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Non-Resonant Sidebands and the 4k Schnupp Asymmetry

Matt Evans

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1 Introduction

Several months ago work with SimLIGO lead me to the conclusion that the Schnupp asymmetry in the 4k interferometers (300mm) left the resonant sidebands (henceforth RSB, $f_{RSB} = 24.5$MHz) slightly over-coupled. This fact made lock acquisition, and interferometer length control in general, difficult, even in the idealized world of SimLIGO.

Exploration of thermal lensing in SimLIGO lead me to further conclude that slightly imperfect thermal load resulted in no reflected TEM_{00} RSB, and thus no REFL_I signal for the CARM degree of freedom. As the thermal lens, or lack there of, gets closer to that of the cold interferometer (IFO), the reflected RSB amplitude increases, thereby explaining the relative absence of difficulty in in controlling the physical IFOs in their current unheated (and poorly mode-matched) state.

Conversations I had with various members of the commissioning team eventually lead Daniel Sigg to write a technical note about the incorrect 4k asymmetry (T030066). In his note Daniel proposes three of solutions to the problem, the third of which, dealing with the use of the non-resonant sidebands, he essentially dismisses as impractical for reasons of control stability. Since that time Daniel and I have discussed this solution in some detail and agree that it does not suffer the problems he suspected. The following is a discussion of the implications of the coupled problems of incorrect asymmetry and thermal lensing, as well as a possible solution involving the use of non-resonant sidebands to produce an error signal for CARM.

2 The Problem

With the current asymmetry, the resonant sidebands will be close enough to critically coupled that alignment fluctuations and thermal lensing variations may cause their reflected amplitude to change sign unpredictably. It has been proposed that we change the asymmetry to ensure that the RSB are under-coupled, but if we aim for the design coupling we may still have large fluctuations in the CARM→REFL_I gain. This will be especially true during lock acquisition, when the ASC system is not active.

Though the exact amount of contrast defect fluctuation has not been carefully measured, the derivative of the fractional reflected RSB amplitude with respect to RSB transmission to the antisymmetric port is 14,

$$\frac{\delta r_{RSB}}{\delta T_{AS}} \simeq 14, \tag{1}$$

and changing slowly in the region of interest ($T_{AS} \sim 3.5\%$). The design value is $r_{RSB} = 0.1$, so less than 1% change in contrast defect will double r_{RSB}. Increasing the asymmetry to $\simeq$ 500mm, so that $T_{AS} \simeq 7\%$, would solve this problem (a 1% change in contrast defect would change r_{RSB} by less that 15%), but would likely cause a host of new problems.

The CARM→REFL_I gain is proportional to r_{RSB} and requiring more than a factor of 2 gain margin will be a limiting restriction on the carefully tailored common-mode servo. The delicate matrix inversion process used during lock acquisition is somewhat more sensitive, currently requiring sensing gains to be known with better than 20% accuracy. Furthermore, modeling of improved thermal lensing scenarios in SimLIGO has shown that even a sensing matrix known to 1% accuracy is not sufficient for reliable lock acquisition in a well mode-matched interferometer. All of these problems make the design control scheme problematic given the current (and even the design) asymmetry.

3 A Possible Solution

The solution I propose is to use the non-resonant sidebands (NRSB, with f_{NRSB} = 68.8MHz), already present for use in the alignment sensing and control system, to generate an error signal for CARM. A number of advantages, and one notable disadvantage, of this scheme are presented below.

3.1 Advantages

The NRSB provide a stable local oscillator to demodulate the carrier against, so the CARM gain should depend only on the carrier amplitude in the IFO, which is stable in detection mode and easily measured during lock acquisition. This is important for the stability of aggressive control loops that do not offer a large gain margin.

The reflected signal resulting from demodulation at the reflection port at f_{NRSB} (REFL_NR) is essentially insensitive to PRC. This should make lock acquisition considerably more robust by eliminating the singularity in the sensing matrix. PRC will behave much like MICH, simply moving from REFL to POB when the carrier amplitude in the PRM is large enough to provide a reasonable signal. This is an important feature because, while lock acquisition is generally not a limiting factor in the current state of the IFOs, it will be much more difficult with the expected improvements in RSB mode-matching which will result from thermal compensation and increased power.

The need for REFL_I in detection mode is eliminated. This allows us to avoid the problem of an uncontrolled REFL_Q corrupting REFL_I. This problem is comparable to the more widely known AS_I problem, both of which have been observed to result in lock loss. While this problem might be mitigated to some degree by the concomitant mode-matching improvement, REFL_NR is simply not subject to this sort of "saturation of the uncontrolled demodulation phase" problem.

The detection mode sensing matrix is diagonal and has simple frequency dependence. CARM→REFL_NR sees the coupled-cavity pole, DARM→AS_Q sees the arm cavity pole, PRC→POB_I and MICH→POB_Q are both frequency independent out to high frequencies. Also, the stability of the NRSB in combination with the bandwidth of the common-mode servo will make the carrier at POB a very stable local oscillator for the PRC and MICH signals.

Marginally, this may help WFS3 and WFS4 by eliminating the LSC component of the signal seen by these detectors. Furthermore, critically coupling the RSB to the AS port (as they are now) makes the AS_Q gain first order insensitive to alignment fluctuations. This is of little concern for control stability, but it might make the gravitational wave data more useful.

This control scheme has been tested successfully in SimLIGO as a means of maintaining interferometer lock. Lock acquisition code that uses NRSB has not, however, been developed at the time of this writing.

3.2 Disadvantages, from an email by Daniel Sigg

One of the disadvantages of using the NRSB is that our current LSC PDs are poorly suited for the task. Because of their rather high junction capacitance we expect the transimpedance gain to go down by about a factor of 10 (or 60 Ohms max over the "tuned" circuit). Here are the numbers: (i) /4 due to lower modulation depth (assumes we increase the NRSB Gamma to 0.1), (ii) x10 due to higher reflectivity, (iii) /10 due to lower transimpedance gain (this is true if we are limited by electronics noise, however it is not necessary true if we detect full power). According to the design we can tolerate the noise to be about 3-4 times above shot noise. Frequency noise coupling measurements indicate we may be a little bit better off. Adding it all up, an LSC PD in reflection using the NRSB will most likely be good enough. Since we don't crave for every photon in reflection, a better alternative might be to use a large area YAG-enhanced Si photodetector. We will loose a factor of 2-3 in efficiency but it should be possible to get a reasonable Q of the tuned circuit.

4 Conclusion

Given that the current situation of poor mode-matching is undesirable as an operating state, I doubt that we can make REFL_I a workable error signal for CARM without going well beyond the design resonant sideband reflectivity. What this means to me is that *the design control scheme is not practical*, that the interferometers work now only because our mode-matching is very poor, and that changing the asymmetry to give the design coupling is not a viable solution. I make this statement especially strong because I want to encourage creative discussion, and discourage a conservative "stick to the design" approach to solving this problem which I believe will be both expensive and futile.

The control scheme proposed herein has few apparent drawbacks and a number of advantages to support it. It is, however, a distinct departure from the design and should be considered carefully before being adopted.