LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Technical Note **LIGO-T1900279-v1** 2019/05/14

Filter Cavity Optics Substrates

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1 Specifications

1.1 Curvatures

Input Optic (FC1) Surface 1 (HR) Flat, ROC: ∞ (±250nm saggitta)

Input Optic (FC1) Surface 2 (AR) Curved, ROC: +2m (±5%)

End Optic (FC2) Surface 1 (HR) Curved, ROC: -512m (±2%)

End Optic (FC2) Surface 2 (AR) Curved, ROC: +2m (±5%)

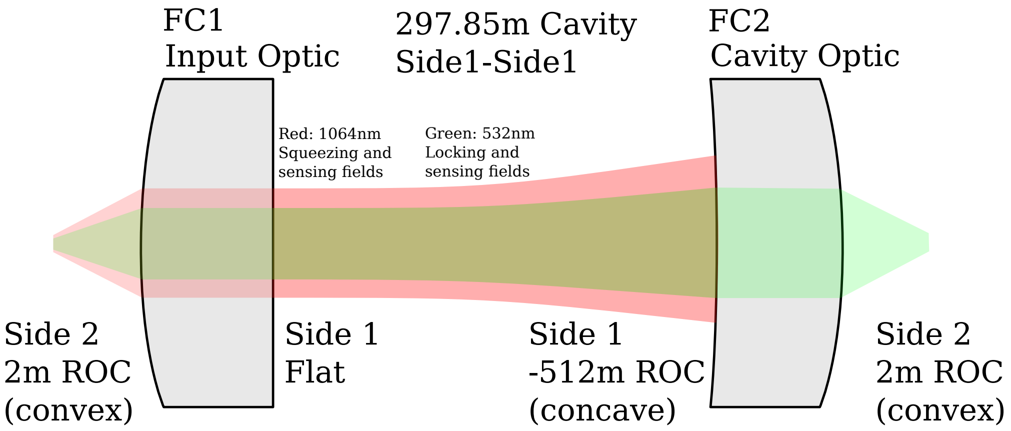

Figure 1: Cavity geometry and mirror specification. The strong side-2 AR-surface curvatures are to reduce the beam size for relay optics.

1.2 Optic Size

The substrate dimensions are for mounting in the HSTS suspension. The specification is 150mm diameter, 75mm thickness. Related optic drawings are the signal and power recycling mirrors, D0901174 or D0901175 which are also mounted in HSTS suspensions (note that the filter cavity optics will have different surface curvatures than either of these drawings). The following section also indicates that, unlike the SRM and PRM optics, the FC optics do not need to include wedges.

1.3 Wedge

Due to the inclusion of strong lenses on the side-2 surfaces, these optics will not include wedges.

With the side-2 curvature specification unique to the FC optics, a 1 degree wedge may complicate procurement. Such a wedge angle is large compared to the divergence angle of the lensed beam, and would still isolate the AR reflection from the incoming/outgoing modes of the cavity, but the FC has substantially lower incident light to cause scatter issues of similar (SRM, PRM) optics. Any direct AR reflection from the convex lensing surface will rapidly diverge, and a baffle may be a suitable alternative for dumping the diverging AR reflection.

2 Substrates

These optics will not carry high power in either 1064 or 532 and so do not need low substrate absorption. The principle design requirement is on uncorrectable mode-matching losses from substrate index homogeneity of the input mirror (FC1).

The target substrate for quick procurement is Corning 7979 Class-0AA or Class-0A glass.

2.1 Homogeneity

Corning 7979 Class-0AA glass is specified for an inhomogeneity $\Delta n \leq 0.5 \cdot 10^{-6}$. This specification is the maximum deviation from the mean. Taking the specification at face value and assuming it would correspond directly to an RMS inhomogeneity, this would cause a wavefront mismatch loss after two passes through the substrate as large as

$$L_{\mathrm{mm}} \leq \left(0.075\mathrm{m}\Delta n \frac{4\pi}{n\lambda}\right)^2 \approx (4\pi \cdot 0.025 \text{ wave})^2 \approx (0.3)^2 \approx 10\%\text{loss} \tag{1}$$

However the spatial scales of the inhomogeneity are large compared to the beamsize, and as is typical for phase-map specifications. Furthermore, the RMS fluctuation is typically smaller than the peak-valley which is dominated at the edges.

Transmission interferometry of 100mm thick Corning 0A glass was performed on the initial LIGO ETMs, documented in T080085. These measurements indicate that in general, the RMS fluctuations in transmission phase maps are generally 3x smaller than the peak-valley. Furthermore, the Zernike polynomials of order ≤ 3 removed (uncorrectable phase deviations) are another factor ≈ 3 lower in RMS, achieving typically $\leq$ 0.03-Wave RMS deviation, corresponding to a wavefront matching loss of:

$$L_{\mathrm{mm}} \leq (4\pi \cdot 0.003\text{wave})^2 \approx 0.14\% \text{ loss} \tag{2}$$

This indicates that Corning IR-Grade 7979 Class-0AA or Class-0A glass should be sufficient to meet index homogeneity requirements of the input optic. The output optic may be a lower grade, as it will only be directed to photodectors and sensors, and will not be required to overlap any other defined mode.

Furthermore, alternative substrate materials such as Heraeus Suprasil do not specify index homogeneity below the $0.5 \cdot 10^{-6}$ level ("Material Specs" from L1300216). Given that no vendor specifies better homogeneity, whichever may deliver the fastest is prefered. If the specification cannot or is not met, the alternative option is for surface polish compensation of the wavefront as per sec. 4.2.2.4.2 (Transmission OPD errors) of T000127. Given that the FC1 optic is flat on side-1, Such a polishing technique may be feasible, but the metrology may not be feasible for an optic with a 2m radius of curvature.

2.2 ROC/Sagitta Tolerancing

As shown in the Following section, the tolerances for saggitta error of the flat FC1 side1 flat surface and the relative error in the ROC of the FC2 side1, -512m is not strict. Not only are those errors correctable through mode-matching, as much as 500nm saggitta error on FC1-side1 or 5% ROC relative error on FC2 side1 will cause less than 0.25% mode overlap loss against the designed cavity mode. The choice of 2% tolerancing above was to keep the Gouy phase and ISC frequencies well-determined, but could be relaxed if needed.

3 Choice of Mirror Parameters

The choice of mirror parameter is driven by the requirements of T1800447. This section provides a short summary of how the chosen parameters meet the following requirements:

- Beam sizes must be appropriate to minimize loss on the mirrors.
- Nearest relay optic feeding the squeezed beam is 44in from FC1 Mirror.
- Gouy phase must give acceptable alignment sensing/cavity stability.
- Gouy phase must not alias high-order modes with the fundamental.
- Gouy phase must not alias high-order modes on useful ISC frequencies.

The beam size requirements as a function of the possible curvatures for a 297.85m cavity are provided by fig 2. The vertical dashed magenta line is the chosen 512m ROC. The Gouy phase of the cavity and its placement of high order modes is shown in fig. 3 and its zoomed version fig. 4. The aliasing study (second panel in those figures) takes the fractional phase of the HOM, multiples by the mode order, and then takes that number modulo 1.0. This is done for all modes up to a given order and the smallest remainder term is plotted. This shows which mode approaches the closest to the HG00 mode and could alias in frequency. The aliasing distance should be large compared to the inverse of the Finesse in each mode. The finesse of the HG00 mode is high (≈ 5000), but clipping loss will be dominant for modes order ≥ 5, and so they will have reduced finesse.

3.1 Cavity Length

The specific cavity length of 297.85m scales the mirror ROC's, and is only weakly driven by the last requirement. It is primarily constrained by the existing 3.125MHz CLF control frequency to not potentially alias on the HG01 frequency, which, while unlikely, could cause considerable ISC issues. To determine the chosen length length, a number of lengths and ROC's were considered to simultaneously meet all criteria. The plots of Fig 5, using frequencies of table 1

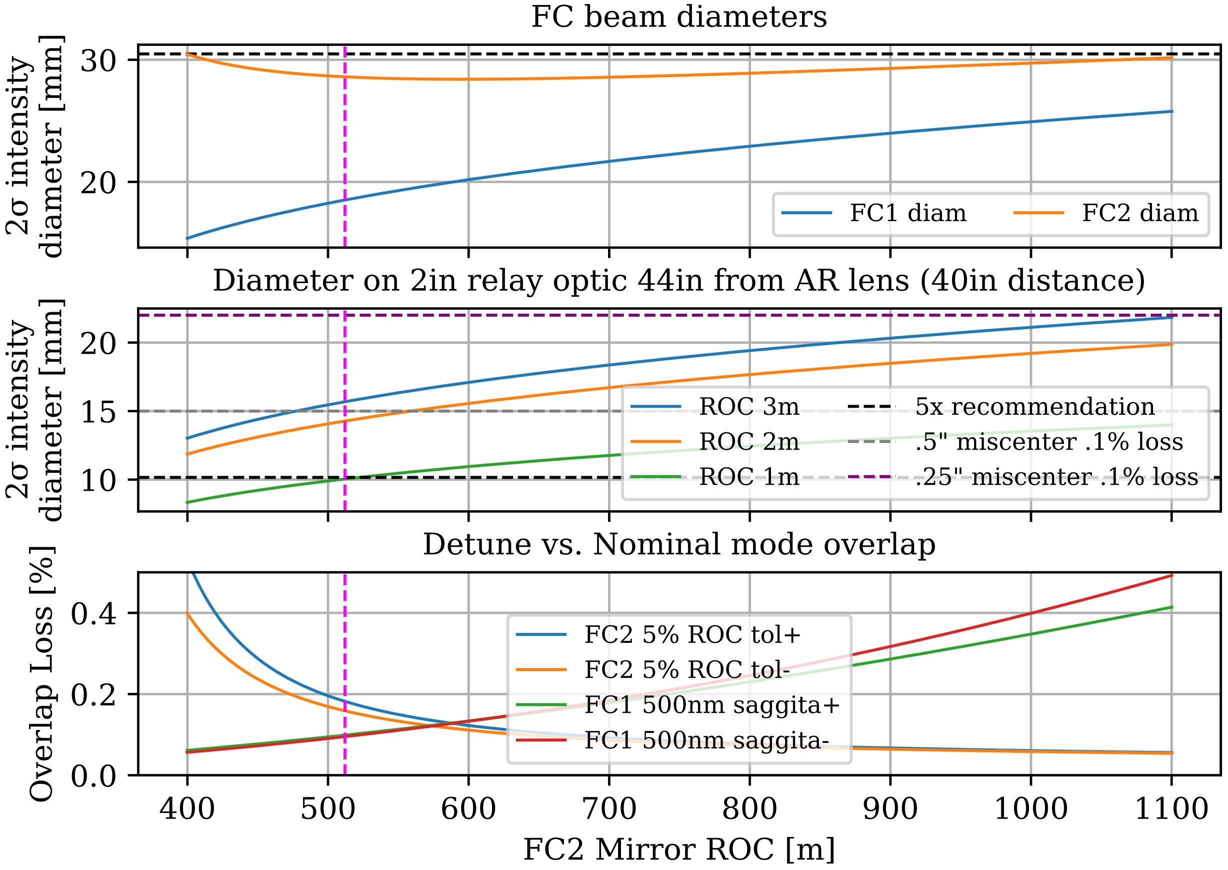

Figure 2: Beam sizes and tolerances for a 297.85m filter cavity. Top: Beam sizes for the 1064 Squeezed beam on each FC Mirror as a function of the FC2 radius of curvature for a 297.85m cavity. Mid: The beamsizes on the nearest input relay optic as a function of the FC1-side1 lens curvature. Limits for this size (dashed) are parameterized by the allowable miscentering on the optic for loss. Bottom: tolerancing for the ROC and saggitta of the FC mirrors from effective uncertainty in the cavity mode (correctable).

RF9	9.099471MHz
RF45	45.497355 MHz
RF40	40 MHz
RF80	80 MHz
CLF	3.125 MHz
FCLF(A)	3.019564 MHz
FCLF(B)	3.522825 MHz

Table 1: Table of used ISC frequencies for fig 5

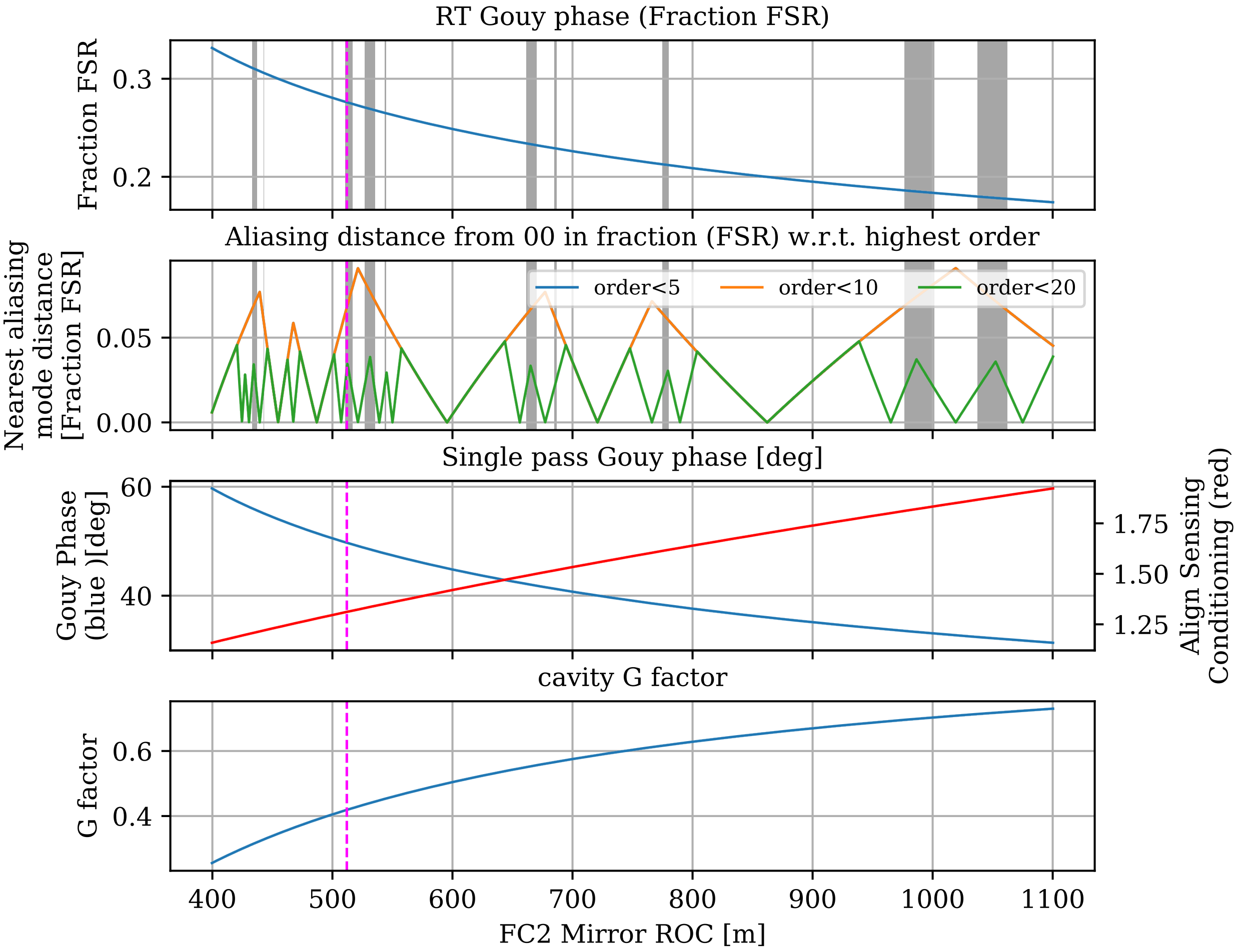

Figure 3: Gouy phase features of 297.85m filter cavity. Top: The Gouy phase as a fraction of the FSR. Second: the aliasing distance of high-order modes to the HG00 in fractions fSR. Third: The single pass Gouy phase useful for alignment sensing, as well as the conditioning of alignment sensing matrix inversion indicating the noise enhancement factor for the worst-sensed DOF. Bottom: The G-factor of the cavity.

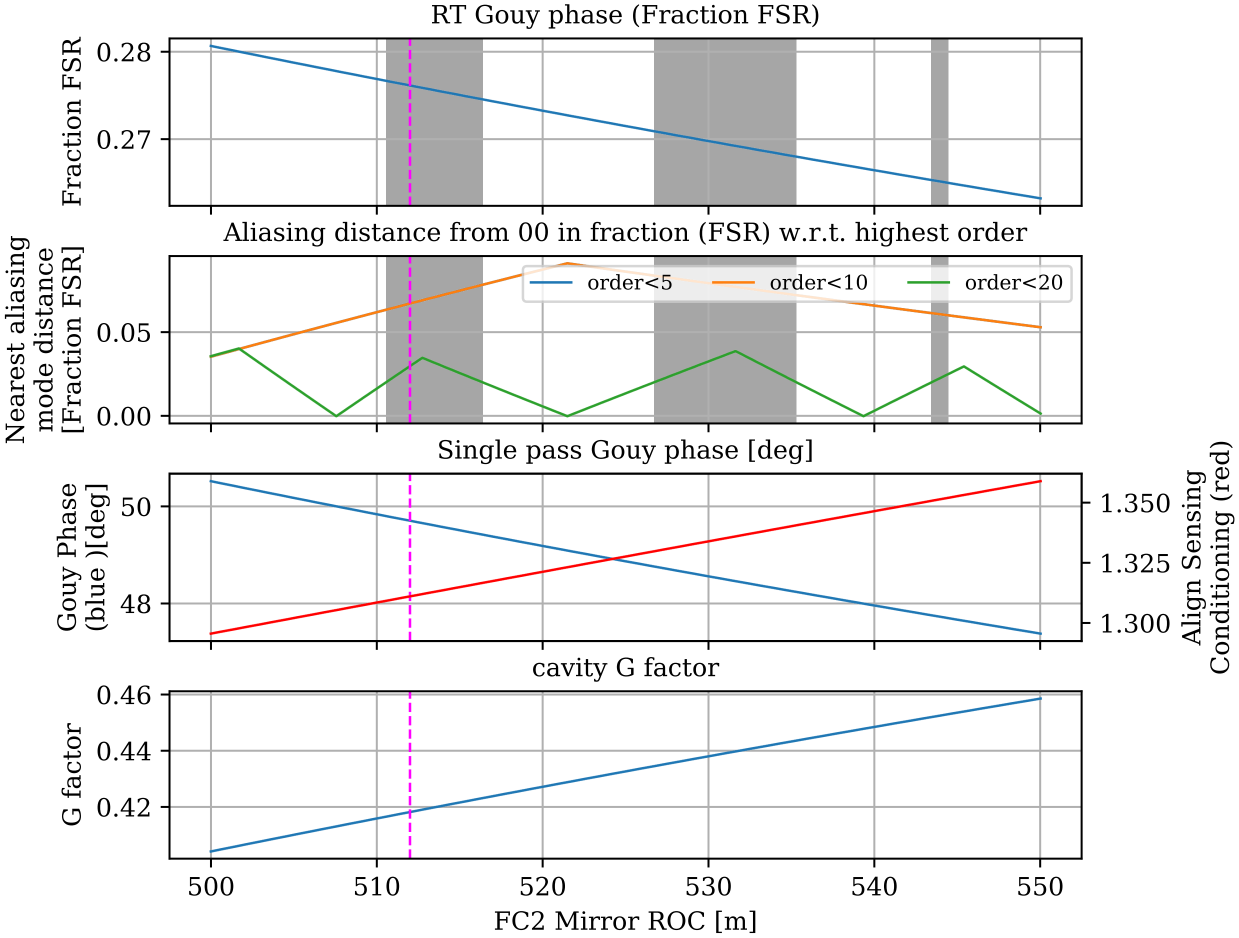

Figure 4: A zoom of fig 3, to show local detail of the aliasing distance. The nearest aliasing mode up to order 10 is of order-7.

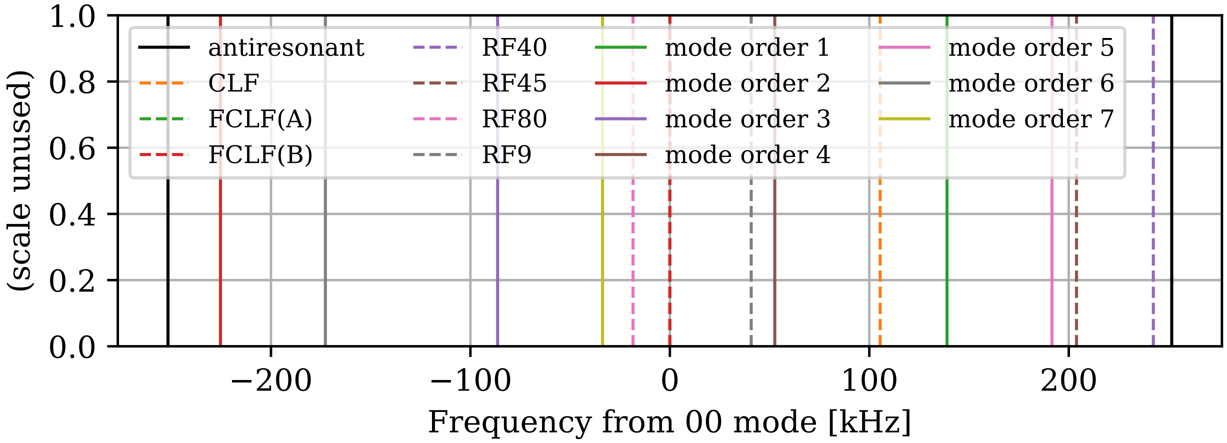

Figure 5: ISC Frequencies and aliased HOM frequencies to show separation and usability of all convenient frequencies. In particular the existing 3.125MHz line used for the squeezer is well separated from all low modes.