LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
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Phase noise analysis of the Coherent Audio/Locking Fields for squeezing characterization

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1 Original layout

This is the layout and noise analysis for the coherent audio field (low frequency CLF witness field) given in G1800721, implemented in LLO-39565 and with some characterization done in LLO-41535.

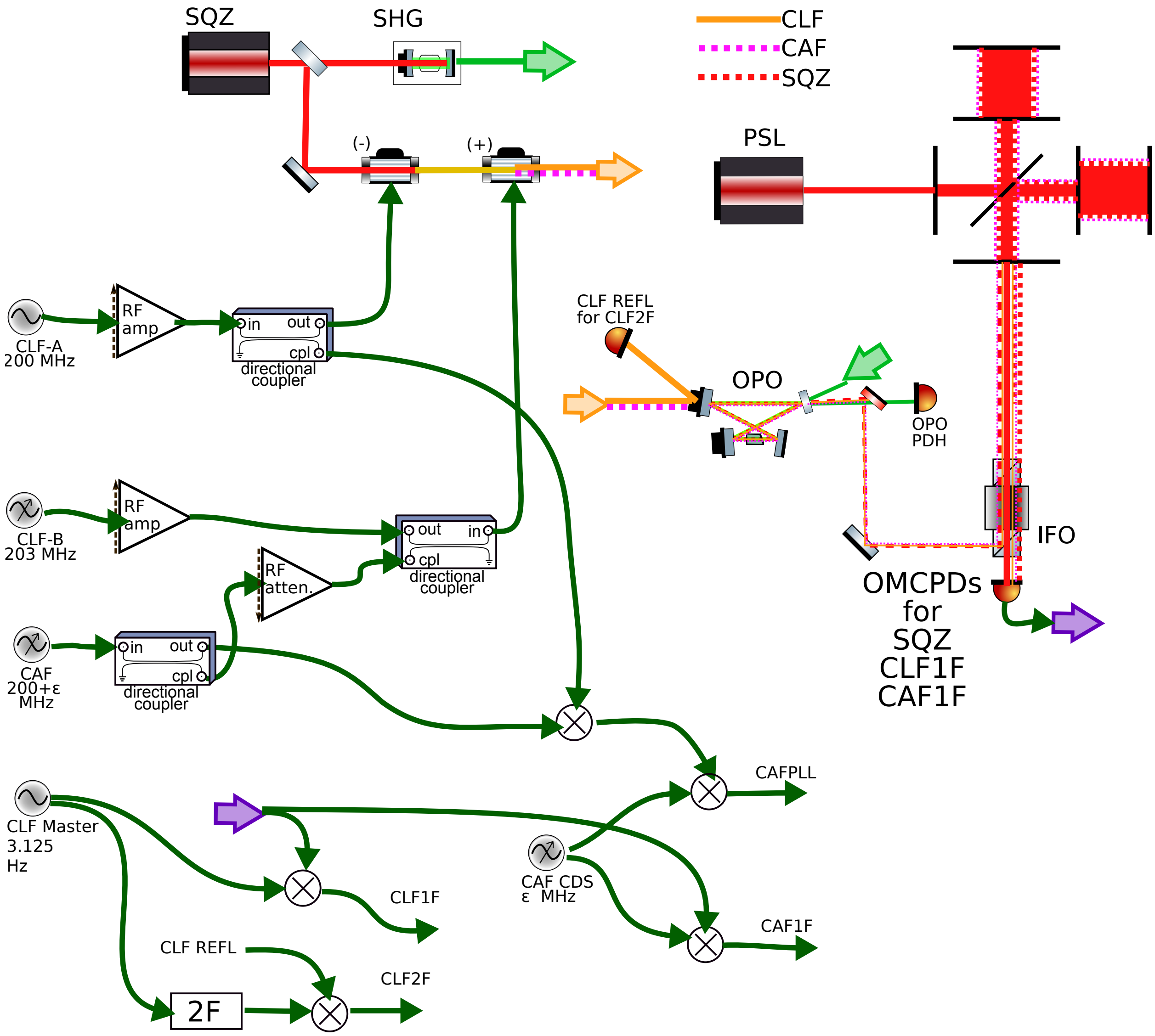

Figure 1: Optical and RF layout of the first generation ALF implementation

Figure 1 shows the optical and RF layout of the characterization field, in context with the CLF field. Both fields are generated from VCO signals. The audio field is added as a small coupling through direction couplers (RF beamsplitters).

The signal flow diagram of the loops and phase couplings is in Figure 2. This diagram segments the couplings with node for the RF additions/subtractions (early nodes) and the optical phase subtractions. The most unintuitive one is the negative sign on the pump in the CLF2F, but not the SQZ field. This is because it is a phase comparison to create the beatnote on the CLF2F field, but the SQZ field rotates with the pump phase. Essentially it

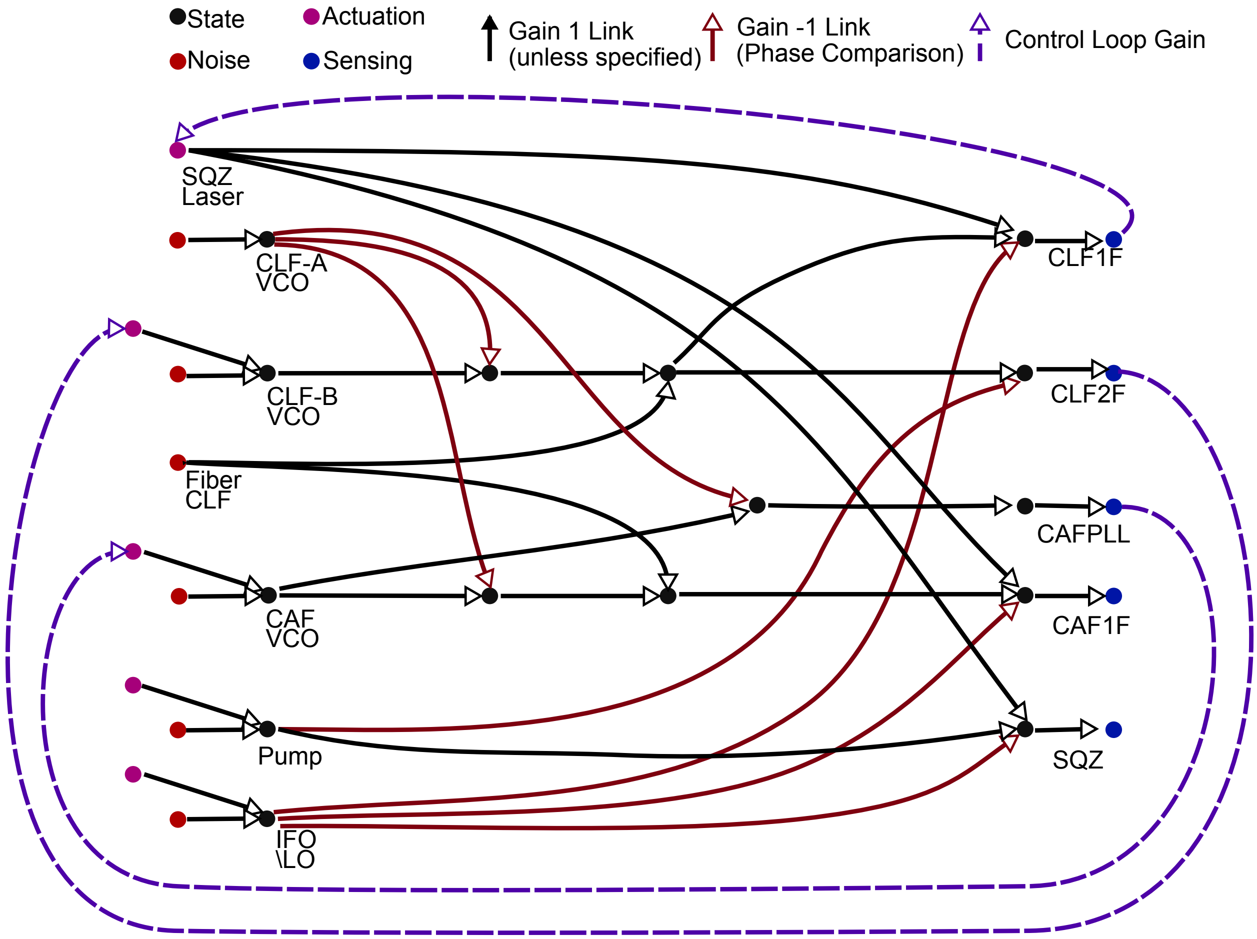

Figure 2: Signal Flow analysis of phase noise in the CLF and CAF loops

must be there because all optical beatnote signals must have one positive and one negative coupling, and the IFO, by convention, is the negative in the diagram. The CLF2F doesn't see the IFO, and its second coupling is the pump..

The diagram corresponds to the open loop couplings

$$S_{\mathrm{CLF1F}} = \hat{N}_{\mathrm{CLF\text{-}B}} + A_{\mathrm{CLF\text{-}B}} - \hat{N}_{\mathrm{CLF\text{-}A}} + \hat{N}_{\mathrm{CLF\text{-}F}} - \hat{N}_{\mathrm{IFO}} + A_{\mathrm{SQZ}} \quad (1)$$
$$S_{\mathrm{CLF2F}} = \hat{N}_{\mathrm{CLF\text{-}B}} + A_{\mathrm{CLF\text{-}B}} - \hat{N}_{\mathrm{CLF\text{-}A}} + \hat{N}_{\mathrm{CLF\text{-}F}} - \hat{N}_{\mathrm{pump}} \quad (2)$$
$$S_{\mathrm{CAFPLL}} = -\hat{N}_{\mathrm{CLF\text{-}A}} + \hat{N}_{\mathrm{CAF}} + A_{\mathrm{CAF}} \quad (3)$$
$$S_{\mathrm{CAF1F}} = -\hat{N}_{\mathrm{CLF\text{-}A}} + \hat{N}_{\mathrm{CLF\text{-}F}} + \hat{N}_{\mathrm{CAF}} + A_{\mathrm{CAF}} - \hat{N}_{\mathrm{IFO}} + A_{\mathrm{SQZ}} \quad (4)$$
$$S_{\mathrm{SQZ}} = \hat{N}_{\mathrm{pump}} + A_{\mathrm{pump}} - \hat{N}_{\mathrm{IFO}} + A_{\mathrm{SQZ}} \quad (5)$$

And in the open loop, the actuator signals are

$$A_{\mathrm{SQZ}} = -G_{\mathrm{1F}} S_{\mathrm{CLF1F}} \quad (6)$$
$$A_{\mathrm{CLF\text{-}B}} = -G_{\mathrm{2F}} S_{\mathrm{CLF2F}} \quad (7)$$
$$A_{\mathrm{CAF}} = -G_{\mathrm{CAF}} S_{\mathrm{CAFPLL}} \quad (8)$$

so in the infinite gain limit, the sensing then becomes:

$$S_{\text{CLF1F}} = \frac{1}{1+G_{1\text{F}}}(\hat{N}_{\text{CLF-B}} - G_{2\text{F}}S_{\text{CLF2F}} - \hat{N}_{\text{CLF-A}} + \hat{N}_{\text{CLF-F}} - \hat{N}_{\text{IFO}}) \tag{9}$$

$$S_{\text{CLF2F}} = \frac{1}{1+G_{2\text{F}}}(\hat{N}_{\text{CLF-B}} - \hat{N}_{\text{CLF-A}} + \hat{N}_{\text{CLF-F}} - \hat{N}_{\text{pump}}) \tag{10}$$

$$S_{\text{CAFPLL}} = \frac{1}{1+G_{\text{CAF}}}(-\hat{N}_{\text{CLF-A}} + \hat{N}_{\text{CAF}}) \tag{11}$$

$$S_{\text{CAF1F}} = -\hat{N}_{\text{CLF-A}} + \hat{N}_{\text{CLF-F}} + \hat{N}_{\text{CAF}} - G_{\text{CAF}}S_{\text{CAFPLL}} - \hat{N}_{\text{IFO}} - G_{1\text{F}}S_{\text{CLF1F}} \tag{12}$$

$$S_{\text{SQZ}} = \hat{N}_{\text{pump}} - \hat{N}_{\text{IFO}} - G_{1\text{F}}S_{\text{CLF1F}} \tag{13}$$

which must be further solved, although one can already tell that the CAF will not be able to remove $\hat{N}_{\text{IFO}}$ and $\hat{N}_{\text{CLF-F}}$.

Solving in the infinite gain limit of $G_{2\text{F}}$ and G_{CAF}.

$$S_{\text{CLF1F}} = \frac{1}{1+G_{1\text{F}}}(\hat{N}_{\text{pump}} - \hat{N}_{\text{IFO}}) \tag{14}$$

$$S_{\text{CLF2F}} = 0 \tag{15}$$

$$S_{\text{CAFPLL}} = 0 \tag{16}$$

$$S_{\text{CAF1F}} = \hat{N}_{\text{CLF-F}} - \hat{N}_{\text{IFO}} - G_{1\text{F}}S_{\text{CLF1F}} \tag{17}$$

$$S_{\text{SQZ}} = \hat{N}_{\text{pump}} - \hat{N}_{\text{IFO}} - G_{1\text{F}}S_{\text{CLF1F}} \tag{18}$$

which shows the proper operation of the squeezing CLF loops, as the final solve then gives:

$$S_{\text{SQZ}} = \frac{1}{1+G_{1\text{F}}}(\hat{N}_{\text{pump}} - \hat{N}_{\text{IFO}}) \tag{19}$$

$$S_{\text{CAF1F}} = \hat{N}_{\text{CLF-F}} - \frac{1}{1+G_{1\text{F}}}\hat{N}_{\text{IFO}} - \frac{G_{1\text{F}}}{1+G_{1\text{F}}}\hat{N}_{\text{pump}} \tag{20}$$

the solving shows that the CAF clearly has the residual phase noise of the fiber and the interferometer, because the CLF loop is not actuating on the CAF.

2 New Layout

By adjusting the injection site of the CAF, the actuation on the CLF-B VCO can then also drive the CAF frequency, imprinting the pump phase and the CLF-fiber phase into the CAF signal. An additional mixer is needed as the CAF must now be referenced from the 203 MHz squeezer signal. As far as I can tell, all workable alternative configurations also need the extra mixer and phase reference to the 3.125MHz master oscillator.

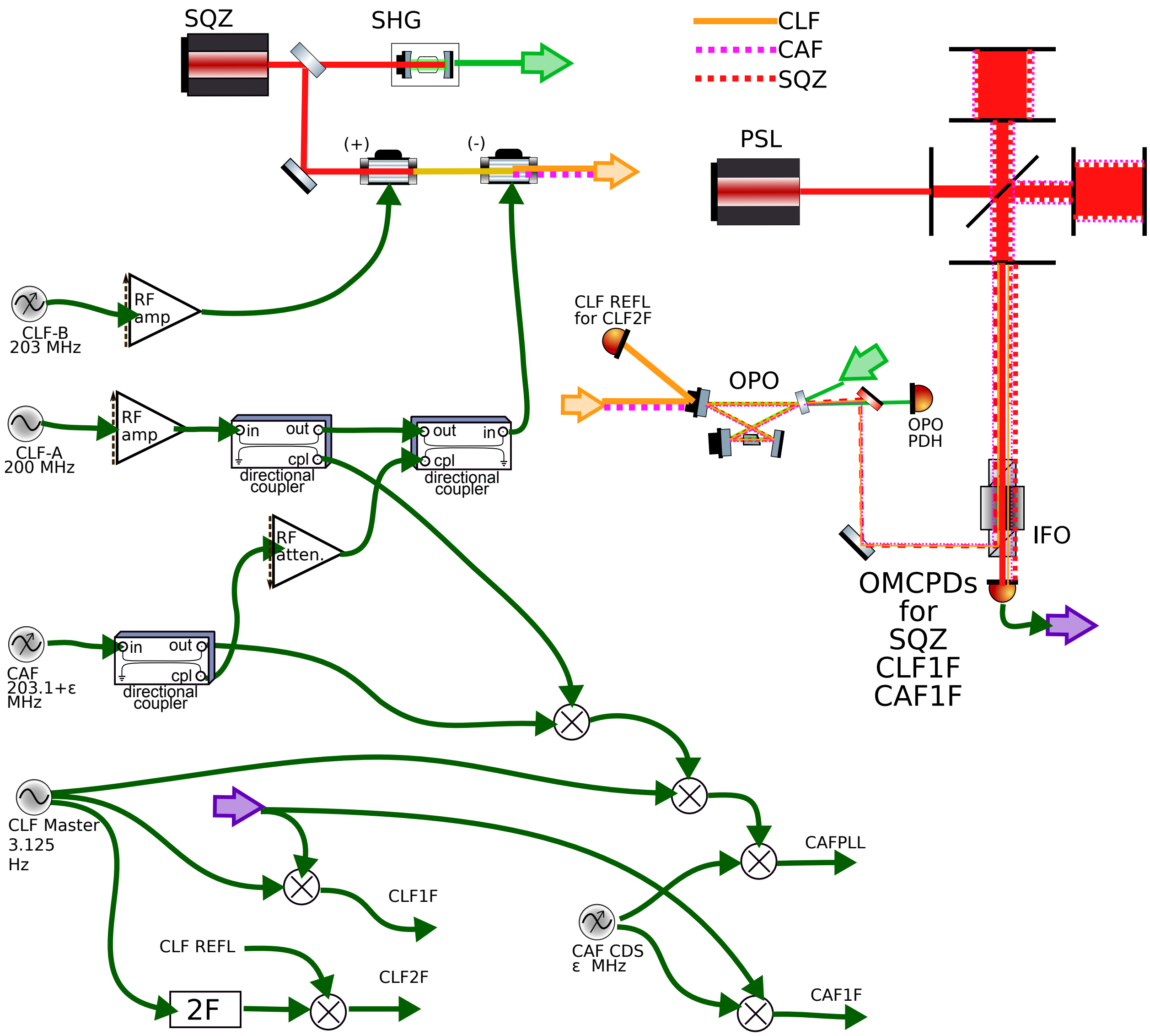

Figure 3: Optical and RF layout of the second generation ALF implementation.

Which corresponds to the open loop couplings (only CAF has changed).

$$S_{\text{CLF1F}} = \hat{N}_{\text{CLF-B}} + A_{\text{CLF-B}} - \hat{N}_{\text{CLF-A}} + \hat{N}_{\text{CLF-F}} - \hat{N}_{\text{IFO}} + A_{\text{SQZ}} \tag{21}$$

$$S_{\text{CLF2F}} = \hat{N}_{\text{CLF-B}} + A_{\text{CLF-B}} - \hat{N}_{\text{CLF-A}} + \hat{N}_{\text{CLF-F}} - \hat{N}_{\text{pump}} \tag{22}$$

$$S_{\text{CAFPLL}} = -\hat{N}_{\text{CLF-A}} + \hat{N}_{\text{CAF}} + A_{\text{CAF}} \tag{23}$$

$$S_{\text{CAF1F}} = \hat{N}_{\text{CLF-B}} + A_{\text{CLF-B}} + \hat{N}_{\text{CLF-F}} - \hat{N}_{\text{CAF}} - A_{\text{CAF}} - \hat{N}_{\text{IFO}} + A_{\text{SQZ}} \tag{24}$$

$$S_{\text{SQZ}} = \hat{N}_{\text{pump}} - \hat{N}_{\text{IFO}} + A_{\text{SQZ}} \tag{25}$$

Now skipping to the closed loop equations:

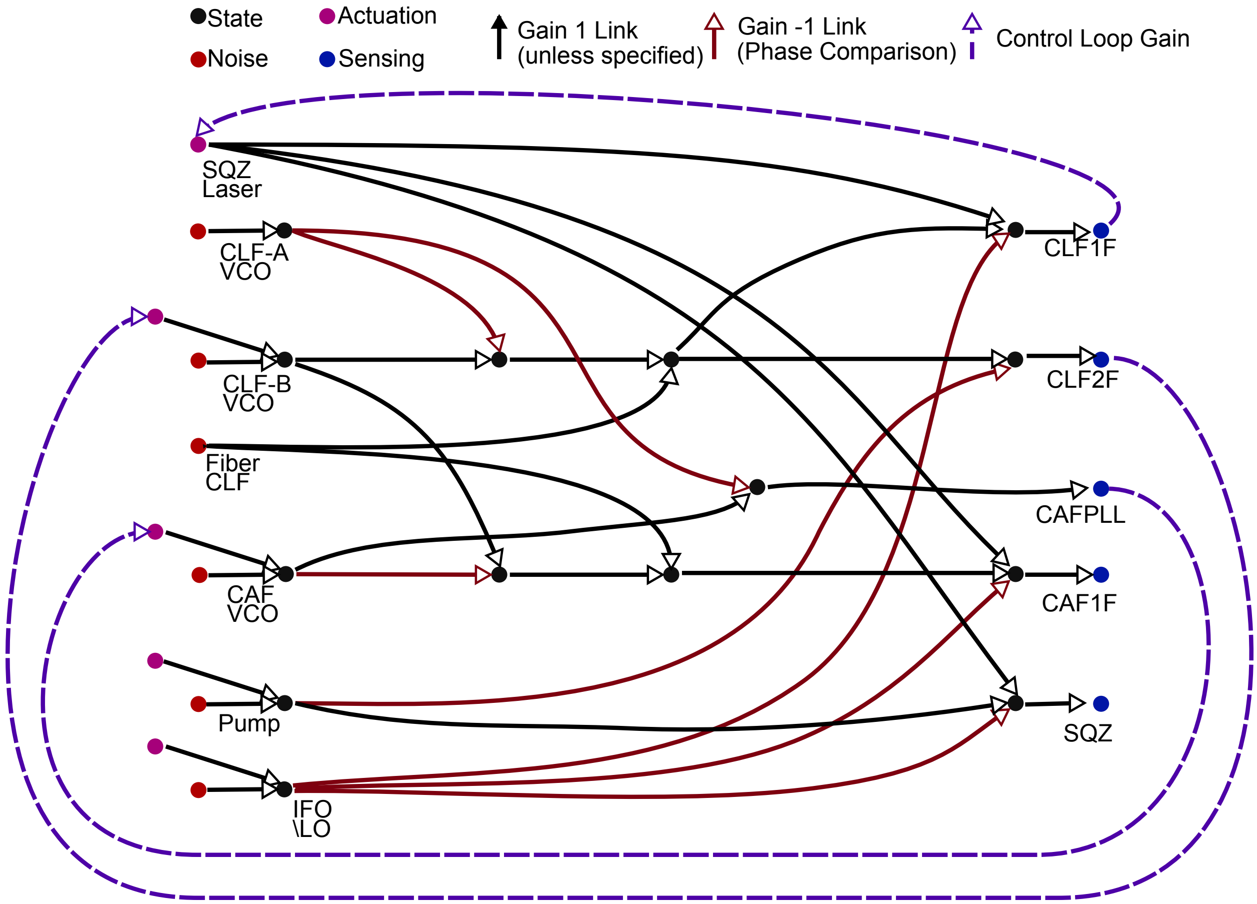

Figure 4: Signal Flow analysis of phase noise in the CLF and CAF loops with the modified CAF layout.

$$S_{\text{CAFPLL}} = \frac{1}{1+G_{\text{CAF}}}(-\hat{N}_{\text{CLF-A}} + \hat{N}_{\text{CAF}}) \tag{26}$$

$$S_{\text{CAF1F}} = +\hat{N}_{\text{CLF-B}} - G_{2\text{F}}S_{\text{CLF2F}} + \hat{N}_{\text{CLF-F}} - \hat{N}_{\text{CAF}} + G_{\text{CAF}}S_{\text{CAFPLL}} - \hat{N}_{\text{IFO}} - G_{1\text{F}}S_{\text{CLF1F}} \tag{27}$$

$$\tag{28}$$

which in the limit of infinite $G_{2\text{F}}$, becomes

$$S_{\text{CAFPLL}} = \frac{1}{1+G_{\text{CAF}}}(-\hat{N}_{\text{CLF-A}} + \hat{N}_{\text{CAF}}) \tag{29}$$

$$S_{\text{CAF1F}} = \hat{N}_{\text{CLF-A}} - \hat{N}_{\text{CAF}} + G_{\text{CAF}}S_{\text{CAFPLL}} - G_{1\text{F}}S_{\text{CLF1F}} + \hat{N}_{\text{pump}} - \hat{N}_{\text{IFO}} \tag{30}$$

or, fully reduced:

$$S_{\text{CAF1F}} = \frac{1}{1+G_{\text{CAF}}}(\hat{N}_{\text{CLF-A}} - \hat{N}_{\text{CAF}}) + \frac{1}{1+G_{1\text{F}}}(\hat{N}_{\text{pump}} - \hat{N}_{\text{IFO}}) \tag{31}$$

which properly shows the residual noise in the interferometer loops, as desired for the CAF.