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Filter Cavity Preliminary Interferometer Sensing Design

L. McCuller, L. Barsotti

Distribution of this document:

LVC

California Institute of Technology
LIGO Project, MS 18-34
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project, Room NW17-161
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
Route 10, Mile Marker 2
Richland, WA 99352
Phone (509) 372-8106
Fax (509) 372-8137
E-mail: info@ligo.caltech.edu

LIGO Livingston Observatory
19100 LIGO Lane
Livingston, LA 70754
Phone (225) 686-3100
Fax (225) 686-7189
E-mail: info@ligo.caltech.edu

http://www.ligo.caltech.edu/

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1 Overview

The control scheme for the filter cavity has a principle requirement to both lower the RMS motion of the cavity sufficiently to not degrade squeezing, while not injecting sensing noise as a length noise that will overly imprint on backscatter. The requirements are outlined in section 8 of T1800447. That document outline a control loop which should function, but leaves open the sensing scheme.

This document outlines the sensing scheme. It is designed around meeting the phase noise requirement $1{\cdot}10^{-6}/\sqrt{\mathrm{Hz}}$ on any sensing field used to infer the length stability of the filter cavity. The challenge of this requirement is that any fields cannot be transported from the the in-air squeezer table without degrading their phase noise. Furthermore, the only absolute opitcal phase reference can meet that noise limit is the IMC and IFO. Using these as references requires them to be stably propagated to the squeezer or vice -versa.

Fortunately, the squeezer is already phase locked to the IFO output beam to maintain the squeeze ellipse angle (the LO / SQZANGLE loop). The following scheme transfers the phase stability of the existing CLF (coherent locking) field to a new "RLF" (resonant locking) field at a filter cavity FSR multiple from the IFO carrier (plus tuning). The resonance in the cavity allows length sensing. To transfer the carrier, CLF and RLF fields between frequencies, phase stable oscillator sources must be used. The filter cavity requires a tunable frequency shift to optimize the cavity rotation angle, and so the VCOs used must itself be sufficiently phase stable (a requirement that most VCO's with a pullability $> 1{\cdot}10^{-4}$ do not immediately meet).

A checklist of considerations for the filter cavity which must be answered by this document are below:

- How does the CLF field and LO lock transfer phase stability to the RLF?
- How is lock acquired in 532?
- how is the filter cavity alignment sensed and how stable is required.
- How are phases established (what procedure)?
- How much noise will arise from RF offsets from intermodulation fields and from OPO sideband images?

A set of items requiring study are below:

- How much worse is AOM seeding when operating at low diffraction efficiency and with multiple beam frequencies?
- How stable is the 2 AOM scheme in phase such that the CLFPD beatnote sensing is not required?
- How much relative phase noise is imprinted between the CLF and RLF due to the OPO?

2 1064 Cavity Length Sensing

The current squeezing phase lock scheme uses two AOMs to generate a clean single upper sideband (the CLF) over the interferometer carrier frequency. This single frequency is injected into the squeezer OPO cavity to monitor both the frequency of the OPO pump light, as well as the phase shifts between the OPO and the OMCPD readout.

The introduction of the filter cavity requires some resonant 1064 light in the cavity to sense its length. The RLF scheme of this document proposes to multiplex the frequencies generated by the squeezer AOMs to generate an additional resonant upper sideband (the RLF) in addition to the CLF already generated.

The filter cavity requirements impose a limit to the optical phase noise allowable on the RLF frequency, and so its generation must ensure meeting that requirement. The interferometer light is the only convenient optical source meeting the phase noise requirement, and can only be transported within the vacuum envelope to preserve the phase stability. The CLF field is stabilized to the IFO light using the LO loop, which ensures the that CLF field in the vacuum envelop can be stabilized to the IFO level, assuming sufficient control gain and sensing noise levels. The key point is that as long as the RLF is generated such that it gets identical modulations as the CLF, the CLF phase noise will be representative of the RLF phase noise. Sec. **??** investigates the current performance and requirements of the squeezer loops.

The RLF is generated to ensure identical noise to the CLF by generating it co-propagating with the CLF at all points. The AOM pair generates the CLF at 3.125MHz by first shifting up by 203.125MHz, then shifting down by 200MHz. To add the RLF, the second AOM additionally shifts down by 200.105MHz. Either AOM can in in principle be used to generate the second frequency, but the first AOM (203.125MHz) is operated in a feedback look which removes optical noise and the 203MHz VCO phase noise from the CLF sideband. The CLF loop must also act on the RLF to ensure all common noises between the fields as of the OMCPD LO-loop sensing point. The sec 10 performs a more in-depth analysis of the loops to indicate that the noise is removed.

The primary catch in generating the RLF such that it shares phase noise with the CLF is that the VCO's used to generate and sense from it must be sufficiently phase stable. This means that the master oscillators generating the frequencies in table 2 must all either meet the phase noise requirements, or be stabilized against sums/differences of frequencies which do.

Fig 1 shows the 2 AOM driving scheme. The RLF frequency must be adjustable for commissioning and tuning the squeezer rotation to match the interferometer, this requires the 200.105MHz AOM driver to be a VCO, which in turn ruins its phase noise performance. This is corrected by stabilizing it to the 200MHz oscillator using a PLL with the phase-stable 105kHz. The noise of the 200MHz oscillator is removed by the combination of CLF and LO loops.

One issue with the 2-AOM RF generation is intermodulation the drives from the saturated operation of the acousto-optic crystal at large drive amplitudes. This is studied in 3.2, and the diagram indicates to operate the 200/200.1MHz AOM below maximum drive efficiency to reduce relative strength of intermodulation product. At this more linear operating point, a variable attenuator may be attached to perform power stabilization of the CLF beam, to reduce intensity noise suspected in the OMCPDs at higher operating power (see sec. 6).

2.1 RLF Scheme Optical Overview

2.2 RLF Scheme Frequencies

:

Frequency	Usage	Reasoning
3.125 MHz	CLF Optical Upper Sideband	various, but could move
200 MHz	CLF AOM Generation (-)	Stable Oscillator
203.125 MHz±1kHz	CLF AOM Generation (+)	Locked by “CLF” loop
503.260 kHz		Filter Cavity FSR (297.85m)
3.019564 Hz±100Hz	RLF Optical Upper Sideband	6x FC FSR + FC tuning
105.435 kHz	FC Signals demod	CLF - RLF optical beatnote
200.106 MHz±1kHz	RLF AOM Generation (-)	Locked by “RLF” loop
3.230 MHz	OMCPD Noise image	3.125MHz + 105kHz

Table 1: Table of used frequencies

2.3 Phase Noise requirement

2.4 Sensing Noise requirements

CLF/RLF power levels LLO is currently using 10uW CLF incident on the OPO, with 4% transmitting through the OPO while it is on resonance (ignoring NLG). With 1% Transmission through the OMC at 3MHz LHO47518, this corresponds to 4nW of the CLF sideband the OMCPDs, sensed against the carrier for a (heterodyne) phase sensitivity to the CLF beam of

$$6.8{\cdot}10^{-6}\frac{\mathrm{Rad}}{\sqrt{\mathrm{Hz}}} = \sqrt{\frac{E_\lambda}{4{\cdot}10^{-9}\mathrm{W}}} = \sqrt{\frac{E_\lambda}{10{\cdot}10^{-6}\mathrm{W}\cdot 4\%\cdot 1\%}} \tag{1}$$

Which is far from sufficient. With

$$9.6{\cdot}10^{-7}\frac{\mathrm{Rad}}{\sqrt{\mathrm{Hz}}} = \sqrt{\frac{E_\lambda}{200{\cdot}10^{-9}\mathrm{W}}} = \sqrt{\frac{E_\lambda}{500{\cdot}10^{-6}\mathrm{W}\cdot 4\%\cdot 1\%}} \tag{2}$$

With some margin provided by the squeezing improvement to the sensitivity (if shot-noise limited in the beatnote). Including the RLF in this sensitivity budget indicates that approximately 1mW must be incident on the OPO, considerably more than currently used.

Seeding and Backscatter

CLF/RLF Intensity Noise The SQZ laser is currently not intensity stabilized, but should be at these power levels. With a laser intensity noise of $1{\cdot}10^{-5}\frac{1}{\sqrt{\mathrm{Hz}}}$, the OMCPDs are operated at 20mW, giving a power dilution

$$D = \frac{20\mathrm{mW}}{200\mathrm{nW}} = 1{\cdot}10^{5} \tag{3}$$

And the quantum limited sensitivity of the OMCPDs (squeezing improved) is

$$M = \frac{Q_{\lambda}}{\sqrt{200\mathrm{nW}}} C_{\mathrm{safe}} C_{\mathrm{sqz}} \sqrt{D} \tag{4}$$

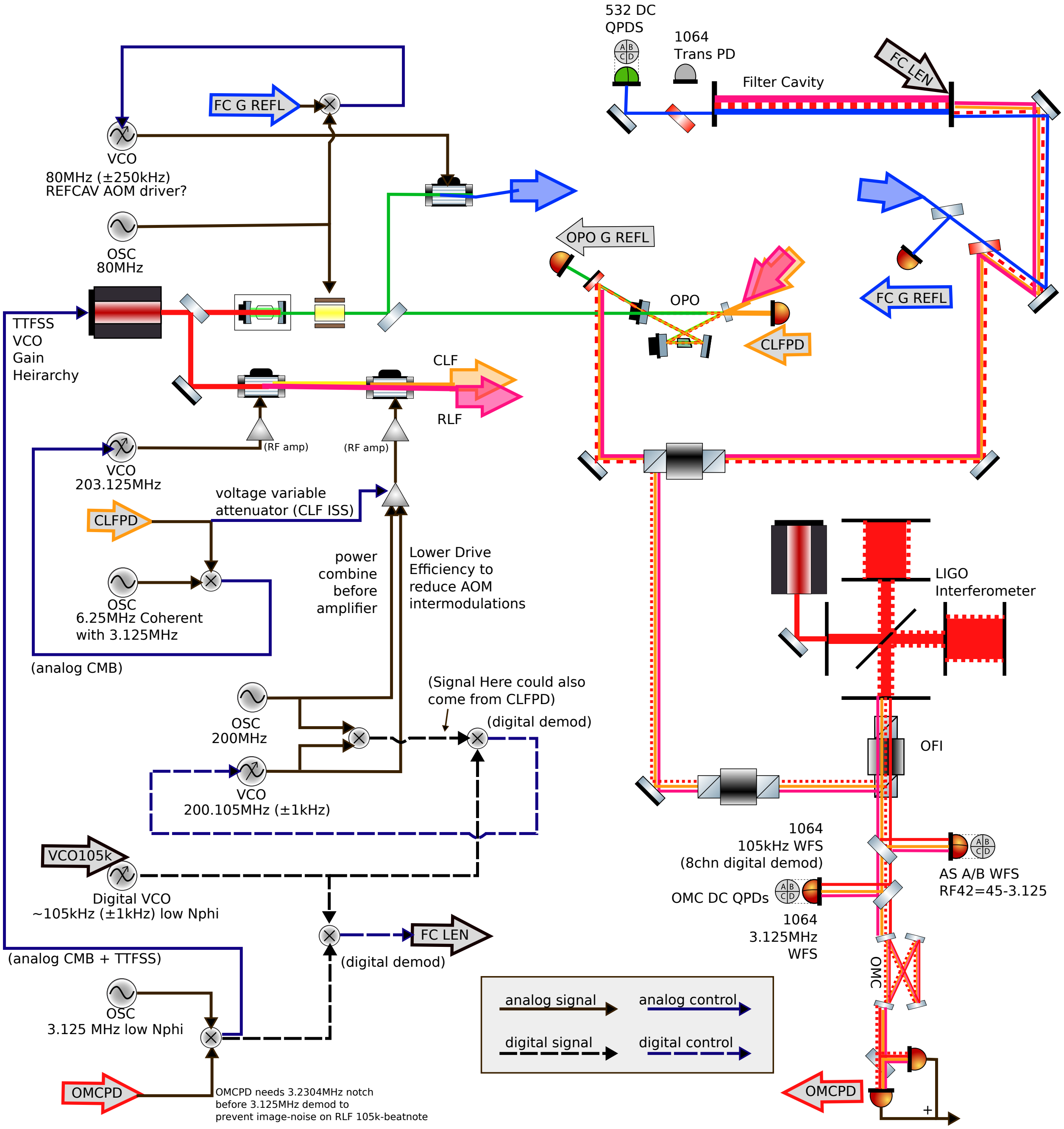

Figure 1: 2 AOM implementation of double-CLF filter cavity sensing scheme.

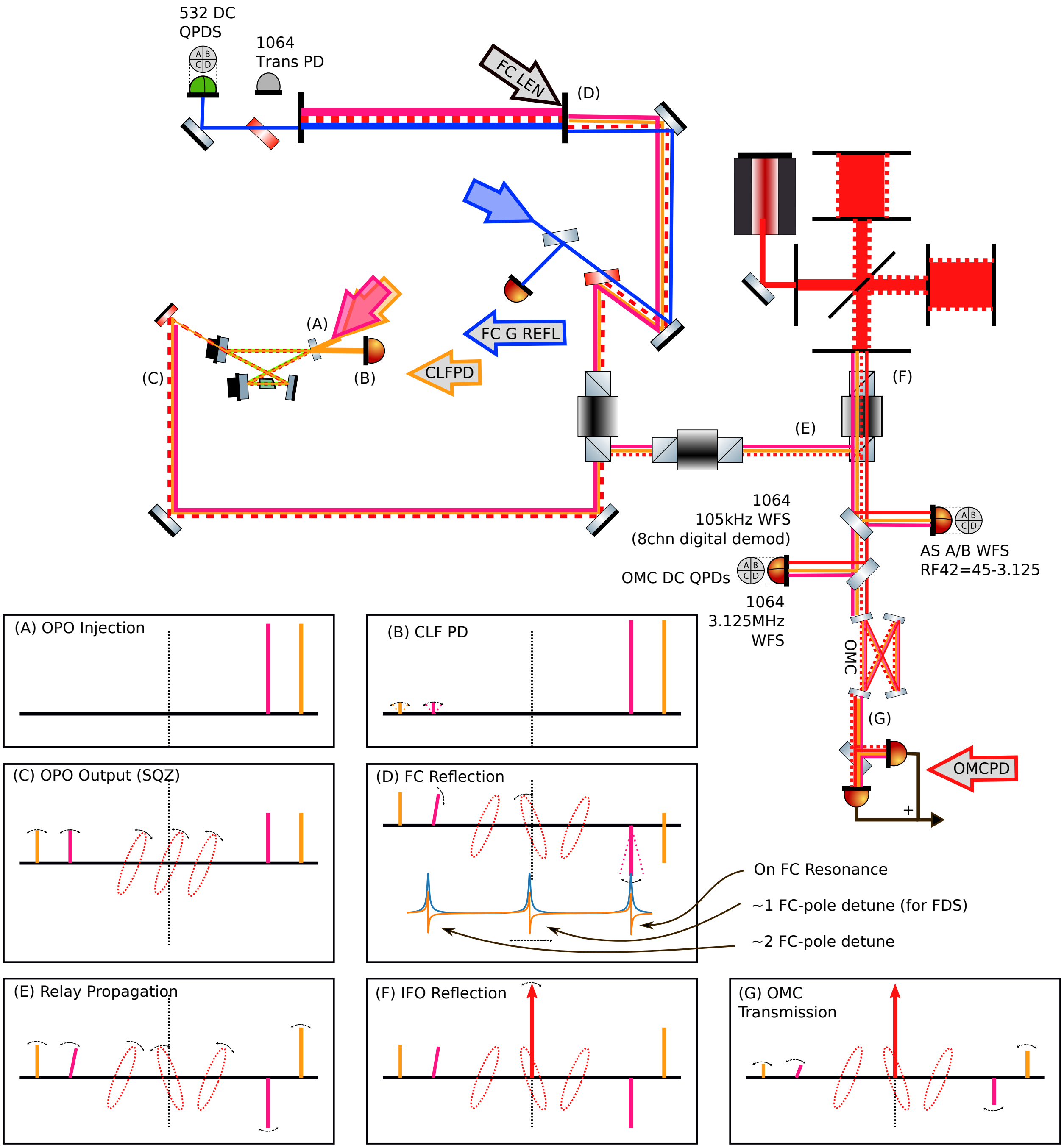

Figure 2: 2 AOM implementation of double-CLF filter cavity sensing scheme.

Figure 3: Transfer functions of the length control loop tuned for a 10 Hz UGF. This shows the sensing noise injection from RLF phase noise of 1e-6rad/rtHz, from T1800447-v4.

3 Current SQZ Loops

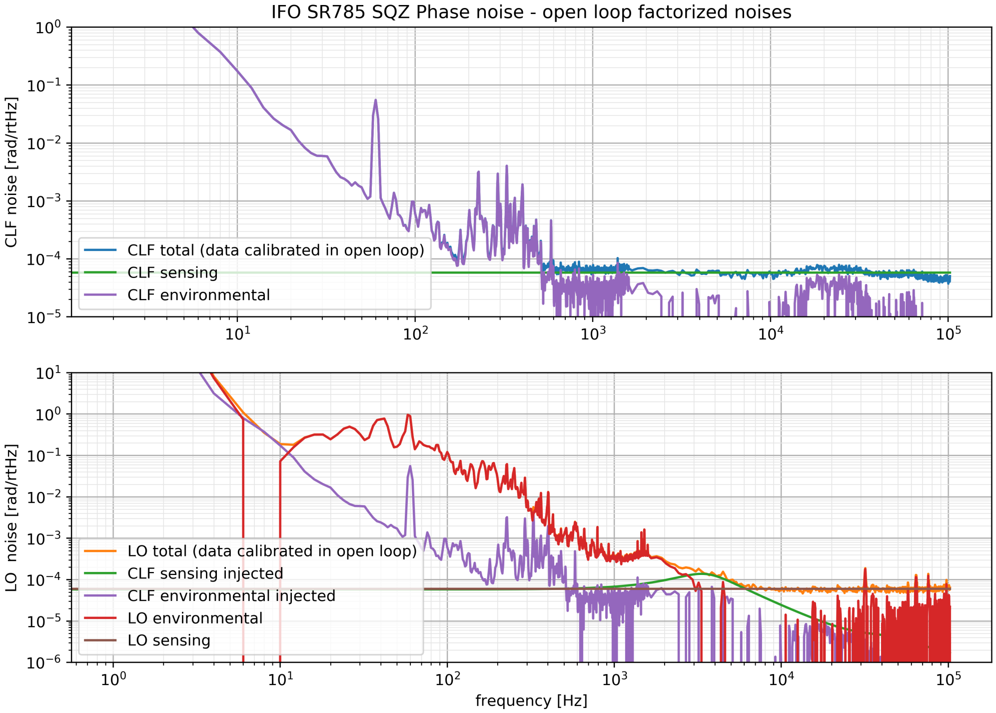

Figure 4:

CLFPD

3.1 Oscillator Phase Noise requirements

Frequency	Usage	Specifications
80.00 MHz	-90dBc @ 10Hz	T1000314
3.125 MHz	-118dBc @ 10Hz	Divided 80MHz T1000314
3.125 MHz	-130dBc @ 10Hz	Crystal (not used?) T1700016
6.250 MHz	-125dBc @ 10Hz	Crystal (not used?) T1600598
10.00 MHz	-130dBc @ 10Hz	Premium timing T1100279
200.0 MHz	-113dBc @ 100Hz	T1700393
203.125 MHz±1kHz	-113(SC), -103dBc (AT) @ 100Hz	T1600599 T1800062
200.105 MHz±1kHz	-113dBc @ 100Hz (assumed)	Similar to T1600599
105.435 kHz	< -130dBc @10Hz	E090003 T080099

Table 2: Table of used frequencies

Frequency Sources It is worth noting that the 80MHz divided down to 3.125MHz is only improved by 28dB, which is not as good as the 3.125MHz crystal, and significantly worse than the . From the existing squeezer block diagram, E1500362 and the RFDistributionLayout.

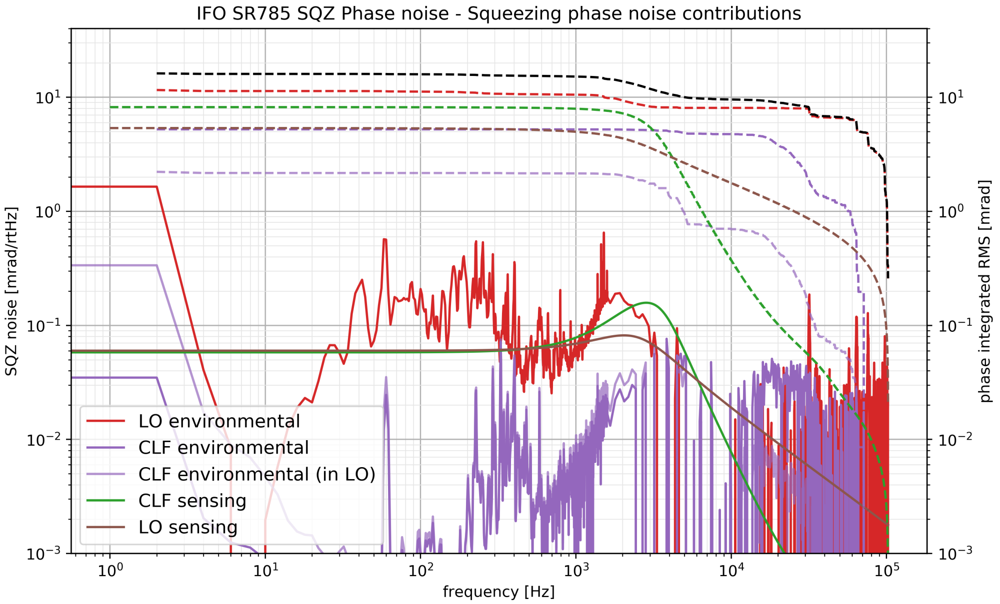

Figure 5: 2 AOM implementation of double-CLF filter cavity sensing scheme.

The 40MHz, 10MHz, 6.25MHz and 3.125MHz are all synthesized from the 80MHz, which gives a phase noise of the CLF loop relative to the IFO of -118dBC

Timing system T1700298 T1700299 20nS jitter on the 1PPS

Digital PLL implementations

3.2 AOM Intermodulation Noises

4 1064 FC Alignment Signals

4.1 Noise Requirements

4.2 Multi-frequency AOM issues

This two-field scheme with an AOM is implemented differently than the audio field. For this field, two equal magnitude CLFs must be driven [1].

5 Digital Demodulation Implementation

5.1 Digital VCO Timing Phase noise

5.2 ADC Phase Noise

6 CLF/RLF AOM ISS

7 532 Lock Acquisition and control

7.1 532 VCO Requirements

8 FC Parameters

The parameters of table 3 are to

λ	$= 1064[\mathrm{nm}]$	Wavelength
E_λ	$= 1.869{\cdot}10^{-19}[\mathrm{J}]$	Energy of a photon
Q_λ	$= \sqrt{\frac{E_\lambda}{2}} = 3.05{\cdot}10^{-10}\left[\frac{\sqrt{\mathrm{W}}}{\sqrt{\mathrm{Hz}}}\right]$	ASD of quantum noise as measured by amp. or phase quadratures.
F_{SQL}	$= 70[\mathrm{Hz}]$	Frequency of optomechanical ampl. to phase coupling $\mathcal{K}(F) = 1$ at A+ design power
F_{FC}	$= \frac{F_{\mathrm{SQL}}}{\sqrt{2}} = 49.5[\mathrm{Hz}]$	Filter Cavity pole for ideal rotation
C_{safe}	$= {}^{1}\!/_{10}$	ASD safety margin of 10x
C_{sqz}	$= {}^{1}\!/_{2}$	ASD reduction from squeezing (6db observed)

Table 3: Parameters for Filter Cavity Calculations

9 Alternative 2CLF (3 AOM) Implementation

In the event that AOM intermodulation with the 2-AOM scheme causes lock-point errors and noise, a 3-AOM scheme is possible. In this case, the RLF and CLF are not generated natively copropagating, and so a control loop derived from an optical signal is necessary. The 105kHz beatnote in the CLFPD DC signal measures the phase offset between the beams, and is the simplest candidate for controlling away differential noise. In this implementation, the 200.1kHz VCO digital PLL is derived from the CLF measurement, rather than the electronics signal.

In this case, the CLF ISS should be implemented on the 203.125MHz AOM.

In addition to the AOM and RF amplifier

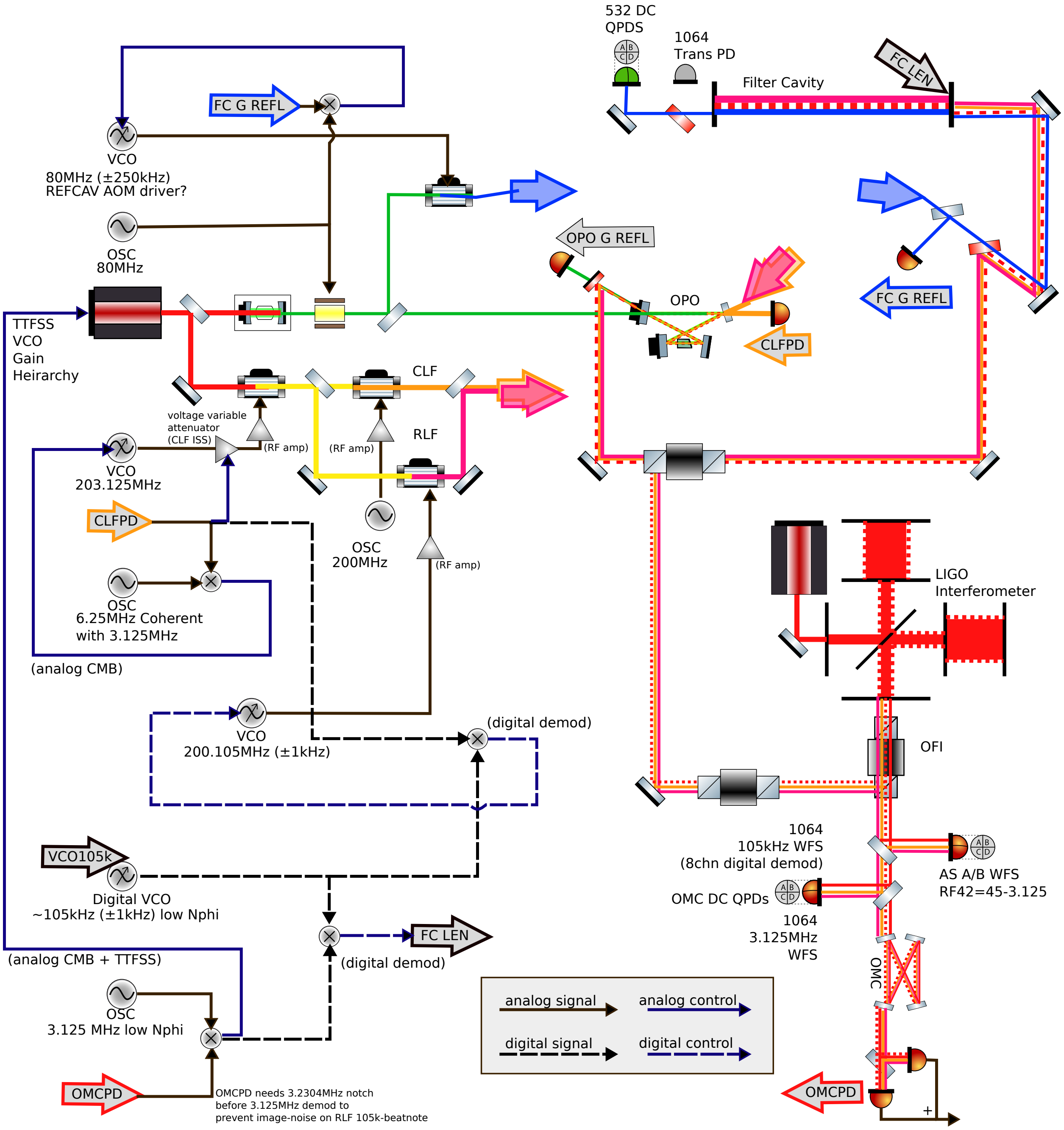

Figure 6: 3 AOM implementation of fig ??. Note that an additional phase lock is required to stabilize the relative phasing between the AOMs.

10 Phasing Transfer Analysis

The transfer analysis of the phase noise through the system and the ability of the master LO/SQZANGLE loop "clean" the phase of the RLF via the CLF sensing and auxiliary loops is nontrivial. It was first studied in the implementation of the audio diagnostic field during the comissioning of the LLO squeezer. Here is a list of relevant log-posts which implemented and studied it.

- T1800475 Original phase noise analysis and VCO topology for phase stability.
- LLO41737
- LLO41643
- LLO42297
- LLO42297
- LLO42233
- LLO41796
- LLO41737

References

[1] D. L. Hecht. Multifrequency acoustooptic diffraction. *IEEE Transactions on Sonics and Ultrasonics*, 24(1):7–18, Jan 1977.