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Enhanced LIGO TCS CO_2 Laser Intensity Servo Requirements

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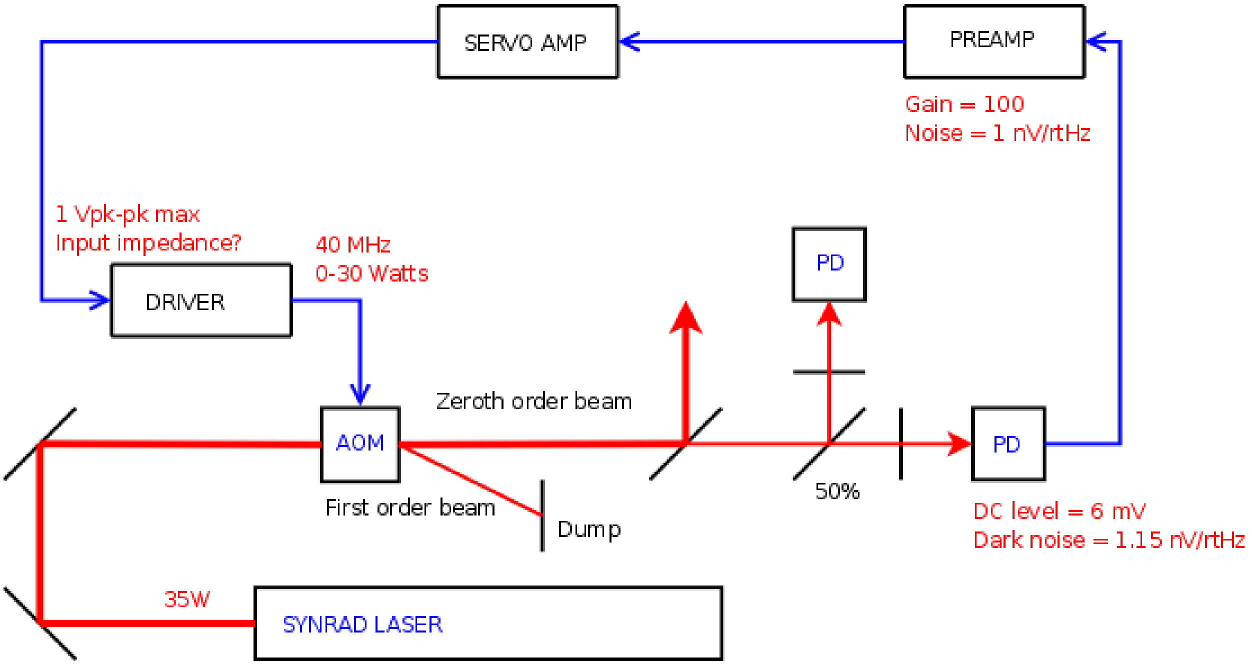

Figure 1: Block diagram of the intensity stabilization servo

1 Introduction

Enhanced LIGO's [2] increased laser power is expected to entail a requirement for increased power [8] from the thermal compensation system (TCS, [4]). At this increased TCS power, thermoacoustic noise from the CO_2 laser is expected to become significant unless measures are taken to stabilize the intensity of CO_2 lasers used for TCS. This document describes requirements for an intensity stabilization servo designed to reduce the thermoacoustic noise to an acceptable level.

The servo operates by dumping excess power via an acousto-optic modulator (AOM). A pick-off of the main CO_2 laser beam (having already passed through the AOM) is directed to a photodiode which provides a measurement of the current intensity of the light. This signal is amplified and filtered and fed back to the AOM.

A block diagram of this scheme is shown in figure 1; the proposed optical table layout is shown in figure 2.

1.1 Estimated TCS power requirement for Enhanced LIGO

The required TCS power may be computed from:

- The absorption of the ITM optics

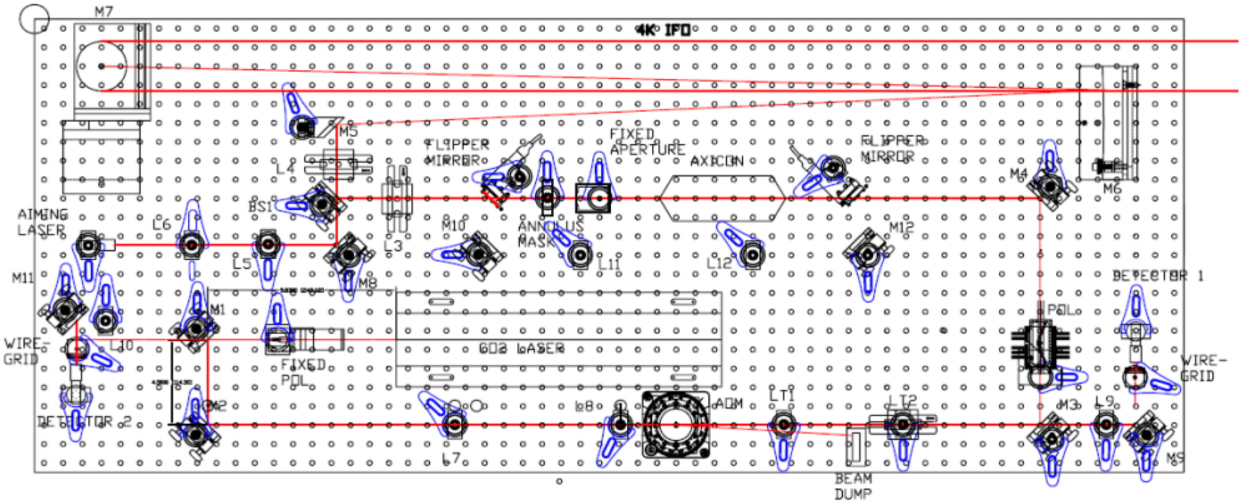

Figure 2: Table layout

- The power in the cavity
- Annular versus central heating factor. (Approximately 11 watts of annular CO_2 power is needed to compensate for every watt absorbed centrally in the substrate.)

The absorption of the test masses has been measured by tracking the frequencies of thermal resonances, as described in [8] and excerpted in Figure 3. These measurements give an estimated absorption of 7 ± 5 ppm for all optics. (These measurements will be repeated using an improved technique during the S5 post-run investigations period.

The circulating power in initial LIGO's final science run was 25 kW for H1 and 17 kW for L1 [5]. Multiplying these by 4, we find approximately 100 kW and 68 kW for the stored power in H1 and L1, respectively, during Enhanced LIGO.

IFO	Optic	YAG absorption	Cavity power	Absorbed power	Annular power req.
H1	ITMX	7 ± 5 ppm	100 kW	700 ± 500 mW	7.7 ± 5.5 W annular
H1	ITMY		100 kW		
H1	ETMX		100 kW		N/A
H1	ETMY		100 kW		N/A
L1	ITMX		68 kW	476 ± 340 mW	5.23 ± 3.74 W annular
L1	ITMY		68 kW		
L1	ETMX		68 kW		N/A
L1	ETMY		68 kW		N/A

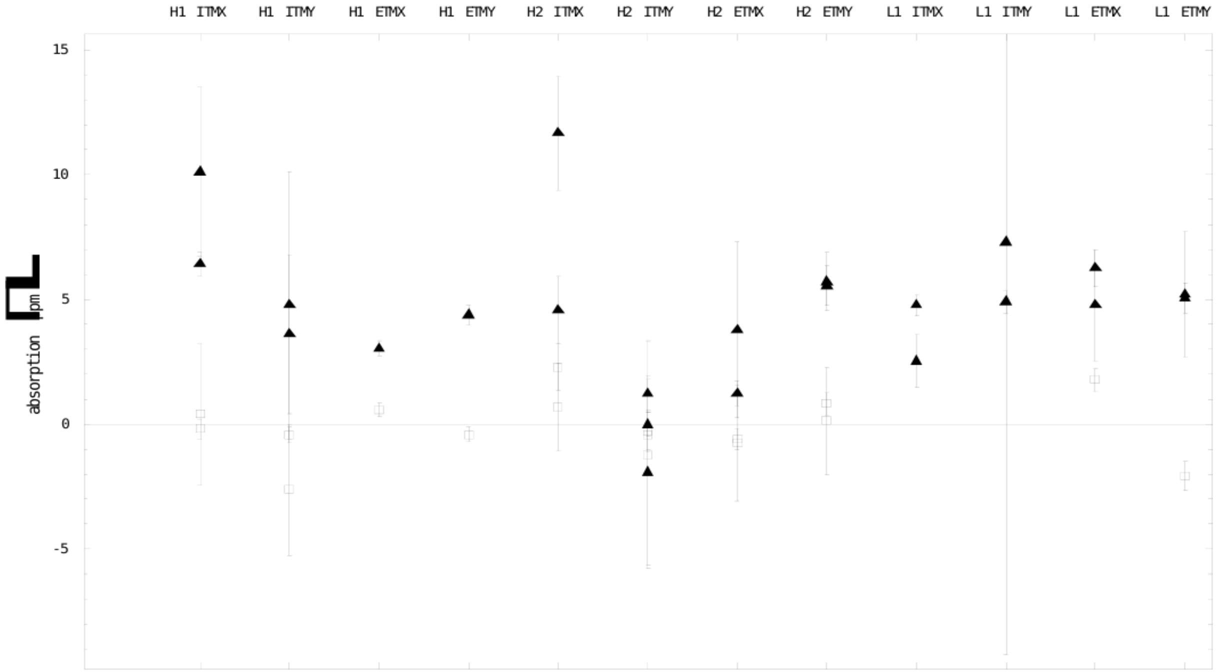

Figure 3: Results of absorption measurements using thermal line tracking (from [8]). The triangles represent measurements of absorption; the empty squares are control measurements which should be consistent with zero.

1.2 TCS laser intensity noise requirements

The coupling of TCS laser noise to displacement noise (see equations 2.45 and 2.46 in [3]) in the interferometer due to the thermoelastic effect is given by

$$n(f) = \frac{\alpha P}{f} RIN \tag{1}$$

where P is the average TCS power (in watts) absorbed in the optic, f is the frequency of interest, RIN is the relative intensity noise (in 1/sqrt[Hz]) of the TCS laser, and where

$$\alpha = \begin{cases} 1.5 \times 10^{-11} m\ Hz/W & \text{central heating} \\ 2.1 \times 10^{-12} m\ Hz/W & \text{annular heating} \end{cases} \tag{2}$$

These relations can be used to turn the Enhanced reference noise curve [1] into a requirement on the relative intensity noise of the TCS lasers. Figure 4(A) shows the maximum TCS RIN allowed, assuming 7.7 watts of CO_2 power applied annularly, subject to the criterion that the thermoelastic noise must be less than one-tenth the Enhanced LIGO reference noise curve. Conversely, the expected noise contribution of TCS due to the thermoelastic effect is shown Figure 4(B), again assuming 7.7 watts CO_2 power applied annularly.

As seen in the figure, the requirement on TCS laser RIN is most stringent in the band $40 - 300$Hz, in which the TCS laser RIN must be below 8×10^{-8} $\mathrm{Hz}^{-1/2}$.

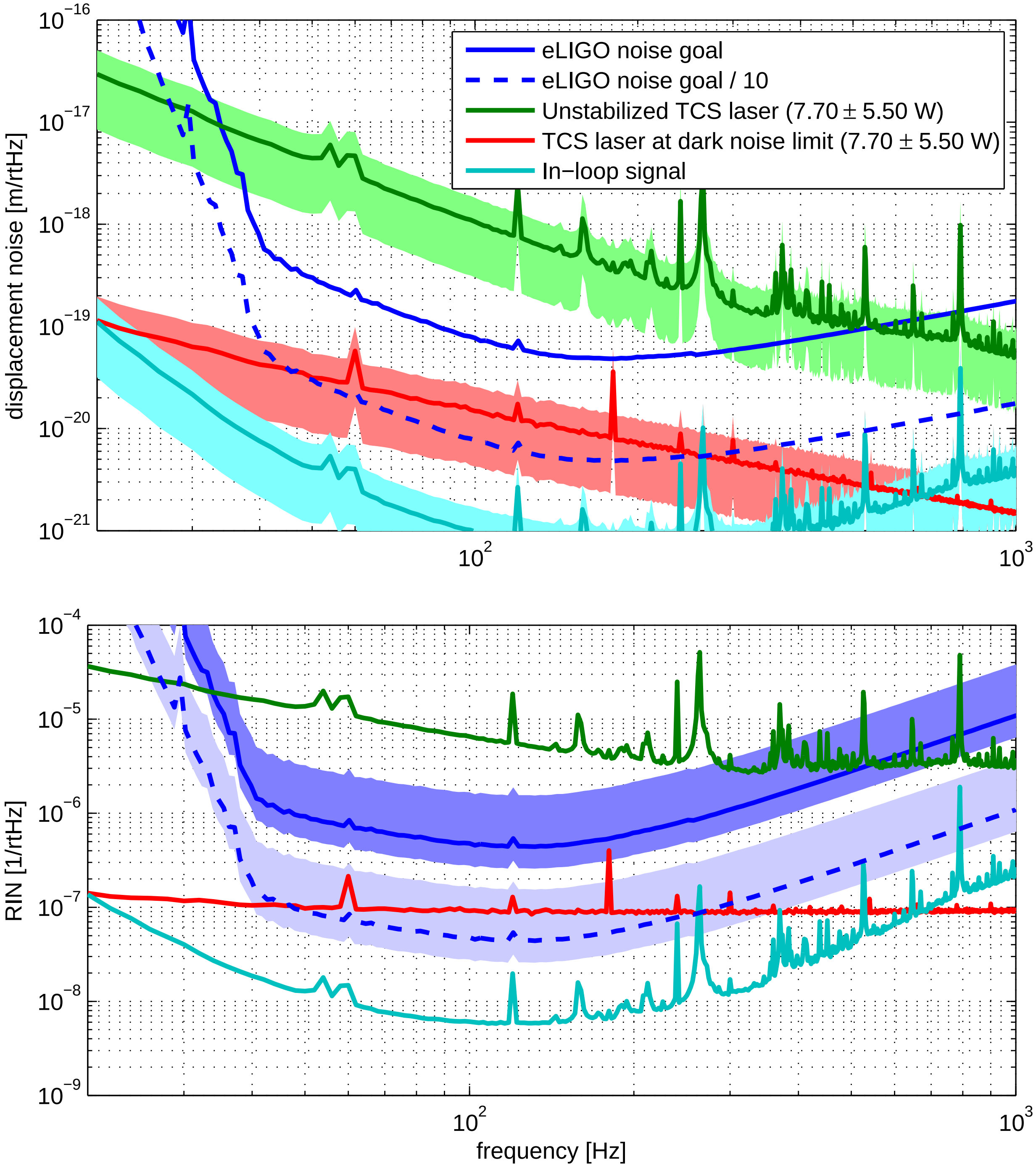

Figure 4: (A) S6 noise goal with TCS thermoelastic noise superimposed; (B) Same data as in (a) but in units of RIN.

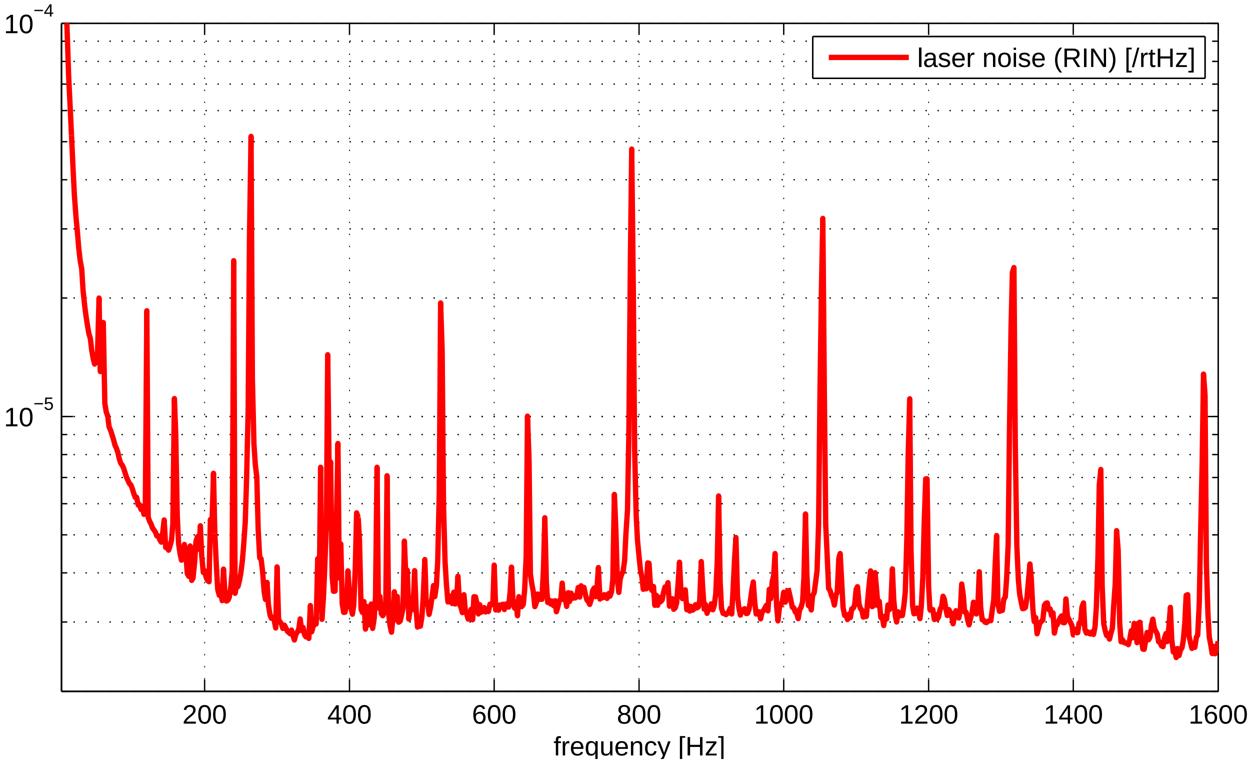

Figure 5: RIN of unstabilized laser

2 Components

AOM	IntraAction	AGM – 406B1
AOM Driver	IntraAction	GE – 4030
Laser	Synrad	J48 – 2W
PD	Boston Electronics / VIGO	PVM – 10.6
Preamp	“Rai’s Low Noise Pre-Amp”	D060205

2.1 Laser

The laser currently under investigation is the Synrad J48-2W, which produces 35 watts of 10.6μm radiation. The measured intensity noise of this laser without any intensity stabilization is shown in Figure 5.

2.2 Photodiode

The photodiode in use is a HgCdTe diode selected by Rai Weiss[7], manufactured by VIGO System S.A. in Warsaw, Poland and purchased through Boston Electronics. At saturation, the diode is expected to have a DC signal of approximately 10 mV. (The dark noise curve in Figs 1 and 2 was taken with a DC level of 7 mV from the diode.) The dark noise of the diode is about 1.1 nV/rtHz, corresponding to a RIN of 1.1×10^{-7}/rtHz at 10mV.

2.3 Preamp

The preamp is a variant of "Rai's Low Noise Preamp," which utilizes an LT1128 low-noise opamp preceeded by an Interfet IF3602 ulta-low-noise dual FET stage. Currently 1.5 nV/rtHz is achieved, but better performance should be possible. 0.7 nV/rtHz is expected.

2.4 Servo amplifier

2.4.1 Design

To push the noise spectrum below one-half of the sensor noise we need a suppression of 200. This can be provided by a servo with the following (open loop) parameters:

poles	40, 100^4, 250 Hz
zeros	0^2, 7, 1500 Hz
UGF	1 and 8902 Hz
Phase Margin	61 degrees

An open-loop bode plot is shown in Figure 6; a closed loop plot is shown in Figure 7. These plots include the phase delay due to the AOM.

2.4.2 Implementation

The proposed servo board is a filter board developed by Nick Smith and Thomas Corbitt at MIT for use on a ponderomotive squeezing experiment there[6]. The board provides four channels. Each channel consists of a differential input received through a BNC connector, an AD829 acting as an inverting differential receiver, an AD600/602 variable gain amplifier, an AD829 inverting gain stage, four AD829 filter stages, an ADG333 switch, and finally an AD829 inverting gain stage. The output is through a D-sub connector.

The AD600 produces a maximum amplitude output of 2.5 volts, with 1.4 nV/rtHz input-referred noise. Its maximum input amplitude is one volt.

The board requires a bipolar 24 volt power supply.

Figure shows an integrated RMS amplitude of the control signal of about 2 mV, assuming

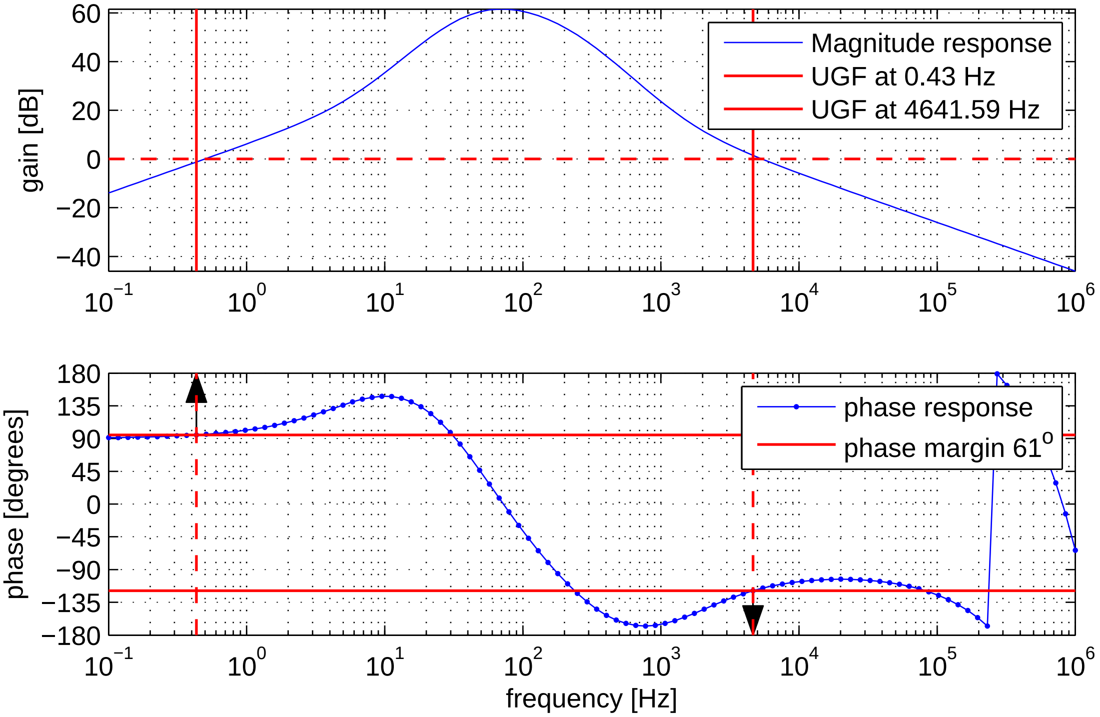

Figure 6: Open loop transfer function of proposed servo loop

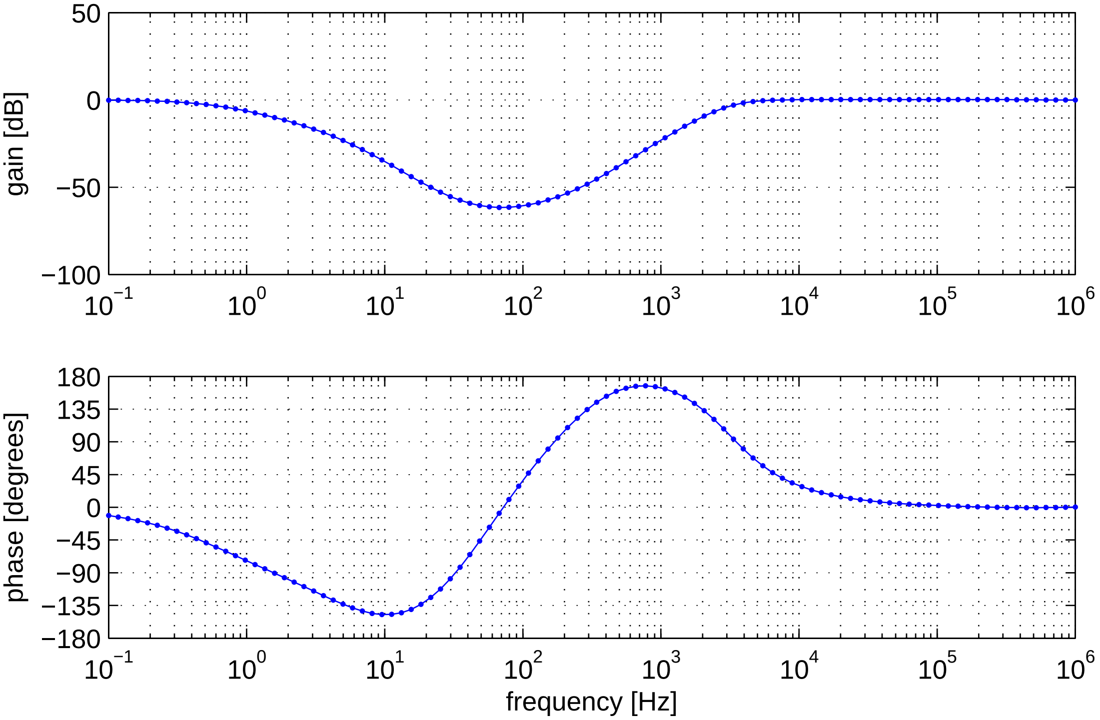

Figure 7: Closed loop transfer function of proposed servo loop

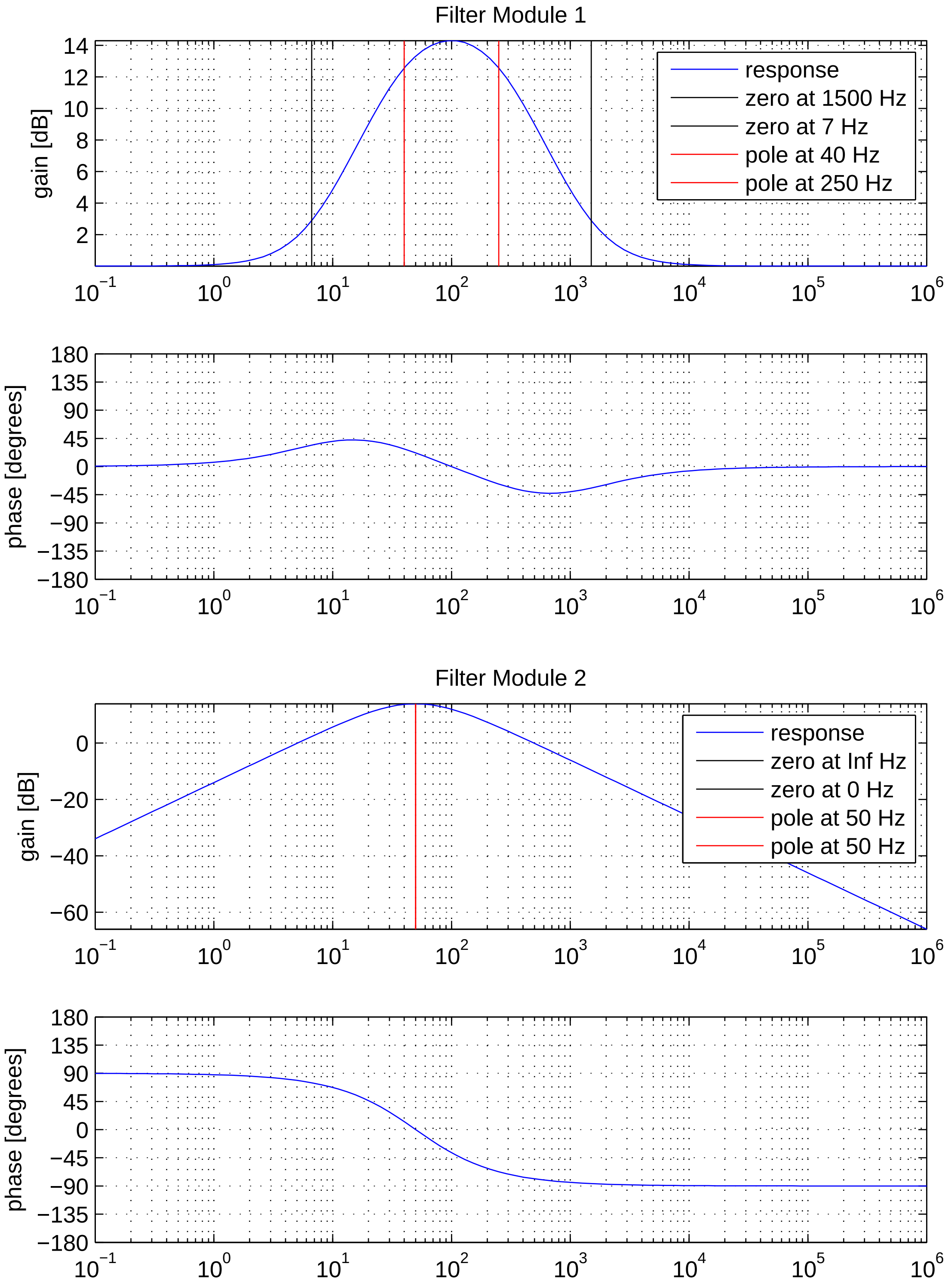

Figure 8: Filter modules for proposed servo amplifier

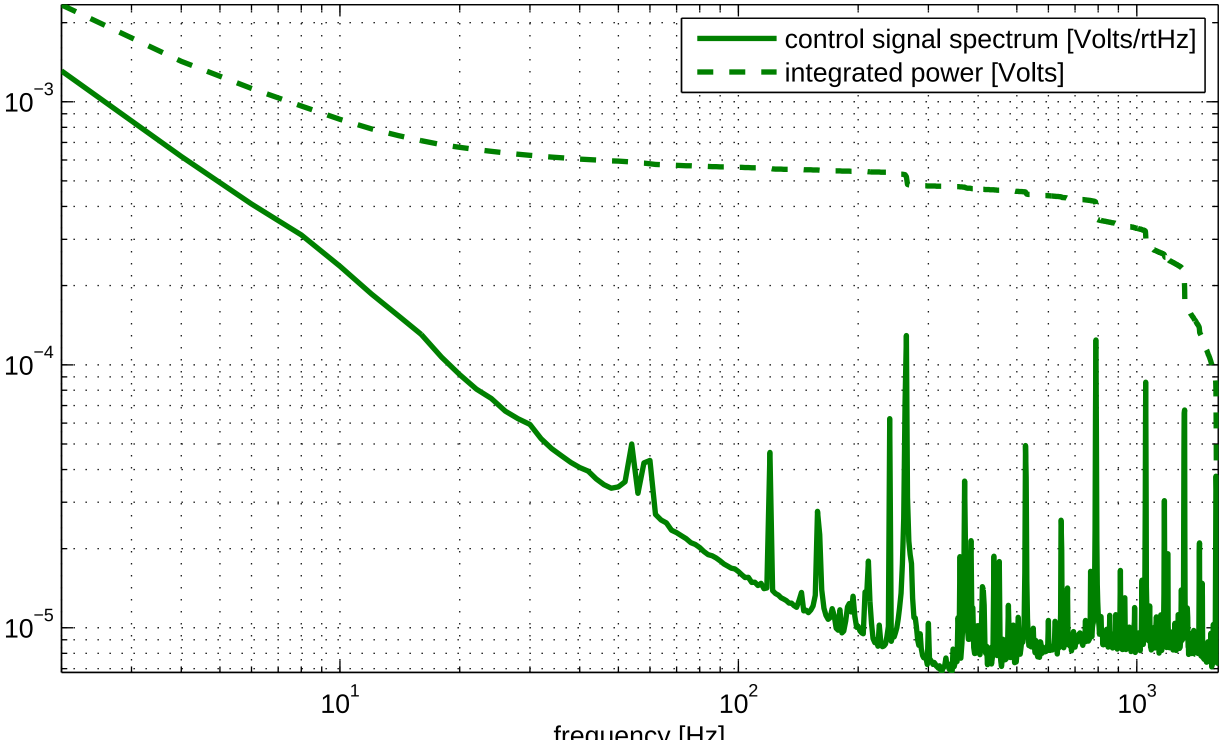

Figure 9: Spectrum of control signal

an operating point of 100 mV for the AOM.

2.5 AOM

The AOM driver nominally takes a $0 - 1$ volt input signal. There is also a DC offset adjustment on the driver. In practice the DC offset will be adjusted to set the operating point of the AOM.

The measured AOM transmissivity and calculated responsivity are shown in figures 10 and 11, respectively. The AOM utilizes a germanium crystal in which the speed of sound is 5400 m/s. The phase lag due to the AOM, assuming that the beam is located 5mm from the transducer, is given in Figure 12.

3 Cooling requirements

The Synrad J48-2W laser's datasheet specifies a max heat load of 500 watts for the J48-2 laser. They also specify a coolant flow rate requirement of 0.8 GPM at 18-22 degrees Celsius and an electrical draw of 14 amps at 30 volts DC (420 watts).

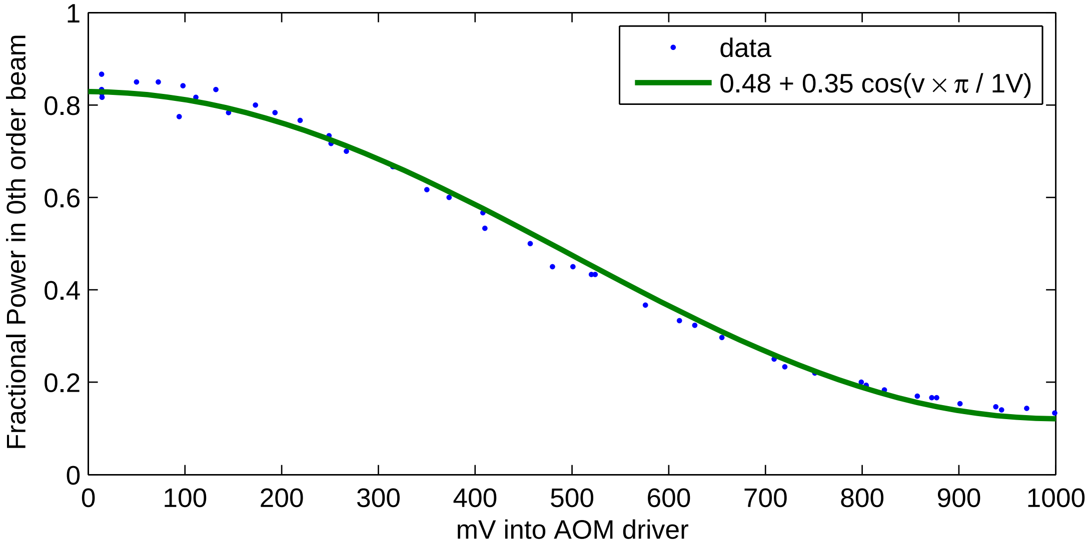

Figure 10: AOM transmissivity

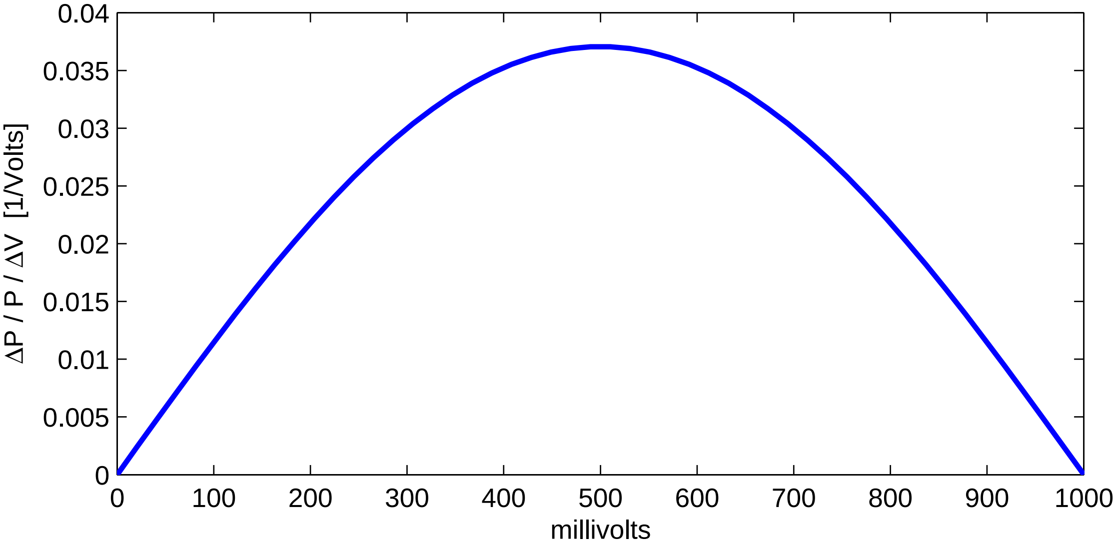

Figure 11: AOM responsivity

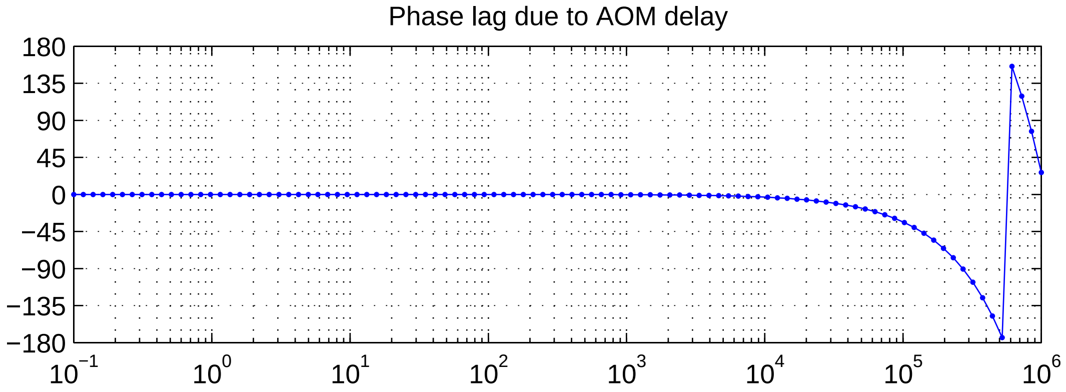

Figure 12: AOM phase lag

There is also the AOM. Its datasheet specifies a coolant flow of 500 ml/min at 20°C. It dissipates a maximum of 30 watts RF drive plus 12% (specified) optical insertion loss, which is 4 watts for a 35 watt input beam.

The chiller in the TCS lab right now is a PolyScience Recirculator model 6206P. The datasheet says it can provide 800 watts cooling capacity at 20°C.

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