LIGO

LIGO laser intensity noise suppression

PSL

The Pre-Stabilized Laser (PSL) subsystem is the light source for the LIGO detector as shown in figure 1

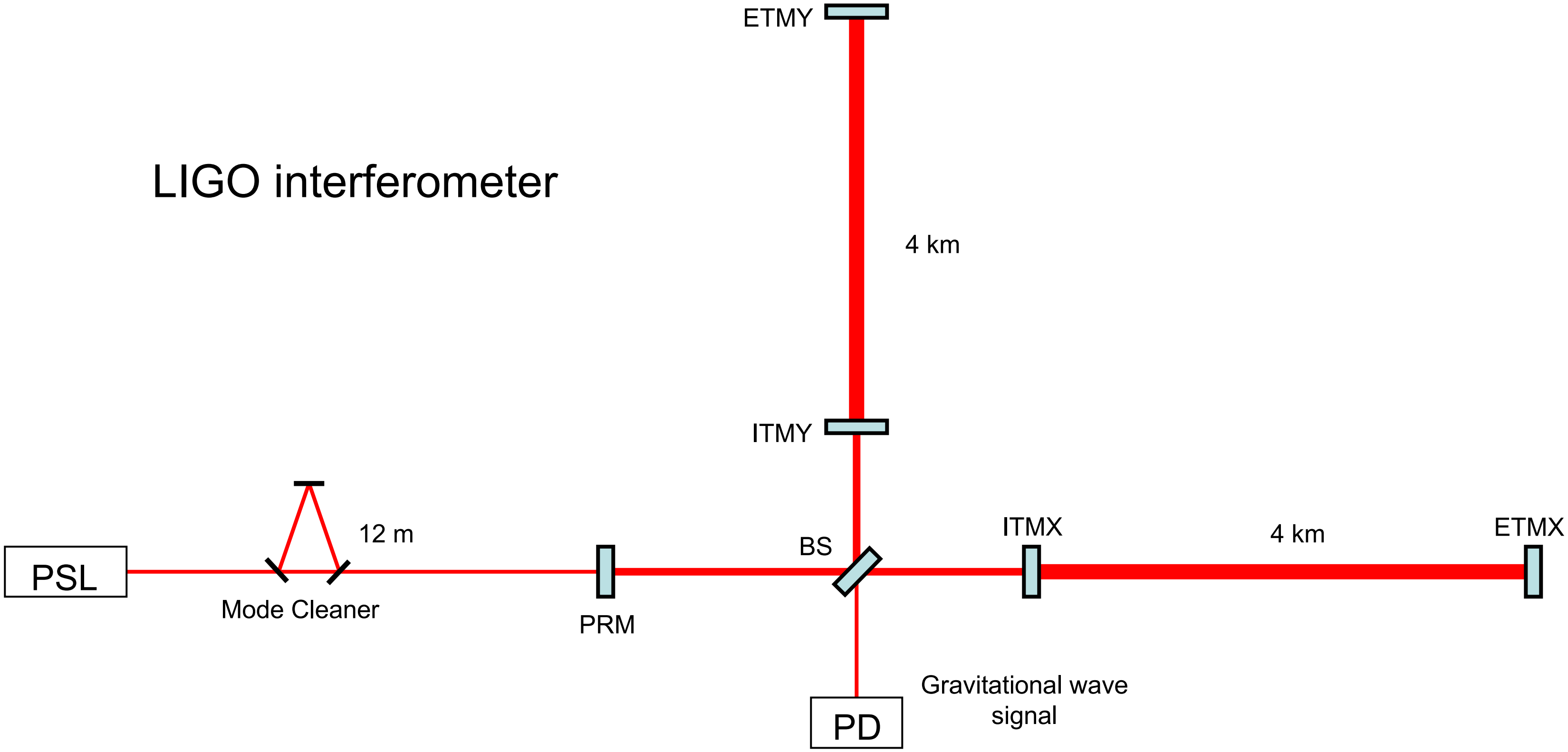


fig 1. LIGO interferometer

The output of the PSL is modematched into the suspended Mode Cleaner before being injected into the LIGO interferometer.

The term *pre-stabilized* is used because the light receives some frequency and amplitude stabilization prior to injection into the interferometer.

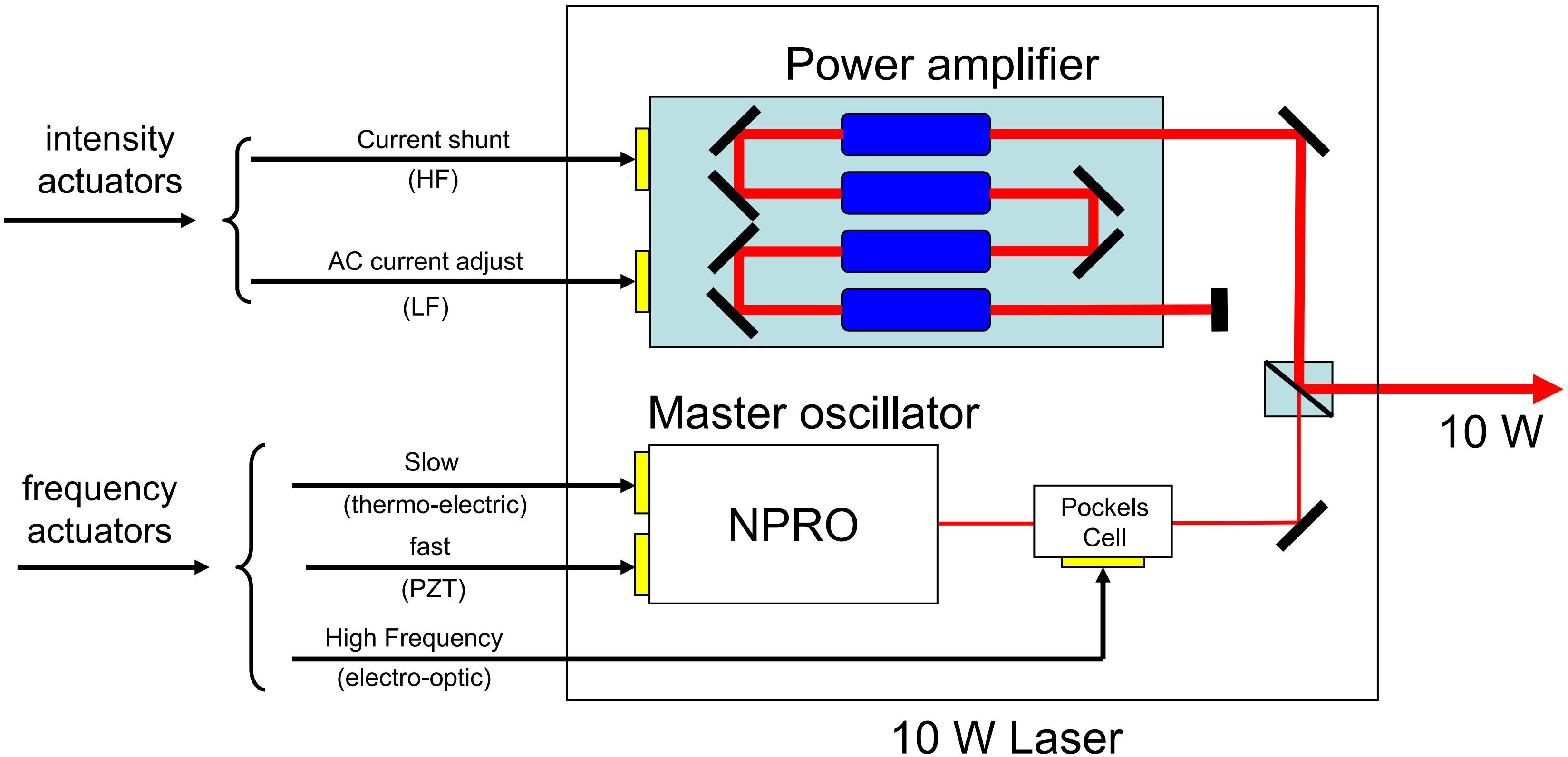
The PSL subsystem includes the LIGO 10 W laser, the Frequency Stabilization Servo (FSS) , the Intensity Stabilization Servo (ISS) and the Pre Mode Cleaner (PMC) servo electronics.

LASER

The LIGO laser is a master-oscillator-power-amplifier (MOPA) configuration developed by Lightwave Electronics Corp. under contract with the LIGO Project.

The laser output has an $M^2 \leq 1.1$ with 10-W cw in TEM_{00} mode.

The control strategy uses the actuators of the master oscillator in order to stabilize the frequency. Power stabilization is achieved by control of the power amplifier output.



10 W Laser

Intensity Servo

The Intensity Stabilization performance requirements are summarized below

Light Power Fluctuations in the GW Band

Photons in the laser light induce a source of noise in the interferometer known as radiation pressure noise. This noise arises from the momentum imparted to the mirrors as statistically different numbers of photons reflect off the mirrors in the interferometer.
To minimize the movement of the interferometer mirrors due to radiation pressure, the intensity fluctuations of the laser must be stabilized as specified in what follows.

The necessary noise (fluctuation) suppression varies with frequency as reported below

$$\frac{\delta P(f)}{P} < 10^{-8}\left(\frac{40\,\mathrm{Hz}}{f}\right) \quad 1/\sqrt{\mathrm{Hz}} \qquad \text{for} \quad f \le 40\,\mathrm{Hz}$$

$$\frac{\delta P(f)}{P} < 10^{-8} \qquad 1/\sqrt{\mathrm{Hz}} \quad \text{for} \quad 40\,\mathrm{Hz} \le f \le 100\,\mathrm{Hz}$$

$$\frac{\delta P(f)}{P} < 10^{-8}\left(\frac{f}{100\,\mathrm{Hz}}\right)^{1/2} \quad 1/\sqrt{\mathrm{Hz}} \quad \text{for} \quad f \ge 100\,\mathrm{Hz}$$

The topology of the intensity stabilization servo designed to meet these goals is shown in figure 3

Intensity Servo topology

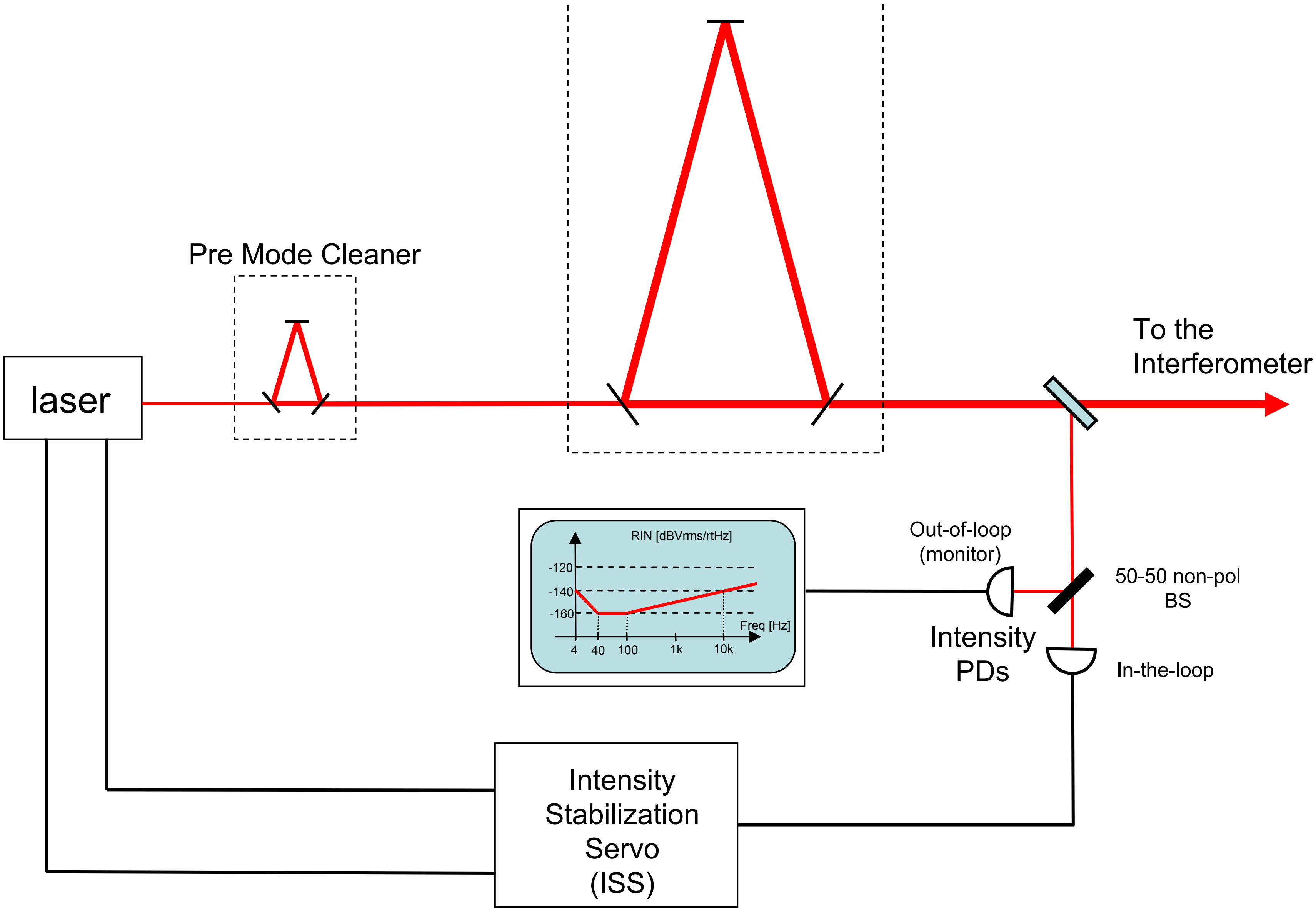


fig 3. Intensity stabilization scheme

A small fraction of the laser light directed towards the interferometer is sampled and split in two equal parts through a 50-50 non-polarized beam splitter. Each part then impinges on a custom designed photodetector.

One photodetector is utilized as an independent monitor and measures the actual level of noise suppression, the other provides the sensor input to the intensity servo electronics.

Sensor

The photodetectors utilized are GAP2000, large area (2 mm active diameter) InGaAs units (Responsivity $\mathcal{R} \approx 0.6$ at the frequency of interest).

The photodiode amplifier is a current-to voltage converter.
A 1 kΩ trans-impedance is chosen to be a reasonable compromise between the lower noise limited constraint and the upper power supply limited voltage.
The photodetector is reverse biased at 7 V to decrease the value of the parasitic capacitance associated with the photodiode.

The photodetector can be either AC or DC coupled to the rest of the servo.
We chose DC coupling due to the high electronics gain at DC complicating the long term robustness of the servo.
High gain AC coupled servos can have difficulty with the control of DC offsets and drift causing saturation.

The photodetectors are located on an optical table outside the vacuum environment.

A block diagram is shown in figure 4.

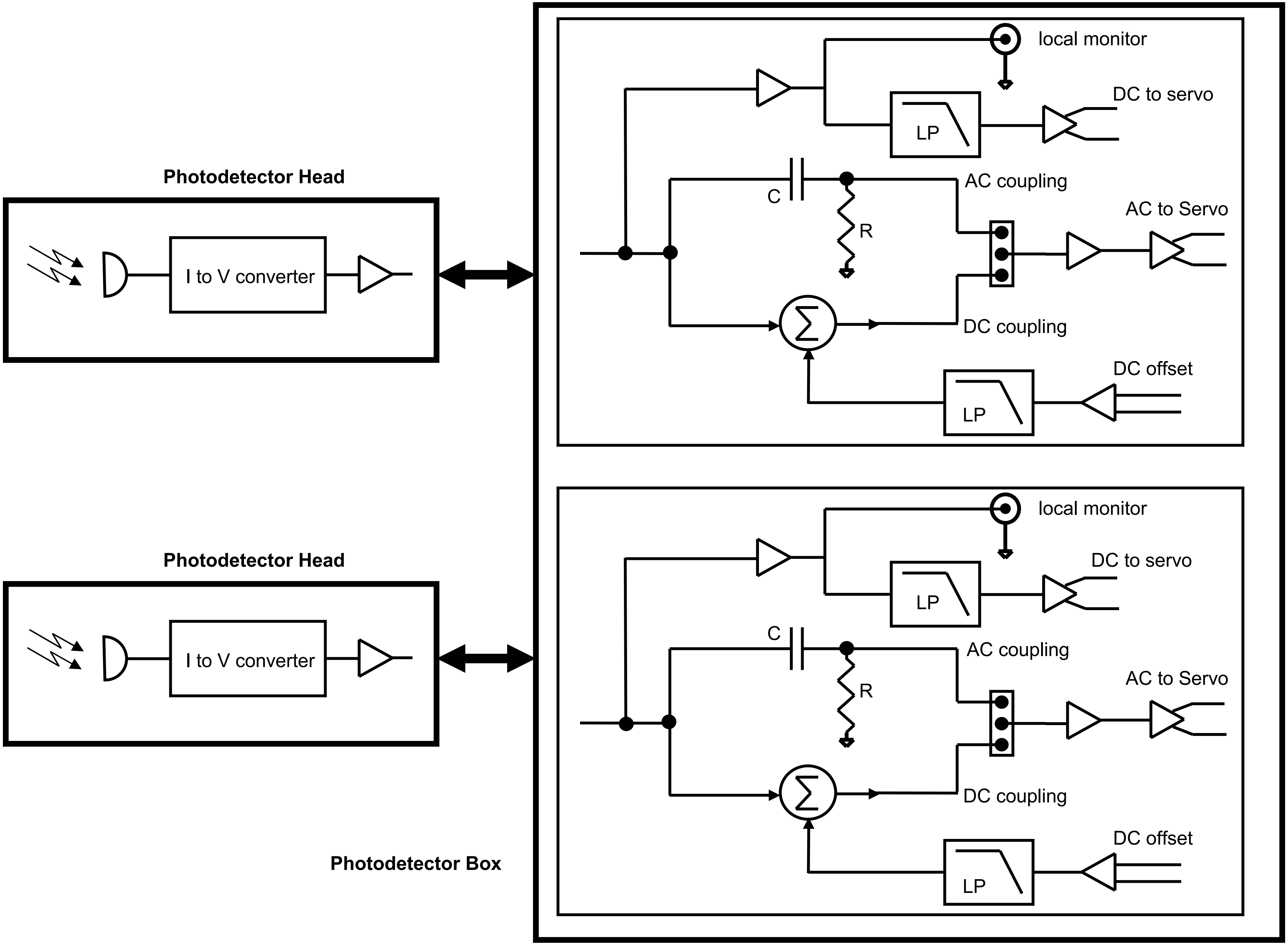


fig 4. Photodetectors heads and electronics

Actuators

The current shunt is used as the high frequency actuator in the ISS and the AC current adjust actuator is used for low frequency actuation. The AC current adjust actuator has about a factor of 10 more dynamic range than the current shunt and is used for relatively large, slow drifts.

The measured characteristics for both actuators are shown below.

The first one shows the transfer function of the **ac current adjust.** It clearly exhibits multiple poles at frequency below 100 kHz, making the design of a fast, high gain control servo based on this actuator extremely difficult.

If this actuator was used alone, it would necessitate direct current modulation of the 20 A diode power supply to achieve intensity stabilization.

To address this issue a second actuator, the **current shunt**, was designed and used.

As the name suggests, it shunts a small amount of current around the laser diodes, thus modulating the diode current.
It is placed in parallel to the power amplifier pump diodes and is biased at 250 mA quiescent current (see fig 5).

Regulation of a smaller current results in a better dynamic response than that exhibited by the ac current adjust actuator.

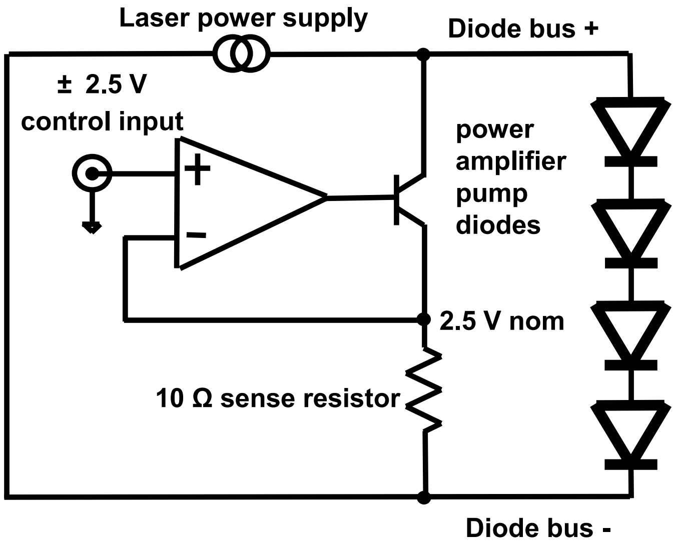
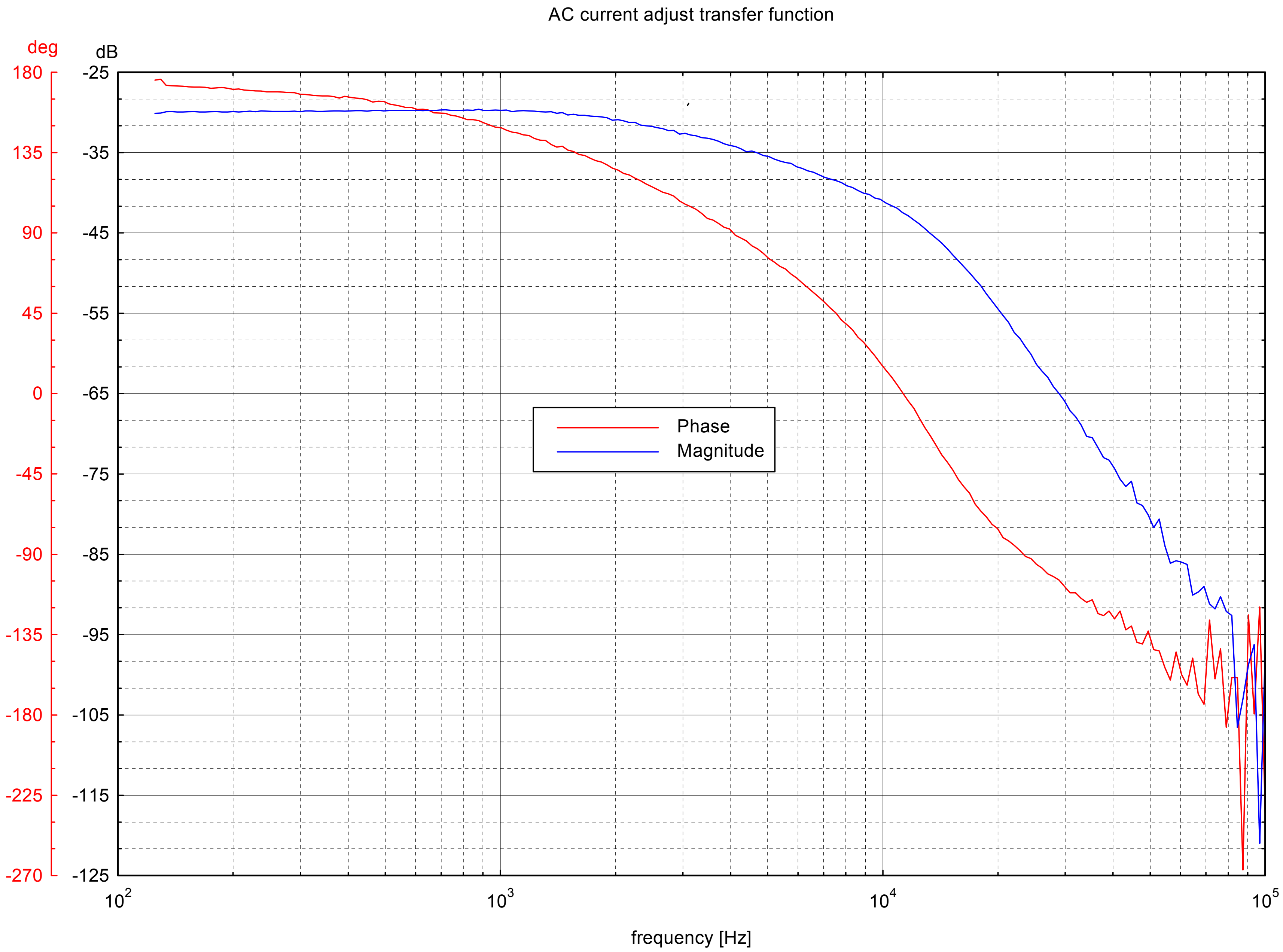
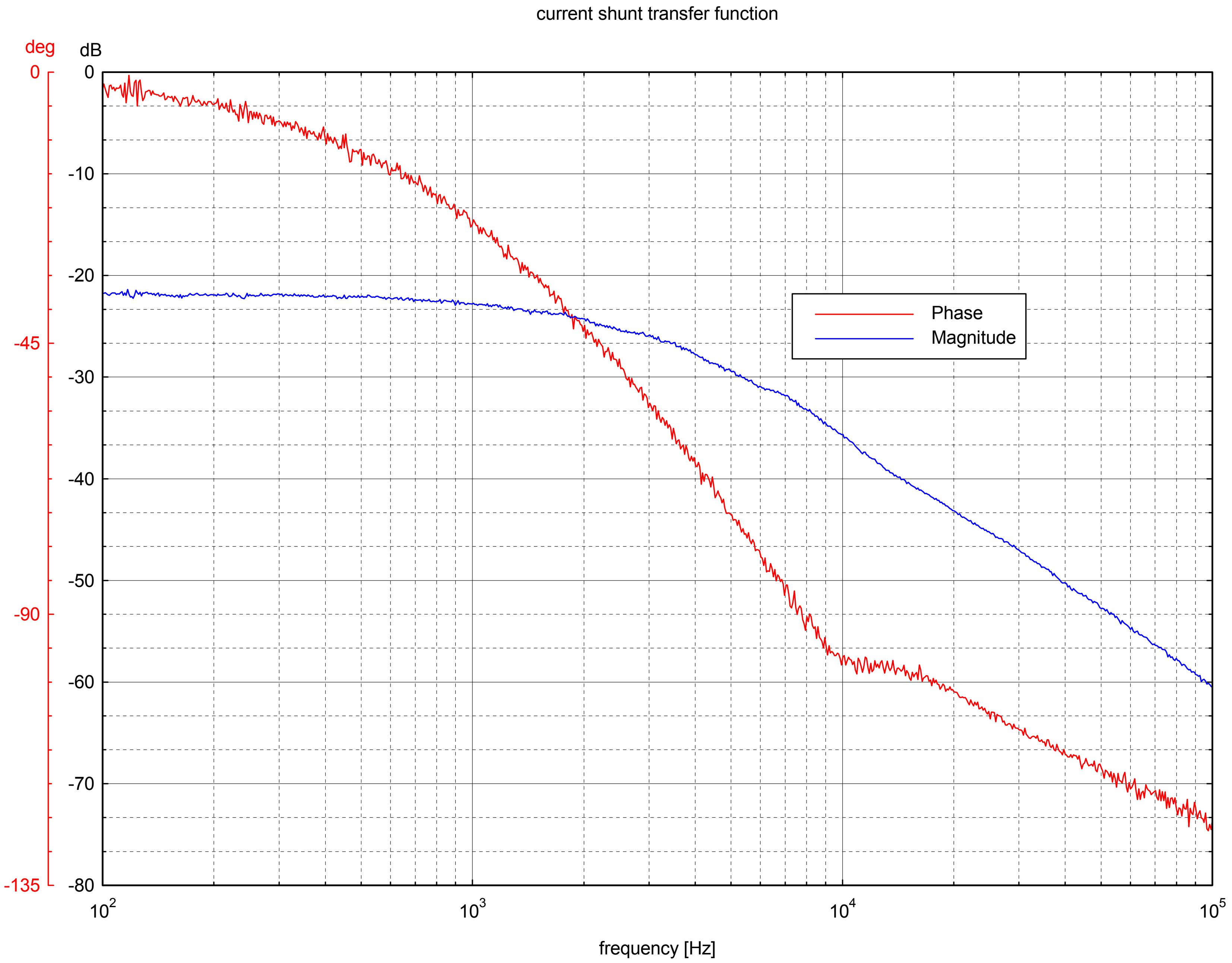


fig 5. current shunt actuator


AC current adjust transfer function
deg
dB
180
135
90
45
0
-45
-90
-135
-180
-225
-270
-25
-35
-45
-55
-65
-75
-85
-95
-105
-115
-125
10^2
10^3
10^4
10^5
frequency [Hz]
Phase
Magnitude


current shunt transfer function
deg
dB
0
-45
-90
-135
0
-10
-20
-30
-40
-50
-60
-70
-80
Phase
Magnitude
10^2
10^3
10^4
10^5
frequency [Hz]

Intensity Servo Board

The strategy adopted was to use the ac current adjust at low frequencies due to its higher dynamic range. This has the effect of maintaining the current shunt drive centered within its available dynamic range.

While designing the control loop for the ISS, a choice was made to cross over the AC current adjust actuator's gain profile with the current shunt actuator gain profile at about 100 Hz. This choice allows for a gain boost at low frequencies which helps in the critical 40 Hz to 100 Hz region. The overall open loop gain curve for the servo is a simplified locus of points that provides the necessary gain to reduce the free running laser intensity noise to the required level.

There are two significant frequency dependent features to the optical plant. The first is a pole at 4 kHz present in the mode-cleaner. In addition, there is a pseudo pole at approximately 2 kHz associated with the upper state lifetime delay in the NPRO pump laser.

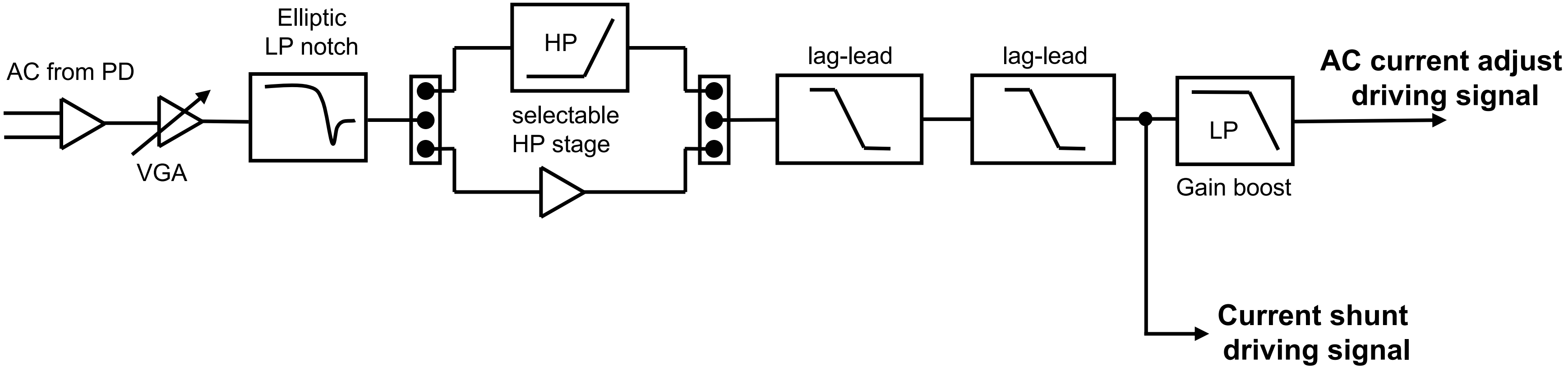


fig 6. Intensity Servo loop shaping electronics

The 4 kHz pole in the mode-cleaner is compensated by a (selectable) 4 kHz zero in the servo electronics. This initially caused saturation in the servo electronics due to amplification of electronics noise above 100 kHz. An inverse Chebychev filter has since been added to the servo electronics to filter this noise without causing excessive phase delay at the unity gain frequency of the servo. The results shown are expected to improve as the servo bandwidth is increased now that this high frequency electronics noise is reduced.

In the hundred-hertz region instead it is worth noticing how close to the required suppression the measured one is, especially considering that the shot-noise limit ($9 * 10^{-9} \quad 1/\sqrt{\mathrm{Hz}}$) was only slightly below the goal.

The presence of the structure is believed to depend upon acoustic coupling (the detectors are not located inside an acoustic enclosure) and possibly beam jitter.

These aspects are currently under investigation.

Post Mode Cleaner RIN @ LLO
06/26/03