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- LIGO -
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Output Mode Cleaner Design

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1 Introduction

The aLIGO Output Mode Cleaner (OMC) enables the DC readout sensing scheme of the interferometer's differential arm length. The OMC is a short $\approx 1\ m$ long cavity used to isolate the fundamental DC carrier mode and its audio frequency phase sidebands from the RF fields and higher order spatial modes. The OMC integrates the DC readout photodiodes (DCPDs), quadrant photodiodes (QPDs), and length actuators required to keep the filter cavity resonant with the carrier.

The aLIGO OMC design derives from that used for Enhanced LIGO (eLIGO) with several significant changes based on our extensive operating experience. The similarities and difference are listed in Table 1:

Similarities:
OMC consists of a 4-mirror cavity with two curved and two flat mirrors
Total length $\approx 1\ m$, with a $\approx 500\ \mu m$ waist size
Two DCPDs and two QPDs mounted directly to breadboard
"Tombstones" on "breadboard" UV epoxy construction

Differences:
A single, long throw PZT stack actuator will replace the short throw PZT and heater combination
The closest resonant higher order mode will be the 5th mode instead of the 4th mode
Super polished, coated tombstones will replace the multi-element mirror and tombstone design
The photodiode preamplifiers will be removed from the suspended breadboard
If possible, the breadboard design will be made stiffer to move resonant frequencies higher

Table 1: OMC design.

The most significant difference between the eLIGO and aLIGO OMCs is the RF sideband frequencies. For eLIGO, the RF sidebands were at 24.5 and 61 MHz while for aLIGO, the frequencies are 9 and 45 MHz. Furthermore, the distribution of light at the AntiSymmetric (AS) port is different. For the starting AS port powers, we use the numbers from §2.1 of Ref. [1] – calculated for the 125 W, NS/NS tuning – reproduced here in Table 2.

Frequency [MHz]	-47	-9.4	0	9.4	47	Total
Power [mW]	64	0.16	82	0.16	100	250

Table 2: Power at the AS port derived from Ref. [1] for Mode 2: 125 W input power, NS/NS tuning.

References

[1] **T070247-v1** ISC group; *AdvLIGO Interferometer Sensing and Control Conceptual Design*

[2] **T0900511-v3** L. Barsotti and M. Evans; *Modeling of Alignment Sensing and Control for Advanced LIGO*

2 Cavity math

We require a few functions to calculate an OMC's transmission. First, we model the four-mirror cavity as a symmetric, lossless linear cavity of length L, with two curved mirrors having radius of curvature, R, and power transmission, T. Then various appropriate equations and symbol definitions are:

g-factor:	$g = 1 - L/R$
Free Spectral Range:	$FSR = c/2L$
One-way Gouy phase	$\phi_G = \arccos(g)$
Finesse	$\mathcal{F} \approx \pi/T$
Airy Fringe	$P(\delta f) = \left(1 + \frac{4\mathcal{F}^2}{\pi^2}\sin^2[\pi\delta f/FSR]\right)^{-1}$
TEM00 power overlap	$P_0(\omega_1) = 4\omega_0^2\omega_1^2/\left(\omega_0^2+\omega_1^2\right)^2$
1-D HOM field overlap	$\kappa_n(\omega_1) = \sqrt{\frac{2\alpha}{1+\alpha^2}\left(\frac{\alpha^2-1}{\alpha^2+1}\right)^n \prod_{i=1}^{n/2}\frac{2i-1}{2i}} \quad \forall n \in 2,4,6,\ldots$
HOM power	$P_{m,n}(\omega_1) = (\kappa_m(\omega_1)\kappa_n(\omega_1))^2$
Effect of astigmatism	$R'(\theta) = R\cos(\theta), \quad \text{or} \quad R/\cos(\theta)$

The g-factor equation assumes a linear symmetric cavity. The TEM00, 1-D HOM field overlap, and HOM power equations assume that the incoming beam waist is co-located with the cavity waist but is of the incorrect width.

3 OMC parameter selection

In order to specify the exact OMC length and mirror radius of curvature, we model the AS port light distribution using the static dark port powers from Table 2. In addition, we assume 5% mode mismatch between the interferometer beam and the OMC such that 5% of the total AS port power is in symmetric HOMs. Finally, we assume that 2% of the total power is distributed as junk light in HOMs according to a power law in the index $n + m$.

We show the input spectrum in Fig. 1 as it would appear in a mode scan using the eLIGO, L1 OMC. In this mode scan, and the following, the frequency on the x-axis is referenced to the TEM00 carrier mode. In comparison with the eLIGO mode scans, the closest RF sideband at 9 MHz is the smallest amplitude while the farther sideband at 45 MHz is almost equal in amplitude. The 4th order HOM is separated from the carrier by about 9 MHz, overlapping the RF sideband; consequently it is most visible in the lower panel.

To select the macroscopic OMC parameters, we calculate the attenuation factor of the OMC.

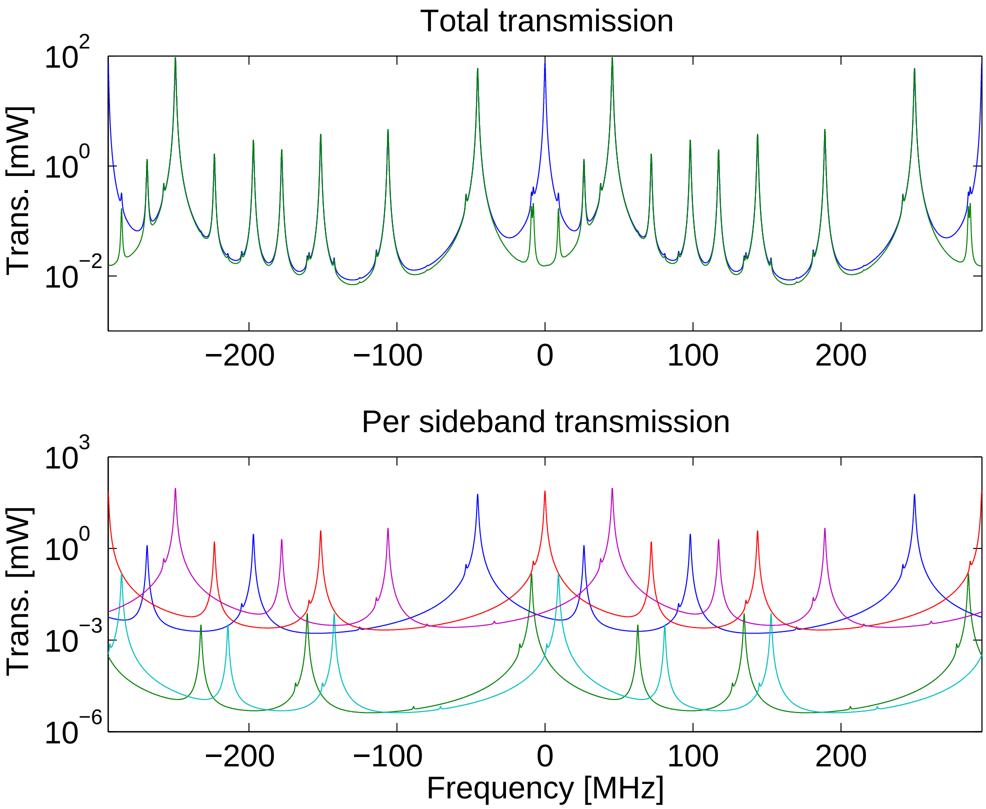


Figure 1: The expected aLIGO AS port spectrum as measured by the L1 eLIGO OMC with $\mathcal{F} = 400$, L = 0.51 m, and R = 2 m. The top panel shows the complete transmission, with and without the carrier TEM00 mode. The lower panel shows the transmission of each of the RF sideband components individually (-45 MHz = blue, -9 MHz = green, carrier = red, +9 MHz = cyan, +45 MHz = purple). The horizontal axis spans the range -FSR to +FSR.

This factor is the contribution to the $\delta f = 0$ transmission for all of the modes except the carrier 00 mode, normalized by the total “junk light” power. Obviously, this attenuation is a function of the cavity length, L, and the mirror radius, R, as they contribute to the FSR and ϕ_G. Figure 2 shows the attenuation factor for a selection of mirrors and a vector of cavity lengths. Here we assume length of 0.9 m is the maximum that can be reasonably fit onto an OMC breadboard of similar physical dimensions to the iLIGO OMC. There are two features to note. First, the increased cavity length increases the isolation of the dominant 45 MHz sidebands, hence the trend to greater attenuation. Second, there are many HOMs that must be avoided for a given mirror.

Both of these figures, the mode scan and the attenuation factor, neglect an important point. The key parameter in judging OMC performance is the reduction of noise, not just the transmitted power. To this end, we evaluate the spacing between the carrier and the nearest HOM, normalized by the free spectral range, as shown in Figure. 3. As this figure makes clear, the 9 MHz RF sideband is often the closest mode. Increasing the cavity length for a fixed finesse increases its effective distance. Above 0.8 m, the closest mode is the first HOM of the lower 45 MHz sideband. Longer than 0.9 m are impractical from a layout perspective.

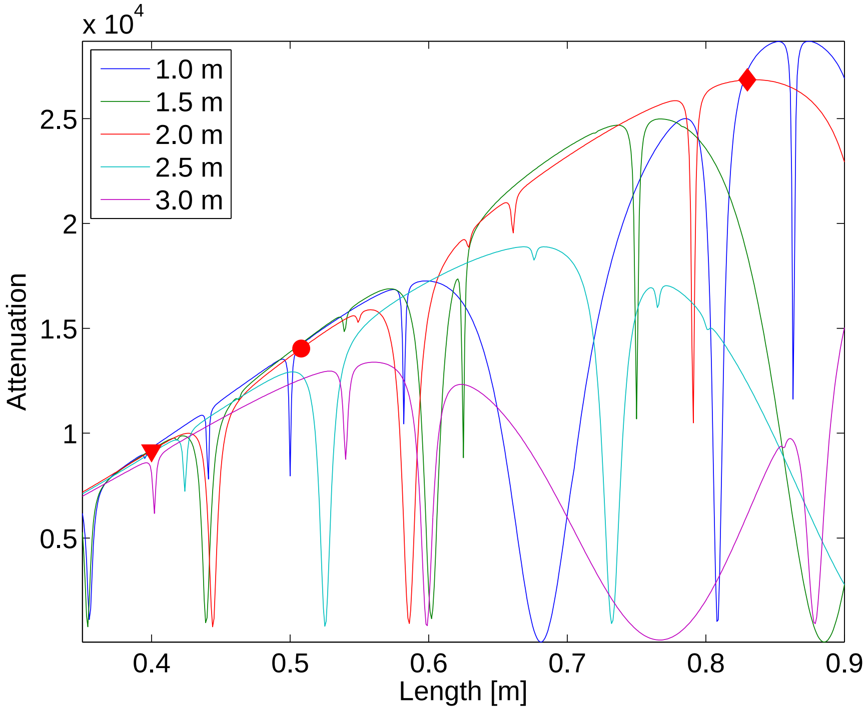


Figure 2: The expected aLIGO OMC attenuation factor for a selection of mirrors and a range of cavity lengths. The finesse is fixed at $\mathcal{F} = 400$. The L1 OMC length is marked with a circle, a "near 5th HOM" length with a triangle, and a "near 3rd HOM" with a diamond.

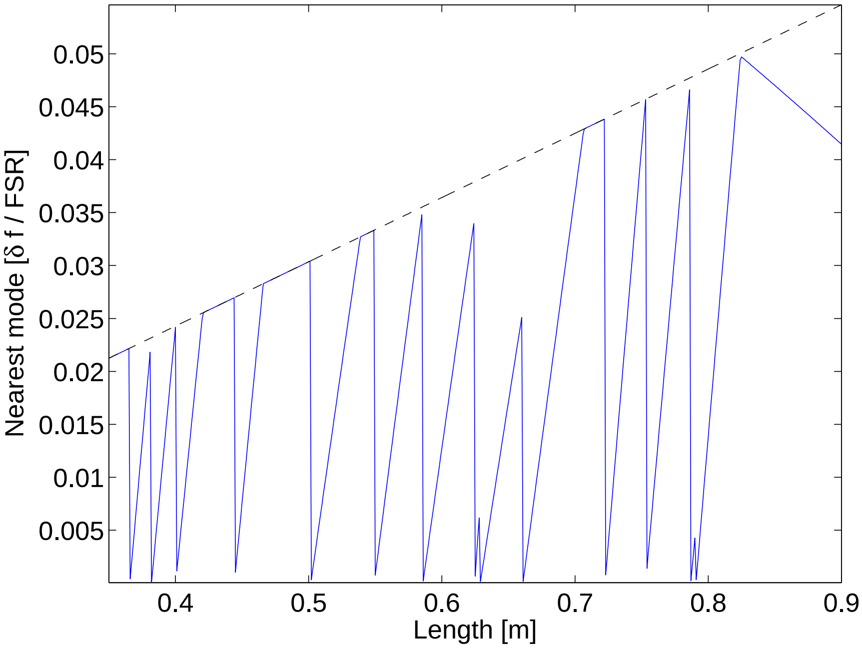


Figure 3: The spacing between the carrier and nearest HOM, normalized by the cavity FSR. The black dashed line shows the spacing of the 9 MHz RF sideband. HOM of order 0 to 7 are included in the calculation.

3.1 Approximations

We have neglected two factors in this analysis that we believe to be relatively insignificant. First, we have neglected to include the round trip loss in the OMC in the analysis of the transmitted light. This will reduce both the transmission and the finesse. However, we believe the excess loss observed in the eLIGO OMCs (about 60 ppm roundtrip) was due to construction techniques that will be avoided for aLIGO. In particular, the use of monolithic tombstones, AR surface bonding, and not heater element should reduce the loss to negligible levels for moderate finesse. Second, the OMC has a folded design that can lead to astigmatism. This effect is minimized by keeping the angle of incidence (AOI) onto each mirror small. The target 6° AOI shifts the Gouy phase by less than 1%, with a corresponding shift in the HOM frequencies.

4 Proposed design

The aLIGO OMC final parameters need not and should not be chosen until the exact AS port spectrum is measured. Until that time, however, we pick a straw man set of parameters based on the data in Figures 2 and 3. The mode cleaner with mirror R=2 m and L=0.714 m maximizes the attenuation factor subject to the constraints of the eLIGO OMC footprint. Furthermore, the L=0.714 m length selects a region in which no HOM (up to n = 7) contaminate the band between the 9 MHz sidebands. Figure 4 shows how the aLIGO OMC will fit into the current footprint.

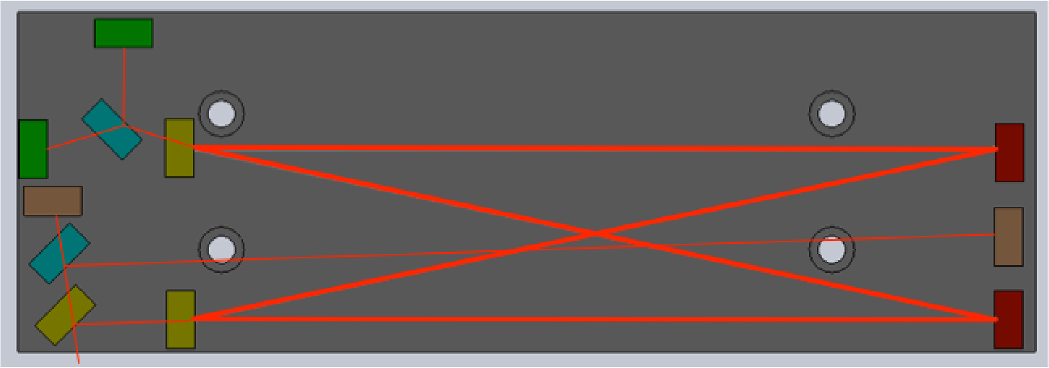
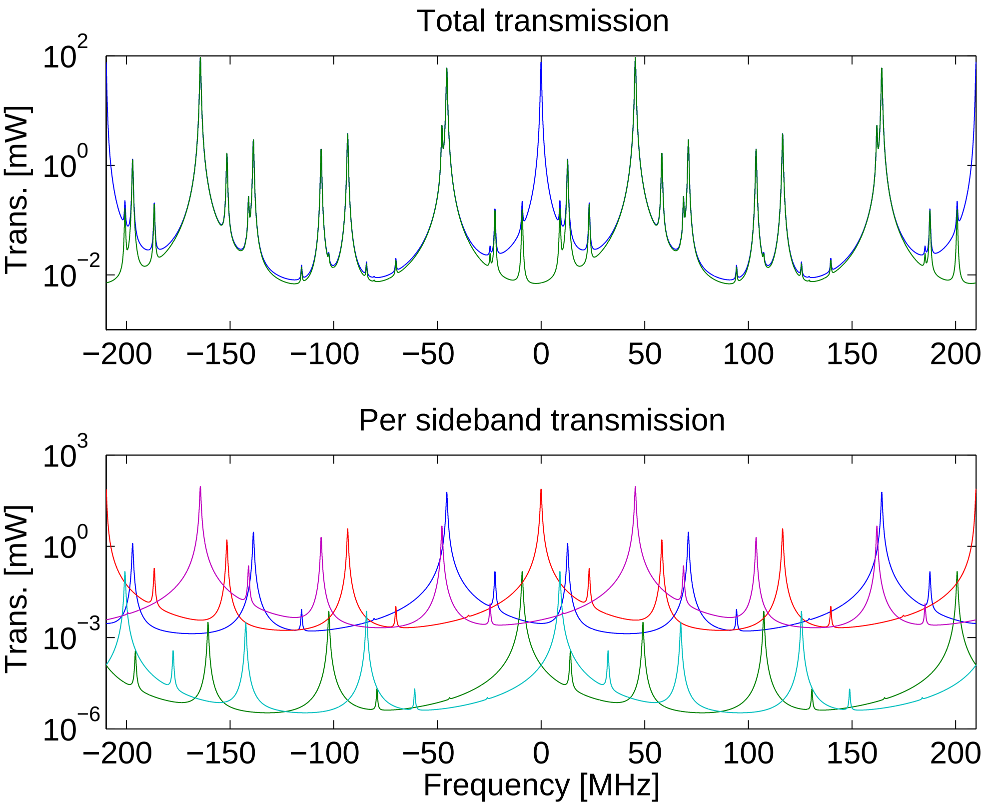


Figure 4: Schematic layout of L=0.714 m aLIGO OMC. The beam path is marked in bright red. R=2 m mirrors are denoted with red boxes, T=8,000 ppm input couplers with yellow, 50/50 beamsplitters with blue, quadrant photodiodes with brown, and DC photodiodes with green. The counterbored holes in the breadboard are for the suspension.

Figure 5 shows a mode scan of an L=0.714 m OMC with an example aLIGO spectrum. The carrier at 0 is roughly centered between the $n+m=1$ and $n+m=2$ modes of the -45 MHz RF sideband. With this length, the round trip Gouy phase is approximately 100°, so that no modes resonate in the vicinity of the carrier TEM00.



Total transmission

Per sideband transmission

Figure 5: Mode scan of a L=0.714 m, R=2 m, F=400 aLIGO OMC with an example aLIGO spectrum.

4.1 Actuators

The combined PZT and heater actuation design of the eLIGO OMC caused significant operational problems. Since then, we have identified a long-throw, multi-layer PZT stack from Noliac[1] that achieves several micron range from a very small, few millimeter thick package. In addition to removing the heater from the design, we will mount the curved mirrors using their back surfaces instead of the front. While placing additional demands on the assembly and mirror specification, this technique should reduce the scatter and loss associated with glue on the mirror front surface.

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[1] www.noliac.com, eg. CMAR04 ID=9 mm, OD=15 mm ring with 2.8μm stroke.