sqrt{\mathrm{Hz}}$ |

Table 1: Additional PSL performance requirements summary.

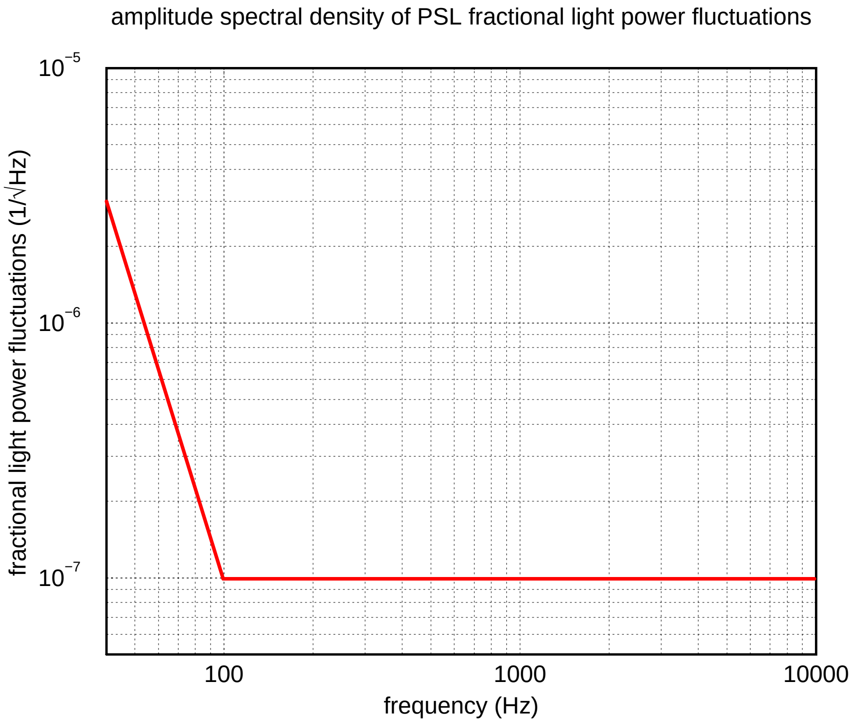

Figure 4: The amplitude spectral density of allowed power fluctuations.

less than $10^{-7}\,1/\sqrt{\mathrm{Hz}}$. Stabilization to this level has been demonstrated over most of this band when stabilizing the master oscillator alone. Stabilization of the power amplifier will be tested during the winter of 1997.

The frequency stabilization block of the PSL is the first of a series of three nested loops that operate in concert, utilizing progressively more stable Fabry-Perot reference cavities, to reduce the frequency fluctuations of the laser light to less than $10^{-7}\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$. The requirement for the PSL frequency stabilization loop is less than $0.1\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 100 Hz. The PSL must also act as a frequency actuator by accommodating two control signals, labeled *Wideband Input* and *Tidal Input* in Figure 6, derived from the two subsequent nested loops, enabling further suppression of frequency fluctuations. These loops utilize a 12-m-long, triangular optical cavity and the 4-km-long interferometer arm cavities as frequency references.

The pre-mode-cleaner block serves to reduce relative power fluctuations at frequencies above 24.5 MHz, the modulation frequency used for gravitational wave (GW) detection, to near the fundamental limit imposed by shot noise in the photodetector current at 600 mW detected power. This is accomplished by the passive filtering at frequencies above the half-bandwith ($\sim 1.5$ MHz) of the triangular, Fabry-Perot cavity.

## 2.1 The LIGO 10-W Laser

The PSL incorporates a 10-W, Nd:YAG master-oscillator-power-amplifier (MOPA) laser system being developed under contract with LIGO by Lightwave Electronics, Inc. in

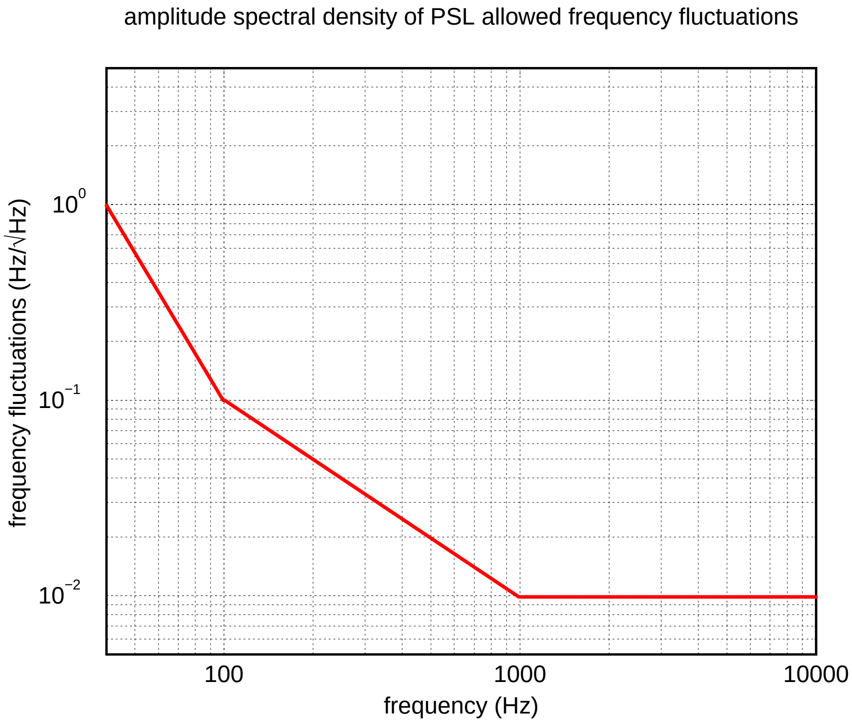

Figure 5: The amplitude spectral density of allowed frequency fluctuations.

Mountain View, CA. The first engineering prototype of the LIGO 10-W laser is scheduled for delivery in October of this year. The MOPA system employs a Lightwave Model 126-1064-700 master oscillator and a two-pass amplification scheme. The amplifier chain consists of four Nd:YAG rods, each pumped by two 20-W laser diode bars. A schematic diagram of the laser is shown in Figure 7.

The vertically polarized 1064 nm output of the Model 126 master oscillator is passed through some beam shaping optics, a polarizing beamsplitter cube, a focussing lens and a half-wave plate before traversing a Faraday rotator. The now horizontally polarized output is transmitted through a thin film polarizer and passed through another Faraday rotator. Another half-wave plate removes the polarization rotation introduced by the second Faraday rotator so that the beam is transmitted through a thin film polarizer before being focussed into the power amplifier. After a double pass through the power amplifier, the horizontally polarized output is transmitted through the thin film polarizer. The half-wave plate and Faraday rotator combine to rotate the polarization to vertical where the thin film polarizer reflects the beam out to become the output of the LIGO 10-W Laser. A summary of the performance parameters and requirements of the LIGO 10-W Laser is given in Table 2.

The performance of the brassboard pre-production LIGO 10-W Laser operated at Lightwave Electronics is shown in Figure 8. The system produced 10 W of single-frequency radiation in a circular $TEM_{00}$ mode with less than 1 W in all higher-order modes.

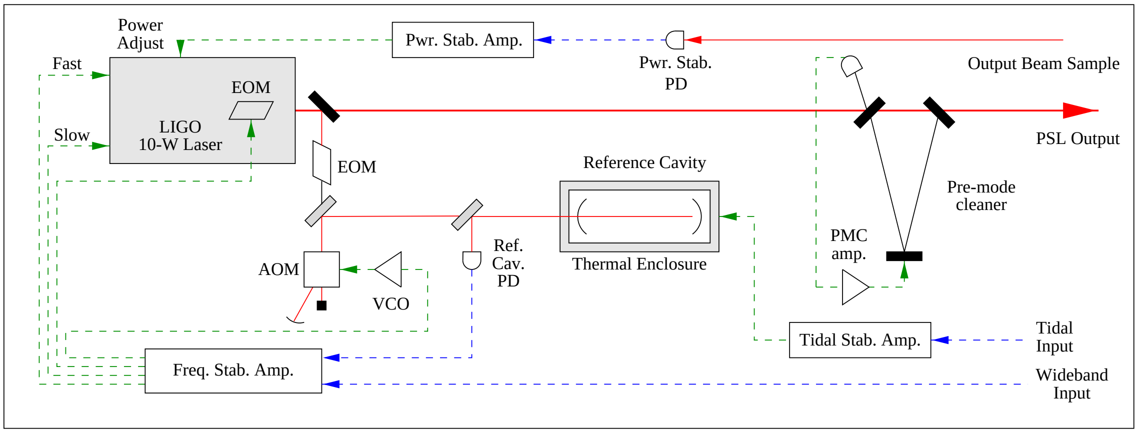

Figure 6: Schematic diagram of the LIGO Pre-stabilized Laser System.

| | |
|---|---:|
| type of laser | $Nd^{3+}$:YAG |
| wavelength | 1064 nm |
| output beam spot size, $w_0$ | 0.22 mm |
| power in circular $TEM_{00}$ mode | $> 10$ W |
| total power in all non-$TEM_{00}$ modes | $< 1$ W |
| polarization extinction ratio | $> 300 : 1$ in the vertical plane |
| relative power fluctuations (100 Hz–10 kHz) | $< 10^{-5}\,1/\sqrt{\mathrm{Hz}}$ |
| frequency fluctuations (100 Hz–1 kHz) | $< 500 \times (100/f)\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ |
| relative pointing angle fluctuations | $< 3 \times 10^{-6}\,1/\sqrt{\mathrm{Hz}}$ |

Table 2: Performance parameters and requirements of the LIGO 10-W Laser.

## 3 Frequency Stabilization

One critical factor affecting the sensitivity of LIGO to gravitational waves is the phase or frequency fluctuations of the laser used to measure the differential length changes in the arms of the interferometer. Inside the gravitational-wave band, the technical noise of the LIGO 10-W laser exceeds the required level by up to nine orders of magnitude. Reduction of frequency noise is therefore a primary concern for the PSL.

The frequency stabilization strategy for the LIGO detectors uses three nested control loops. Each loop utilizes a more frequency sensitive reference cavity (see Figure 9). The first loop, the PSL frequency control loop, employs a 200-mm-long fixed reference cavity as the frequency fluctuation sensor. This first stage reduces the free-running frequency noise of the laser to $0.1\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 100 Hz. The reference cavity utilizes a monolithic fused silica spacer with a low-loss mirror optically contacted to each end. Housed inside a vacuum chamber, the reference cavity is suspended by two loops of wire with springs and is mounted to a three-tier vibration-isolation stack. Movement of the reference cavity is restricted by eddy current motion dampers.

The second loop uses a 12-m-long triangular ring mode-cleaner. The second stage

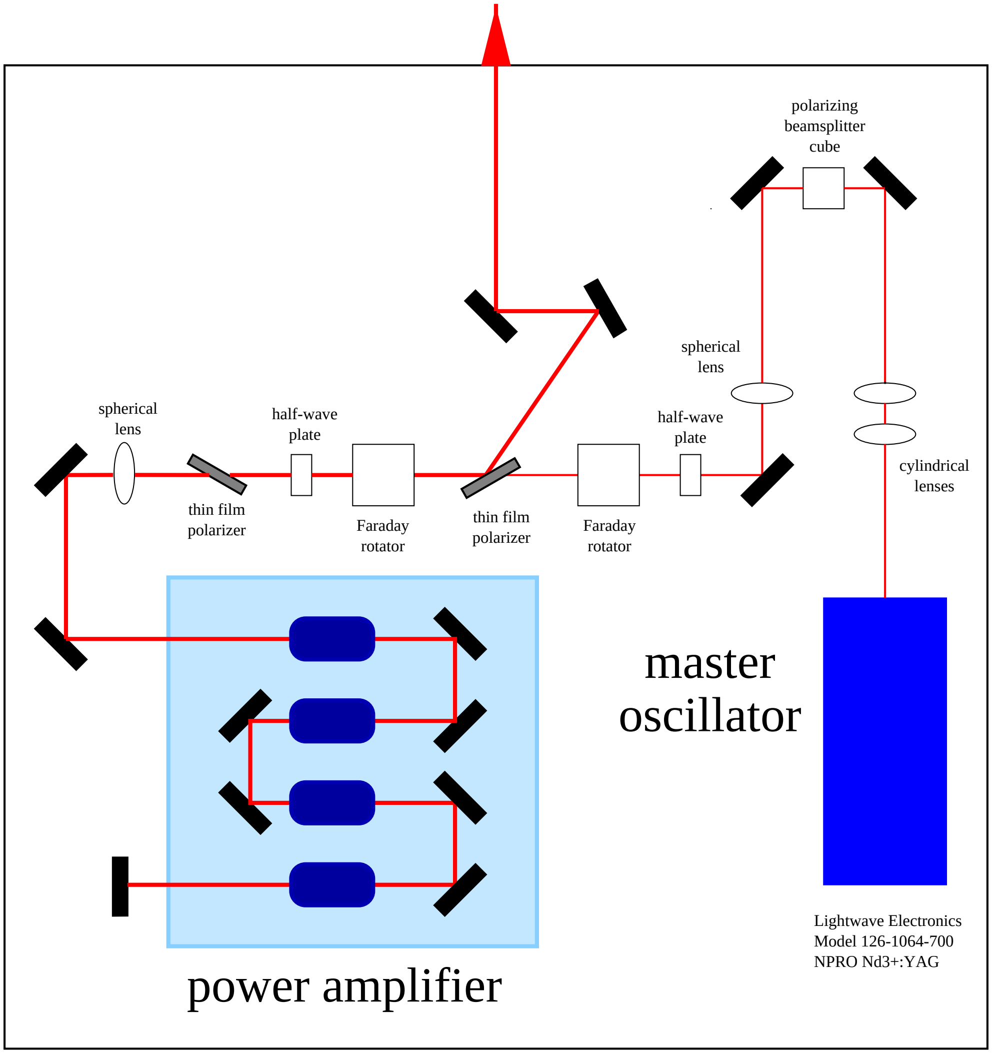

Figure 7: The geometry of the LIGO 10-W Laser.

enables stabilization of the laser frequency beyond the sensitivity of the PSL reference cavity to less than $10^{-4}\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 100 Hz.

The third loop uses the 4-km Fabry-Perot cavities in the arms of the LIGO interferometer to further stabilize the frequency of the laser light to $10^{-7}\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$.

The frequency actuators for frequency stabilization are the SLOW and FAST inputs to the LIGO 10-W laser and an electro-optic modulator (EOM). The SLOW actuator is a thermo-electric cooler that varies the optical path length of the NPRO cavity to change the laser frequency. The FAST actuator is a piezo-electric transducer (PZT) bonded to the NPRO crystal that varies the optical path length of the oscillator cavity via stress induced index of refraction changes. The EOM, or Pockels cell, is mounted inside the 10-W laser head, between the master oscillator and power amplifier rather than after the power amplifier, in order to reduce the power density at the EOM crystal.

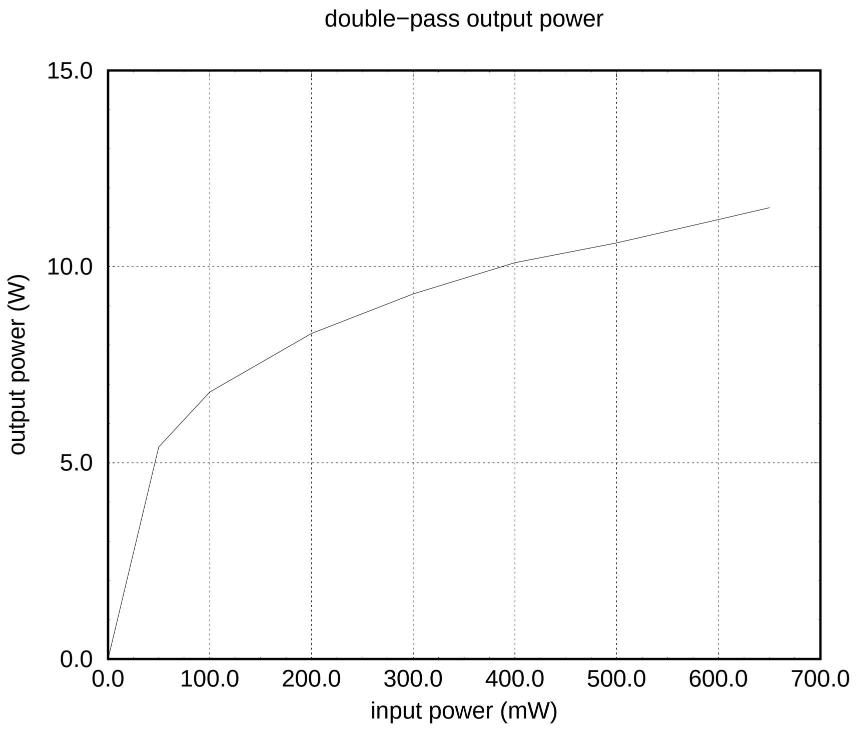

Figure 8: Output power of the LIGO 10-W Laser amplifier as a function of the input power.

The overall, low-frequency, open-loop gain of the PSL frequency stabilization servo is approximately 130 dB and the unity gain frequency is around 900 kHz. The crossover frequency between the SLOW and FAST actuators is 0.1 Hz and the crossover frequency between the FAST and EOM actuators is 12 kHz.

During development work, we used a frequency stabilization feedback control loop with comparable parameters to stabilize an NPRO master oscillator similar to that which is used in the LIGO 10-W laser. Measurements made at the servo error point (inside the loop) indicated that the frequency had been stabilized to below $10\,\mathrm{mHz}/\sqrt{\mathrm{Hz}}$ from a few hertz to 10 kHz. Later, measurements made using a frequency sensor outside the frequency stabilization loop confirmed that the laser frequency had been stabilized to below the required level.

In order to facilitate additional frequency stabilization by the two subsequent nested loops, the PSL provides two frequency actuators, the *Wideband* and *Tidal* inputs. Before being directed toward the reference cavity, a sample of the 10-W laser output double passes an acoustic-optic modulator (AOM) as shown in Figure 6. The AOM is driven by a voltage controlled oscillator (VCO) operating at a nominal frequency of 80 MHz with a range of ± 5 MHz. The light that reaches the reference cavity is thus shifted in frequency by 160 ± 10 MHz. The wideband input signal, derived from servo loops utilizing the 12-m mode-cleaner and the LIGO 4-km arm cavities as frequency sensors, thus controls the frequency of the PSL output light by varying the frequency of the signal that drives the AOM. A frequency shift thus induced in the light reaching the reference cavity results in an error signal in the PSL frequency stabilization control loop which is reduced by the action of the FAST, SLOW, and EOM actuators, thus offsetting the actual PSL output frequency to compensate for the frequency shift introduced in the light going to the reference cavity. The tidal actuator similarly utilizes the PSL frequency control loop actuators to make low frequency corrections to the absolute laser frequency by changing the length of the reference cavity via a thermal actuator.

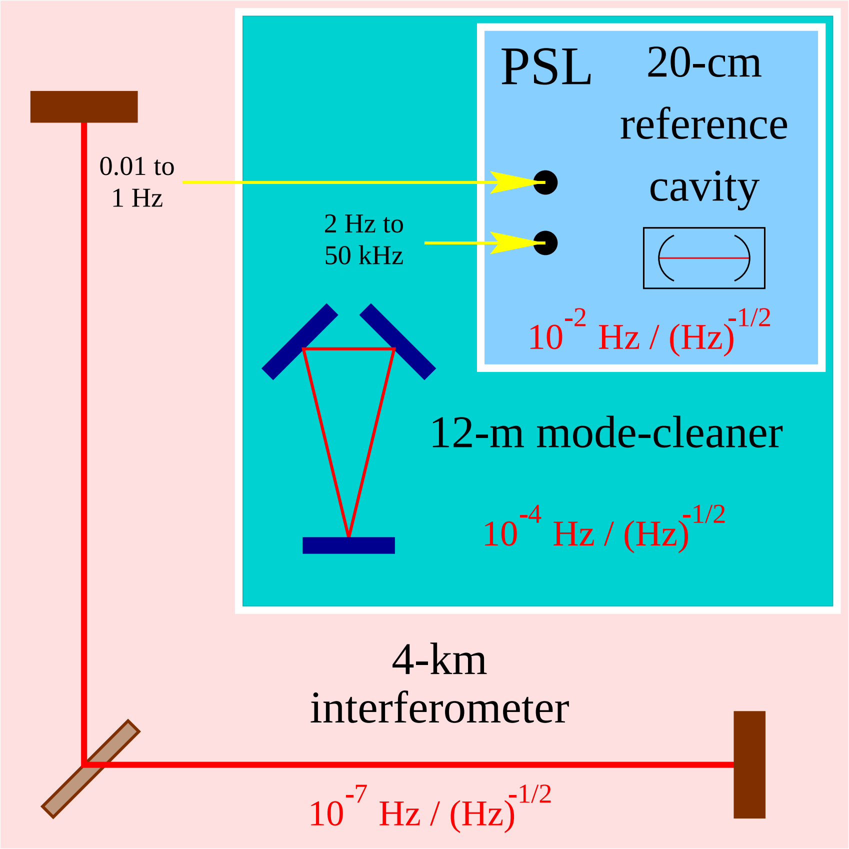

Figure 9: The PSL frequency stabilization strategy.

## 4 Power Stabilization

Another factor affecting the ultimate sensitivity of gravitational wave detectors is power fluctuations in the laser light. There are three related but distinct categories of requirements for the power stability of the PSL. First there is a requirement on low-frequency variations in the PSL output power. Second, allowed relative power fluctuations in the gravitational-wave band are severely constrained, and third, there is a stringent requirement on the shot-noise-limited power fluctuations at the modulation frequency for the sidebands used for gravitational wave detection. Each of the three categories of requirements is satisfied by a different control strategy.

### 4.1 Low Frequency Power Fluctuations

The low-frequency variations in the PSL output power are required to be less than 1 % peak-to-peak over any 24-hour period. Even if the LIGO 10-W Laser alone should meet this requirement, other factors may cause the output power of the PSL to drift by more than 1 %. The LIGO 10-W Laser has monitors for the output power of both the master oscillator and the amplifier output. The power will also be monitored at the output of the PSL and after the 12-m-long, triangular mode-cleaner. At low frequencies the LIGO 10-W Laser output power can be adjusted via two independent actuators. The master oscillator power can be adjusted via voltages applied to the master oscillator power adjust actuator, which varies the current to the pump laser diode. In addition, 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.

### 4.2 Fractional Light Power Fluctuations in the Gravitational-wave Band

The PSL is required to provide power-stabilized light to subsequent interferometer subsystems. The requirements for stabilization in the gravitational wave band are shown in Figure 4 and apply to both the carrier and the sidebands used for gravitational wave detection.

During development work the power adjust actuator of the master oscillator was utilized to stabilize the power fluctuations in the GW band. While power fluctuations were stabilized to the required level over most of the frequency band of interest, this was found to be unsatisfactory for two reasons: first, the internal relaxation oscillation suppression loop (the noise eater) conflicted with the power stabilization loop because they both use the same actuator, 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 thermally-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 the power fluctuations is the current to the laser diodes in the power amplifier.

### 4.3 Shot-noise-limited Power Fluctuations

The requirement for this category of fluctuations is that the amplitude spectral density of relative power fluctuations in the output beam of the PSL at frequencies above 24.5 MHz and 29.5 MHz (the modulation frequencies of the sidebands used for gravitational-wave detection for the 4-km and 2-km interferometers respectively), 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). Because the LIGO 10-W laser utilizes a 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

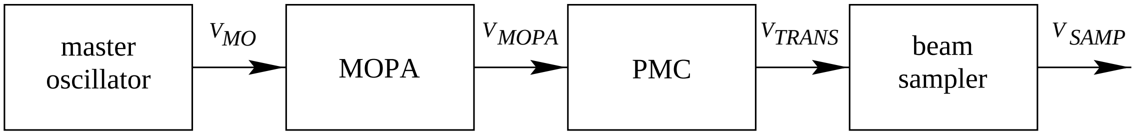

Figure 10: Flow diagram for the shot noise calculation.

the master oscillator.[2]

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

Here $V_{MOPA}$ 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[3]

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

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), $V_{SAMP} \sim V_{MO} + 2$. 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.

The filtering of the PSD of relative power fluctuations as a function of frequency by a Fabry-Perot cavity is given by

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

where $f_c$ is half the resonance bandwidth (FWHM) of the cavity. Combining the above equations according to the flow diagram in Figure 10, and solving for the cavity half-width yields

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

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, $\eta$.

---

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

[3] *ibid.*

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 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 master oscillator 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.

### 4.4 Pre-mode-cleaner Design

During the past year, 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.

Figure 11 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.

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 [2]. 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 (situated between the master oscillator and the power amplifier inside the 10-W laser head) signal. This technique has not yet been tested by the PSL group. Preliminary calculations using expected parameters indicate that the shot-noise-limited locking accuracy of the PMC will be approximately $7\,\text{MHz}/\sqrt{\text{Hz}}$. 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.

## 5 Schedule

Installation of a prototype PSL at the Hanford site is scheduled for April 1998. The prototype will be used during the initial shakedown stages of the interferometer. Final versions of the PSL will be installed at Hanford in November 1998, with installation at Livingston Parish the following January.

The first LIGO interferometer is scheduled to be fully operational by January 2000 with triple coincidence operation planned a year later.

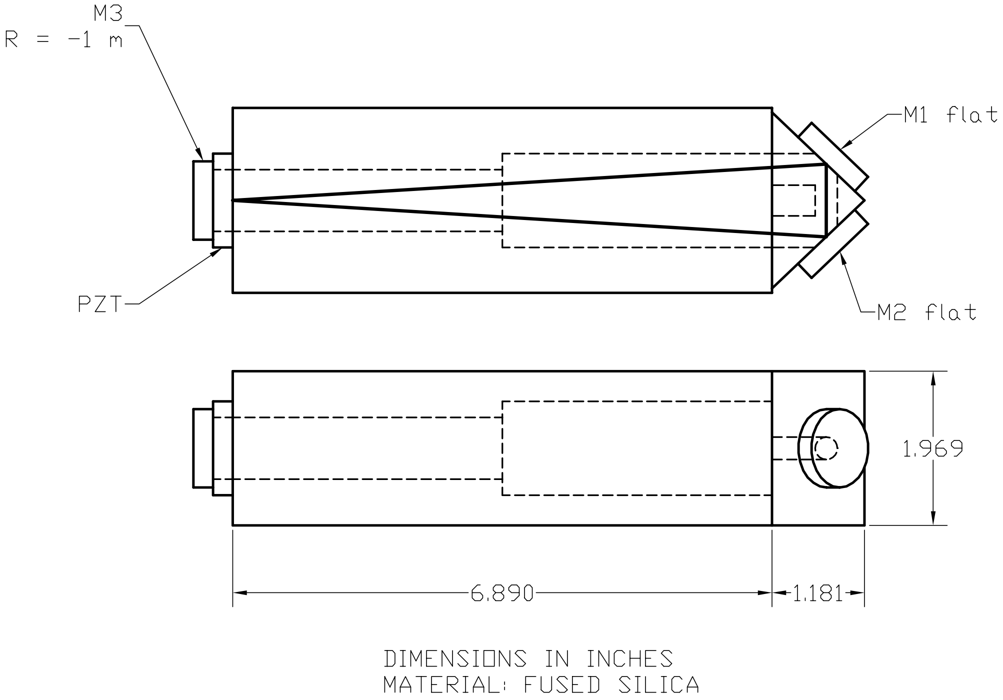

Figure 11: Mechanical drawing of the Stanford PMC.

# References

[1] Taylor, J. H. and Weisberg, J. M.
*Further Experimental Tests of Relativistic Gravity Using the Binary Pulsar PSR 1913 + 16*
*Astrophys. J.* **345**, 434—450, (1989).

[2] Drever, R. W. P. *et. al*
*Laser Phase and Frequency Stabilization Using an Optical Resonator*
*Appl. Phys.* **B31**, 97—105 (1983).