Output Mode Cleaner Design

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Distribution of this draft:

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1 INTRODUCTION

This note examines the design of an output mode cleaner for trial on an initial LIGO interferometer. There are several motivations behind the idea of trying an output mode cleaner:

- *Reduction of AS I signal.* Our current hypothesis is that the AS I signal (i.e., the RF signal present on the anti-symmetric port photodetectors that is in an orthogonal RF phase to the main differential arm signal) is produced by angular fluctuations in the interferometer. The AS I signal at frequencies above several Hertz imposes a limit on the light power an individual photodetector can sustain. This is true even with the AS I electronic servo that suppresses the AS I signal at the output of the photodetector preamp. Furthermore, at present operating conditions, the AS Q noise introduced by the AS I servo is only a factor of two below shot noise. An output mode cleaner should largely remove the AS I signal due to higher order modes, to greatly reduce the problems of AS I saturation and noise injection.

- *Improvement in shot noise sensitivity.* An output mode cleaner with significantly reduce the detected carrier light at the anti-symmetric port, giving a reduction in shot noise, with little reduction in the signal sensitivity. In LIGO-T030004-00-D, it was estimated that an output mode cleaner could improve the shot noise sensitivity by a factor of 2.4.

- *Saturation at 2fm.* Eventually, when a properly thermally lenses recycling cavity is achieved and the RF sideband efficiency is significantly increased, the sideband power should dominate the carrier power at the anti-symmetric port for optimal shot-noise sensitivity. Then the largest component of the photocurrent will be a constant 2fm sine-wave, from the beat of the upper and lower sidebands. It could become large enough to produce non-linearities, either immediately in the photodiode, or in the pre-amp, even though there is a 2fm trap in the photodiode load circuit (the traps are not quite as deep as hoped for, and it appears the pre-amp output must remain well below the supply voltage). With an output mode cleaner, the detected carrier light power would be substantially reduced, allowing a reduction of the modulation depth, which in turn would reduce the 2fm signal.

The basic concept is to make a small, triangular mode cleaner that would pass the TEM00 mode of the carrier and RF sidebands within the same resonance. The main requirements and design considerations are:

- Pass the TEM00 mode of the carrier with >95% power transmission, reject the first-order misalignment modes (m+n = 1) by a factor of at least 100 (in power), and reject higher-order modes up to (m + n = 6) by a factor of at least 30 (in power).

- Pass the TEM00 mode of the sidebands with >75% power transmission, and reject the even modes (m + n = 2, 4, 6) by a factor of at least 30 (in power). We wish to ensure that nearly all the detected sideband power is in the TEM00 mode, even if a thermally-lensed, stable power recycling cavity is not achieved. For reference, FFT simulations indicate that in the cold state, roughly 50% of the sideband power in the recycling cavity is not in the TEM00 mode.

- An error signal and suitable actuation is needed to lock the length of the mode cleaner to resonance. Alignment may be done manually, with no zero-crossing error signal (at least for the testing phase).
• Sufficient mechanical isolation must be provided so that fluctuations of the mode cleaner length do not introduce excess noise into the GW channel.

• Back-scattering from the mode cleaner must be considered and controlled so that it does not introduce excess noise into the GW channel.

Here is a summary of the proposed output mode cleaner (OMC) design parameters; the following sections motivate the design choices:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity finesse</td>
<td>&gt; 20</td>
</tr>
<tr>
<td>Cavity round-trip path</td>
<td>10 cm</td>
</tr>
<tr>
<td>Cavity bandwidth</td>
<td>≥ 100 MHz</td>
</tr>
<tr>
<td>Geometry</td>
<td>triangular ring cavity; fixed spacer with bonded mirrors</td>
</tr>
<tr>
<td>g-parameter</td>
<td>0.39</td>
</tr>
<tr>
<td>Mounting &amp; isolation</td>
<td>in-vacuum, single stage suspension</td>
</tr>
<tr>
<td>Locking and control</td>
<td>PZT-mounted end mirror, dither lock in transmission</td>
</tr>
<tr>
<td>Alignment</td>
<td>manual</td>
</tr>
</tbody>
</table>

2 CAVITY DESIGN

The basic notion is to use a triangular cavity, to reduce retro-reflected light, with mirrors bonded to a spacer. The usual such mode-cleaning cavity uses two flat mirrors mounted close to each other with faces oriented somewhat less than 90 degrees to each other, and a concave spherical mirror to close the triangle, as shown below.

\[
\omega_0^2 = \frac{\lambda}{\pi \sqrt{(R - l)}}
\]

\[
R = R_0 \cos \theta \quad \text{(tangential plane)}
\]

\[
R = \left(\frac{R_0}{\cos \theta}\right) \quad \text{(sagittal plane)}
\]

\[
l = \text{(round trip path)/2}
\]

The optical design parameters that must be established are: cavity free-spectral-range (round trip path length); cavity finesse; radius of curvature of the end mirror; angle of incidence on the end mirror. The first three parameters are examined in the following sections; here the angle of incidence is examined.
The choice of angle of incidence on the end mirror is a trade-off between lower back-scattering and larger mode ellipticity as the angle of incidence is increased. From the formula for the beam waist size, \( \omega_0 = \beta(R-l)^{1/4} \), where \( \beta = (\lambda \sqrt{l/\pi})^{1/2} \), we can calculate the relative waist size difference due to the effective radius of curvature difference:

\[
\frac{d\omega_0}{\omega_0} = \frac{1}{4g} \frac{dR}{R},
\]

(1)

\( dR/R = \cos\theta^{-1} - \cos\theta \approx \theta^2 \) \( (\theta < 25 \text{ deg.}) \)

where \( g = 1 - l/R \) is the cavity g-parameter. For \( g = 0.39 \) (see next section), the error is:

\[
\frac{d\omega_0}{\omega_0} \approx 0.02 \left(\frac{\theta}{10 \text{ deg.}}\right)^2,
\]

(2)

suggesting a maximum angle of incidence of approximately 10 degrees.

## 3 Mode Suppression

The cavity finesse and g-parameter determine how strongly higher-order modes are suppressed. This is shown in Figure 1 for a cavity finesse of 30. There are a couple of good choices of g-

![Figure 1: Power transmission of TEM\( mn \) Hermite-Gauss modes through a Fabry-Perot cavity that is resonant for the TEM\( 00 \) mode. The cavity is half-symmetric, formed by a plane mirror and a mirror of radius of curvature R, separated by a length L. The cavity finesse, which determines the width of the curves, is chosen here to be 30.](image-url)
parameter: \( g = \{0.15, 0.39\} \), which are distinguished by relatively better suppression for modes \( m + n = \{4, 5\} \), respectively.

For \( g = 0.39 \), Figure 2 shows the mode suppression as a function of frequency offset from resonance (relative to the cavity bandwidth); i.e., this figure shows how higher order modes of the sidebands are suppressed, as a function of how far from resonance they are.

![Figure 2: Mode suppression for a cavity with \( g \)-parameter \( g = 0.39 \), for a non-resonant TEM\(_{00}\) mode. The horizontal axis is the ratio of the modulation frequency to the cavity bandwidth (the latter being defined as the free-spectral-range divided by the finesse).](image)

\[ P_r \bigg/ P_{inc} = \frac{\Omega_m \cdot \text{BRDF} (\theta)}{T^2} = \frac{\text{BRDF} (\theta) \left( \frac{\lambda}{l} \right)^2}{T^2} \left( \frac{1 - g}{g} \right), \]

where \( P_{inc} \) is the incident power on the cavity, \( \Omega_m \) is the solid angle of the TEM\(_{00}\) mode of the cavity (\( \Omega_m = \lambda^2/\pi \omega_0^2 \)), and \( T \) is the power transmission of the cavity’s input and output mirrors.

4 BACK-SCATTERING

While the main beam reflection from a ring cavity is directed away from the incoming beam direction, there is still a retro-reflected beam that arises from the diffuse scattering at the cavity’s mirror surfaces. A fraction of the light that is scattered at each surface is scattered into the counter-propagating TEM\(_{00}\) resonant mode of the cavity, and is leaked through the input coupler directly back into the incoming beam direction. Since the distribution of the surface scattering, as characterized by the bi-directional reflectance distribution function (BRDF), falls at least as quickly as \((\text{angle-of-incidence})^2\), this retro-reflection is dominated by scattering at the cavity end mirror. The retro-reflected power \( (P_r) \) from such a triangular cavity is:

\[ P_r \bigg/ P_{inc} = \frac{\Omega_m \cdot \text{BRDF} (\theta)}{T^2} = \frac{\text{BRDF} (\theta) \left( \frac{\lambda}{l} \right)^2}{T^2} \left( \frac{1 - g}{g} \right), \]
To reduce $P_r$, one should choose a large $g$-parameter, and a long, high-finesse cavity. The last two criteria are in conflict with passing the rf sidebands on the same resonance as the carrier with high efficiency and low noise susceptibility, so a compromise is required. A finesse around 30 is needed to meet the mode suppression goals, and we will see later that a length of 5 cm is about the longest we would want to use. Choosing the larger $g = 0.39$ value, we have:

$$\frac{P_r}{P_{inc}} \bigg|_{g = 0.39} = 2.7 \times 10^{-8} \left( \frac{30}{F_{mc}} \right)^2 \left( \frac{\text{BRDF}(0)}{10^{-5}} \right) \left( \frac{5 \text{ cm}}{l} \right),$$

where $F_{mc}$ is the cavity finesse. To gauge the BRDF, refer to Figure 3, which shows a plot from the Newport catalog of the BRDF of their “ultra-low loss supermirrors”.

Note that since the retro-reflected beam arises from a counter-propagating mode that resonantly builds up in the cavity, the above expression gives the reflected power relative to the incident power in the TEM$_{00}$ mode only. Higher-order modes in the incident beam should have negligible retro-reflection.

For the anti-symmetric port beam, only a small fraction of the carrier power is in the TEM$_{00}$ mode. In the H1 interferometer, the difference in round trip losses between the two arms is estimated to be 30 ppm; this produces a contrast defect of $(1 - C_{00}) = 2 \times 10^{-6}$, compared to the estimated total contrast defect of approximately $10^{-3}$. So, for 200 W of power on the beamsplitter, the retro-reflected (carrier) power from the OMC is estimated to be: $200 \cdot 10^{-6} \cdot 2.7 \times 10^{-8} \approx 5 \times 10^{-12}$ W.

We can compare the back-scattering from the OMC to that from the LSC photodiode. The BRDF of the photodiode (EG&G C30642G) has been measured to be approximately $4 \times 10^{-5}$ /str at 6.5° incidence (T970068-00-D). The beam is typically focused on the diode to a waist radius of 150µm, corresponding to a solid angle of $1.6 \times 10^{-5}$ str. The power back-scattered into the incident mode would then be $6.4 \times 10^{-10}$ of the incident power, smaller than the back-scattered power from the OMC by a factor of about 40. However, back-scattering from the photodiode was originally analyzed assuming the full AS port carrier power of about 0.1 W incident on the diode(s); so the total back-scattered power would be approximately $6 \times 10^{-11}$ W, an order of magnitude larger than the above estimate for the OMC. So in the end the OMC appears to provide a reduction in the back-scattered power by about a factor of ten.

Next we consider the phase noise produced by this back-scattered light. The phase of the back-scattered field will be randomly modulated as it reflects from mirrors and beamplitters on its way back to the interferometer. The back-scattered carrier field is then retro-reflected from the Michelson, and travels back to the AS port photodetector, where, depending on the overall phase accrued in this trip, it will heterodyne with the sidebands to produce a signal. Assuming a worst case carrier phase shift, the signal will be linearly proportional to the phase fluctuations picked up along the back-scattering path. This back-scattering signal ($S_{sc}$), relative to the signal corresponding to the SRD phase sensitivity ($S_\phi$), is:
\[ \frac{S_{sc}}{S_\phi} \leq \frac{4\pi l_{sc}(f)}{\lambda} \sqrt{\frac{A_F P_r}{P_{bs}}} \frac{1}{\delta \phi_{SRD}}, \]  

where \( l_{sc} \) is the (one-way) path length fluctuation of the scattered light path, \( P_r \) is the carrier TEM\(_{00} \) mode power retro-reflected from the OMC, \( A_F \) is the power attenuation of the in-vacuum Faraday isolator, \( P_{bs} \) is the carrier power on the beamsplitter, and \( \delta \phi_{SRD} \) is the SRD phase sensitivity. To ensure that \( S_{sc} \) is negligible, the r.h.s. of the above equation should be less than 0.1, leading to:

\[ l_{sc} < 10^{-10} \frac{\text{m}}{\sqrt{\text{Hz}}} \left( \frac{\delta \phi_{SRD}}{7 \times 10^{-11} \text{rad}/\sqrt{\text{Hz}}} \right) \left[ \left( \frac{10^{-3}}{A_F} \right) \left( \frac{2 \times 10^{-6}}{1 - C_{00}} \right) \right]^{1/2}, \]  

where a Faraday isolation factor of 1000 (30 dB) is assumed, and \( \delta \phi_{SRD} = 7 \times 10^{-11} \text{rad}/\sqrt{\text{Hz}} \) for frequencies above 150 Hz.

What path fluctuations \( (l_{sc}) \) might we expect from the ISC-table optics? We can get an estimate by looking at the pre-stabilized frequency noise of a LIGO laser, as measured by an MC\_F spectrum (mode cleaner control signal). These frequency noise spectra have broad peaks in the one-to-several hundred hertz region, that are thought to be due to doppler shifting from acoustically driven opto-mechanical mount resonances. The H2:100-MC\_F spectrum, e.g., has a peak just above 200Hz, at a level of approximately 0.3 Hz/Hz\(^{1/2}\). If this is produced by doppler shifting from a moving mirror, the mirror velocity would be: \( v \approx c(\delta v/\nu) \approx 3 \times 10^{-7} \text{ m/sec}/\sqrt{\text{Hz}} \); and the corresponding mirror motion would be: \( x = v/2\pi f \approx 2 \times 10^{-10} \text{ m}/\sqrt{\text{Hz}} \).

This is just above the limit given in Eq. (6) above, but there are reasons to believe the situation might be better: this example used a peak in the MC\_F spectrum, and most of the spectrum lies below this level; with the acoustic enclosure, the sound level at the ISC table is probably lower than at the PSL table. Nonetheless, these estimates highlight the fact that the OMC should be designed with reduction of back-scattering in mind.

## 5 OMC Noise

Since the carrier and sidebands are at different points on the OMC resonance curve, length fluctuations of the OMC will produce a linear (AS\_Q) signal: the slope of the transmitted field phase-versus-length curve will be different for the carrier and sidebands, so that an OMC length fluctuation will effectively rotate the phase of the carrier constraint defect field out of the ‘wrong phase’, and partially into the phase that produces a heterodyne signal with the sidebands. This effect is analyzed in the Ph.D. thesis of Agnes Domijon (Virgo Project), as follows (there appear to be a couple of numerical errors in the thesis which, hopefully, are corrected here). Denote the carrier, and upper and lower rf sideband fields (TEM\(_{00} \) mode component only) incident on the OMC by \( E_c, E_1, \) and \( E_{-1} \), respectively. The change in the OMC field components, due to a change in the OMC length, is given by:
\[
\delta E_c = E_c \frac{i r^2}{1 - r^2} \delta \phi \\
\delta E_{\pm 1} = E_{\pm 1} \frac{i r^2 e^{\pm i \phi(\Omega)}}{1 - r^2 e^{\pm i \phi(\Omega)}} \delta \phi
\]

where \( r \) is the field reflectivity of the OMC input and output mirrors, \( \delta \phi = 2 k \delta l \) is the round-trip phase shift due to a length change of the OMC, and \( \phi(\Omega) = 2 \Omega l / c \) is the round-trip phase offset from resonance of the rf sidebands (modulation frequency \( f_m = \Omega / 2 \pi \)). The signal at the modulation frequency is computed using:

\[
S_\Omega = \delta [E_1 E_1^* + E_2 E_{-1}^*] e^{i \Omega t} + \text{c.c.}
\]

With the approximations \( \phi(\Omega) \ll 1 \) and \( r \approx 1 \), the signal is:

\[
S_\Omega = 8 J_0(\Gamma) J_1(\Gamma) P_{in} g_{cr} t_{sb} \frac{F_{mc}}{\pi} \sqrt{1 - C_{00}^2} k \delta l \left[ \frac{2 f_m}{\Delta \nu_{mc}} \cos \omega_m t + \left( \frac{2 f_m}{\Delta \nu_{mc}} \right)^2 \sin \omega_m t \right],
\]

where, following the LIGO symbol conventions, \( J_n \) is the Bessel function of order \( n \), \( \Gamma \) is the modulation depth, \( P_{in} \) is the interferometer input power, \( g_{cr} \) is the carrier recycling cavity field gain, \( t_{sb} \) is the field transmission of the sidebands from input to anti-symmetric port, and \( \Delta \nu_{mc} \) is the bandwidth (free-spectral-range/finesse) of the OMC. This is to be compared to the signal produced by a differential arm length change (T970084-00-D):

\[
S_{\Delta L}(f) = 8 J_0(\Gamma) J_1(\Gamma) P_{in} g_{cr} t_{sb} k r_c' \Delta L_D \frac{1}{1 + s_c} \sin \omega_m t,
\]

where \( r_c' \) is the derivative of the arm cavity reflected field with respect to the arm cavity round trip phase, \( \Delta L_D = \Delta (L_1 - L_2) / 2 \), and \( s_c = if / f_c \), with \( f_c \) being the arm cavity pole frequency. The ratio of the two signals is:

\[
\frac{S_\Omega}{S_{\Delta L}} = 2 \left( \frac{F_{mc}}{F_c} \right) \sqrt{1 - C_{00}^2} \left( \frac{f_m}{\Delta \nu_{mc}} \right)^2 \frac{\delta l}{\Delta L_D} (1 + s_c),
\]

where \( F_c \) is the arm cavity finesse, and the approximation \( r_c' \approx 2 f_c / \pi \) is used. Our interferometer and proposed OMC parameters are:

\[
F_c = 215 \\
f_m = 25 \text{ MHz} \\
\Delta L_D = 5 \times 10^{-20} \text{ m/\sqrt{Hz} at 150 Hz} \\
1 - C_{00} = 2 \times 10^{-6} \\
F_{mc} = 30 \\
\Delta \nu_{mc} = 100 \text{ MHz}
\]
These give, at 150 Hz:

\[ \frac{S_{\Omega}}{S_{\Delta l}} = 7 \times 10^{14} \cdot \frac{\delta l}{\text{m/Hz}} \]  

To ensure that the OMC length signal is at least 10× below the differential arm signal, we require a length stability of:

\[ \delta l < 1.4 \times 10^{-16} \text{ m/Hz}. \]  

What kind of isolation is needed to reach this level? The calibrated spectrum of a PMC control signal can be used to assess the length fluctuations of a cavity similar in construction to the proposed OMC, but with no acoustic or seismic isolation. The L1:PSL-PMC_PZT signal indicates length fluctuations of order 10^{-13} m/\sqrt{Hz} at 100 Hz, so clearly some type of isolation is required. Mounting the OMC in a small vacuum enclosure will provide acoustic isolation, leaving the question of how much mechanical vibration isolation is needed.

Let’s model the OMC as a right circular cylinder, or cross-sectional area \( A \). A force \( F \) applied to one face of the cylinder will change its length as \( \Delta l/l = F/YA \), where \( Y \) is the Young’s modulus of the material. If the face is mounted to a surface which is vibrating with an acceleration \( a \), this applies as:

\[ \Delta l/l = ma/YA = l\rho a/Y, \]  

where \( \rho \) is the density of the material. For fused silica, and a length of 5 cm, this gives:

\[ \Delta l/l = 1.6 \times 10^{-9} a \text{ sec}^2/\text{m}. \]  

Typical ISCO table accelerations are 10-20 \( \mu \text{m/Hz}^{1/2} \), leading to:

\[ \Delta l \sim 10^{-15} \text{ m/Hz}. \]  

Now, there will clearly be some reduction of this effect (factor of 10?) from the fact that the acceleration will be applied close to the center of mass of the OMC, rather than at one end. On the other hand, the OMC assembly will not be as stiff as a solid cylinder of fused silica: part of the spacer material will be a PZT, which will have a smaller Young’s modulus than fused silica; and the bonding of the assembly is bound to be less stiff as well. So, it seems prudent to provide at least an order of magnitude of vibration isolation at 100 Hz.

### 6 LOCKING

The proposed method of locking the OMC on resonance is a dither lock: with the end mirror of the OMC mounted on a PZT, modulate the OMC length with the PZT at some out-of-band frequency (10-100 kHz), lock-in detect the OMC transmitted light at the modulation frequency, and feed the lock-in output back to the PZT to stabilize on the resonance. Having the end mirror on a PZT actuator is preferable to the Virgo approach of thermally tuning a monolithic cavity because it provides much faster actuation. While such a composite cavity design may be mechanically noisier than a monolithic block, it is believed that it is still compatible with the length noise requirement given in the preceding section.

If the upper and lower rf sidebands were balanced in amplitude, the dither lock zero-point occurs when the carrier is at the center of the resonance, as desired. However, since the carrier TEM_{00} mode power will be much smaller than the rf sideband power, relatively small imbalance of the
sideband amplitudes will tend to pull the dithering zero-point away from the carrier resonance. This is a potential problem with dither locking that will have to be assessed.

There are a couple of other questions to answer regarding locking:

- sensitivity and shot-noise level of the error signal
- how tightly to resonance must the lock be held? (to maintain shot-noise limited sensitivity)

A basic block diagram of the locking setup is shown below. Hopefully, a strong enough lock can be obtained with a relatively low bandwidth servo (unity gain ~10 Hz), so that the error signal can be heavily filtered before it reaches the PZT.

Figure 4: Block diagram of the proposed OMC length locking system. A commercial lock-in amplifier provides a reference sine wave (10-100 kHz) which modulates the OMC length. The lock-in detects this signal on the LSC PD DC output. For the feedback, the lock-in output is routed through a spare LSC ASI channel (AS1, or AS4), and uses the ASI digital filter bank, DAC, and dewhitening filter. A medium- or high-voltage amplifier is needed to drive the PZT through a wavelength or more of travel. The PZT driver output will need to be low-pass filtered to avoid excess length noise of the OMC.
7 GEO OUTPUT MODE CLEANER

The output mode cleaner design for GEO is very similar to the design outlined above. A table of the GEO OMC design details are listed below, and the following pages contain drawings of the GEO OMC. For initial tests on H1, the GEO OMC will be used, on loan from GEO. LIGO will need to supply the mount, suspension system, vacuum enclosure, and controls for the cavity.

<table>
<thead>
<tr>
<th></th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finesse</td>
<td></td>
</tr>
<tr>
<td>Round trip path, bandwidth</td>
<td>100.11 mm, 100 MHz</td>
</tr>
</tbody>
</table>
| End mirror ROC, \( g \)-parameter | ROC = 75 mm, \( g \) = 0.33  
                                     | ROC = 85 mm, \( g \) = 0.41            |
| Beam waist radius               | 120 µm \( (g = 0.33) \)                 |
|                                 | 142 µm \( (g = 0.41) \)                 |
| Mirrors: polish coating         | Halle (conventional polish)             |
|                                 | Ebert (e-beam coating)                   |
| PZT                            | Piezomechanik-Dr Lutz Pickelmann GmbH   |
|                                | model HPSt 1000/25-15/5,               |
|                                | 5 µm/1000 V, 125 nF, 700 N/µm stiffness |

Table 1: Design parameters of the GEO output mode cleaner (see also the drawings on the following pages). It is believed that all pieces are bonded together with Vac-Seal epoxy. GEO had made two sets of end mirrors with different radii-of-curvature (ROC). The mirrors will have much higher loss than super-polished, ion-beam coated mirrors: acceptable to maintain the finesse, but, in the long run, probably unacceptable for back-scattering.
Optical beam path
Round trip: 100.11mm
End mirror type 1: $R=75$, $d=74.893$
End mirror type 2: $R=85$, $d=84.906$