Signal Response Measurements of Advanced Interferometer Configurations

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Abstract. Future gravitational wave detectors will include some form of signal mirror in order to alter the signal response of the device. We introduce interferometer configurations which utilise a variable reflectivity signal mirror allowing a tunable peak frequency and variable signal bandwidth. A detector configured with a Fabry-Perot cavity as the signal mirror is compared theoretically with one using a Michelson interferometer for a signal mirror. A system for the measurement of the interferometer signal responses is introduced. This technique is applied to a power-recycled Michelson interferometer with resonant sideband extraction. We present broadband measurements of the benchtop prototype's signal response for a range of signal cavity detunings. This technique is also applicable to most other gravitational wave detector configurations.

1. Introduction

Interferometer configurations of increasing complexity are now being investigated for use as gravitational wave detectors. Future detectors will most probably include some form of signal mirror to manipulate the frequency response of the detector with the goal of optimising the sensitivity. For example, Advanced LIGO [1] is currently planning to use resonant sideband extraction (RSE) [2], a configuration employing a signal mirror in addition to the power recycling mirror and arm cavities of LIGO. In this paper, we discuss two alternative configurations in which the signal mirror is replaced by a variable reflectivity mirror. The advantage of these configurations is the ability to alter both the peak frequency and the signal bandwidth independently. These two configurations and their signal responses are discussed in section 2.

With the addition of the signal mirror it is becoming increasingly important to be able to accurately measure and characterise the signal response of these devices. In section 3 we present a method capable of measuring the signal response of an interferometer over a broad range of frequencies. We present results obtained using this technique for a simple cavity and for a power recycled Michelson interferometer with resonant side-band extraction.

2. Advanced Configurations

Signal recycling [3] is a configuration capable of altering the GW detectors frequency response. By moving a mirror placed at the dark port of the interferometer by a fraction of a wavelength the peak frequency of the detector can be varied over a wide range. The bandwidth however, remains fixed, determined by the finesse of the signal recycling cavity which is mainly dependent on the signal mirror reflectivity. Currently this technique is planned for use in GEO600 [4].

Many gravitational wave groups are now focussing their research efforts on interferometers employing RSE. Resonant sideband extraction is a variant of signal recycling which adds cavities to the interferometer arms. This forms a three mirror cavity between the arm cavity mirror and the signal mirror. By varying the signal mirror position both the peak signal frequency and bandwidth of the detector are altered. However, the relationship between peak frequency and bandwidth is constrained as these parameters cannot be independently adjusted.

It is desirable to have an interferometer with both a tunable peak frequency and bandwidth. One extension of simple signal recycling [5] is to substitute a Fabry-Perot cavity in place of a signal mirror (see figure 1(a)). This cavity acts as a variable reflectivity signal mirror (VRSM). By detuning the phase of this cavity its reflectivity can be tuned over a wide range. An alternative technique to realise a VRSM is to couple a second Michelson interferometer to the main Michelson interferometer dark port as depicted in figure 1(b). The VRSM reflectivity can be altered by changing the Michelson fringe position. This configuration may have several advantages over the cavity alternative. Below we discuss and present numerically modelled signal responses for each configuration.

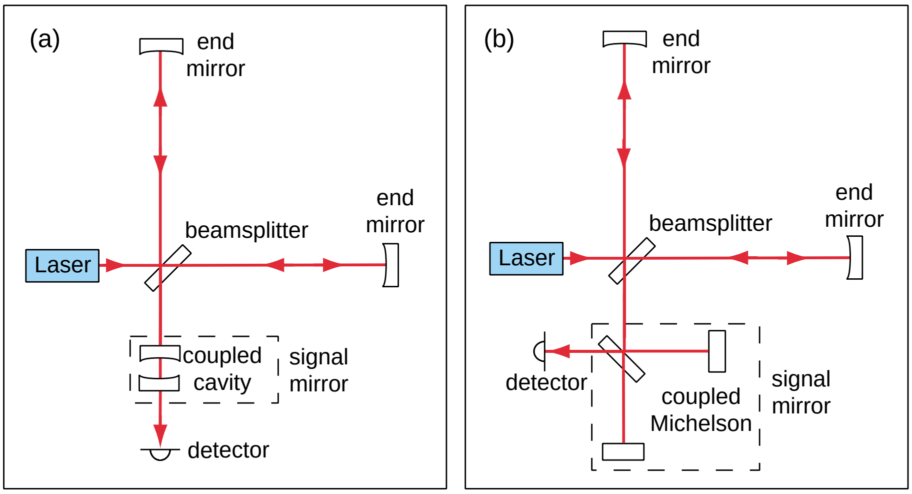

Figure 1. Schematics of Michelson interferometers with (a) cavity VRSM and (b) Michelson interferometer VRSM.

2.1. Fabry-Perot cavity VRSM

This configuration has two length degrees of freedom which influence the signal response. The motion of the cavity VRSM can be expressed in a basis of common and differential mode motion or as the individual motion of the front and back mirrors. Moving the mirrors by the same amount in the same direction (common mode motion) provides an identical result as moving the signal mirror in a simple signal recycling system. Figure 2(a) shows the peak frequency changes without a change in the signal bandwidth when the cavity VRSM common mode is detuned. When the mirrors are moved by the same amount in opposite directions (differential mode motion) the reflectivity of the cavity VRSM is changed. This situation is depicted in figure 2(b).

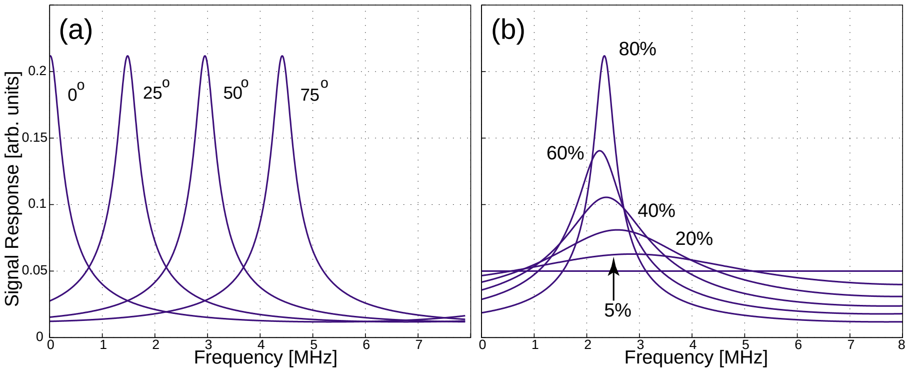

Figure 2. Signal response for a Michelson interferometer with cavity VRSM. (a) common mode offset of the cavity VRSM by 0^o, 25^o, 50^o and 75^o. (b) differential mode offset of the cavity VRSM to give reflectivities of 0%, 5%. 20%, 40%, 60% and 80%.

Differential mode offsets predominantly result in a change in the signal bandwidth. However, there is also a change in the peak signal frequency due to the change in phase shift of the cavity VRSM and the signal cavity itself. In an attempt to find a simple way to independently vary the signal bandwidth we consider the behaviour of the system undergoing displacements of the individual mirrors. Figure 3 shows the signal responses as the back and front mirrors are individually moved.

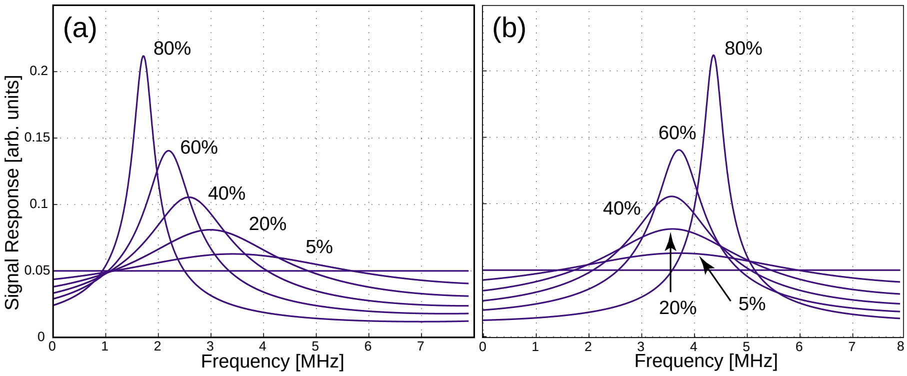

Figure 3. Signal response for a Michelson interferometer with cavity VRSM. (a) back mirror and (b) front mirror offset.

It can be seen from the plots in Figure 3 that when detuning either the front or the back mirror both the peak frequency and bandwidth are altered. To keep the peak frequency constant both mirrors must be tuned simultaneously in a manner that preserves a constant signal cavity phase. This motion will depend upon the ratio of the signal cavity finesse to the cavity VRSM finesse.

The responses shown in figure 3(a) are very similar to the responses expected from an RSE device. This is not surprising as this configuration is homologous to an RSE system, that is, both configurations are different forms of three mirror cavities. In an RSE system only the signal mirror can be moved (as the arm cavities must remain on resonance with the carrier) which is equivalent to an offset of the cavity VRSM back mirror.

2.2. Michelson interferometer VRSM

An alternative configuration couples a second Michelson interferometer to the main Michelson interferometer (see Figure 1 b). The two degrees of freedom for the Michelson cavity VRSM are the common and differential mode. The signal responses for this common and differential mode offsets are presented in figure 4.

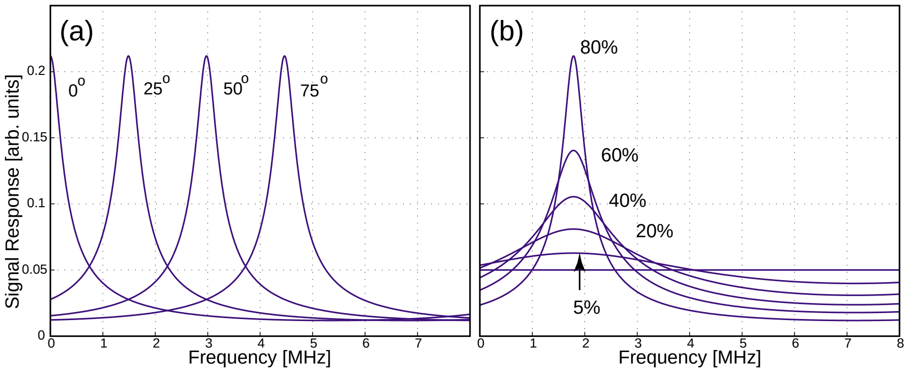

Figure 4. Signal response for a Michelson interferometer with Michelson VRSM. (a) common mode offsets of the Michelson VRSM by 0^o, 25^o, 50^o and 75^o. (b) differential mode offset of the Michelson VRSM to give reflectivities of 0%, 5%. 20%, 40%, 60% and 80%.

The common mode offset determines the peak frequency in the same manner as the cavity VRSM system. Common mode detuning simply adds a phase delay inside the Michelson VRSM and does not change its reflectivity. The differential mode determines the bandwidth without altering the peak frequency of the device. This is because the Michelson VRSM reflectivity is changed without adding a phase shift to the signal recycling cavity. Comparing figures 4 and 2 we can see that the Michelson VRSM allows orthogonal peak frequency and bandwidth adjustment.

Another potential advantage of this configuration is the smooth (sinusoidal) Michelson VRSM reflectivity profile. The reflectivity can in principle be tuned from 0% to 100% providing excellent control of the gravitational wave detector bandwidth.

3. Frequency response measurement

In this section we introduce a technique to measure the signal response of an interferometer. We illustrate this technique by first applying it to a Fabry-Perot cavity. We then detail a signal response measurement for a more realistic gravitational wave detector; a power recycled Michelson interferometer with resonant sideband extraction.

The details of this bench top prototype interferometer are discussed in detail elsewhere [6], [7] and here we concentrate only on the signal response measurement.

The peak response of bench-top interferometers system is typically in the MHz region. This is well outside the linear frequency range of most PZTs (typically only about 20-50 kHz when attached to a standard 1 inch optic). Using methods based on averaging and normalising the broadband response of the PZTs can still provide a signal response at these frequencies, however, the signal to noise ratio is typically quite low. Another method is to use broadband phase modulation at the input of the interferometer, and then calculate the transfer function between this and a signal injected into the arm cavities. This is a convoluted way to test the signal response of the interferometer and requires an arm length mismatch to couple the modulation sidebands to the dark fringe. Injecting a signal with broadband modulators inside the arm cavities [8] was avoided for reasons of loss and thermal distortions.

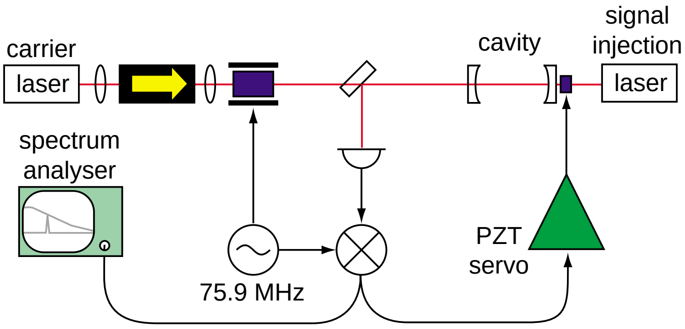

Figure 5. Experimental layout used to measure the broadband frequency response of an arm cavity

The method we used to map out the signal response was to inject an auxiliary laser through the end mirror of one of the arm cavities. The auxiliary laser acts as a substitute for the signal sidebands induced by a gravitational wave. The main advantage of this technique is that its bandwidth is limited only by the photodetection/demodulation electronics and so can very easily cover the signal frequencies of interest (tens of MHz) with high signal to noise ratios. The technique also allows the positive and negative signal frequency responses to be independently measured. This is an advantage when characterising a detuned interferometer with an asymmetric signal response. This is not possible using techniques based on phase modulation (produced either piezo-electrically or electro-optically) without altering the demodulation frequency.

We first demonstrate how this technique can be applied to a simple cavity using standard Pound-Drever-Hall locking. Figure 5 shows the experimental layout used to measure the signal response of one of the arm cavities. The cavity was locked and the error signal was observed on a spectrum analyser. In this case the error signal was obtained from the demodulated output at the reflected port. The auxiliary laser was tuned to have nearly the same frequency as the carrier laser. We ensured that the difference frequency was greater than the servo bandwidth so that the lock was not disrupted by the auxiliary laser. A large peak was observed, arising from the interference between the auxiliary laser and the modulation sidebands. It is important to note that this was the beat between the auxiliary laser and the modulation sidebands, not the beat between the auxiliary laser and the carrier as we are observing the demodulated detector output.

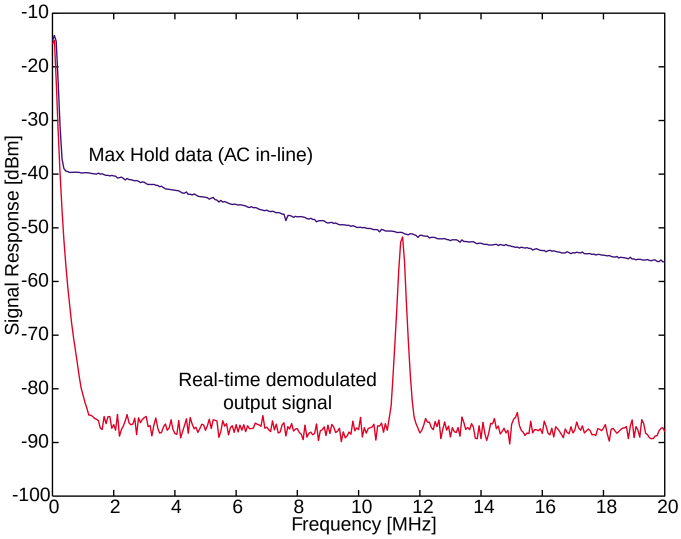

Figure 6. Spectrum analyser traces illustrating how the frequency response of the system is measured by the use of a auxiliary laser. Lower trace: real time signal (beatnote) after demodulation. Upper trace: broadband frequency response obtained using MAX HOLD function on RF spectrum analyser as the frequency of the auxiliary laser is manually changed.

As the auxiliary laser frequency was manually tuned the frequency of the beat note changed accordingly. By using the MAX HOLD feature on the spectrum analyser the signal response of the cavity was mapped out. The lower trace of figure 6 shows the real-time peak produced by the auxiliary laser while the upper trace shows the signal response obtained using the MAX HOLD function. Note the large signal to noise ratio of more than 30 dB at frequencies up to 20 MHz. Only the RF power spectrum of the error signal is measured and so unfortunately no phase information of the signal transfer function is retained. Phase information could be obtained if the auxiliary laser was phase locked to the carrier with an offset determined by the source of a network analyser, for example. This was not performed firstly as the amplitude response was adequate to demonstrate successful detuning and secondly due to the considerable added complexity of such a system.

The situation was slightly different when measuring the response of the RSE system. The signal must be measured at the differential mode error signal output as this is where the gravitational wave signal would appear. In our case this was the transmitted port detector demodulated output (for more details of the control system see reference [7]). As a sideband (the auxiliary laser) was injected in only one of the arm cavities this effectively added both a common and differential mode signal in equal amounts. The common mode signal, however, does not reach the detector at the transmitted port and so the signal response was identical to that produced if we were injecting a truly differential mode signal‡.

‡ This is assuming that the arm cavities are identical.

Figure 7 shows the measured frequency responses of the power recycled RSE Michelson interferometer for various detunings of the signal cavity. Both positive and negative signal frequencies are presented, clearly showing the asymmetry of the signal response for detuned cases. Of course when the signals reached the spectrum analyser the positive and negative frequencies were indistinguishable. The positive and negative frequency responses of figure 7 were recorded separately and combined during plotting.

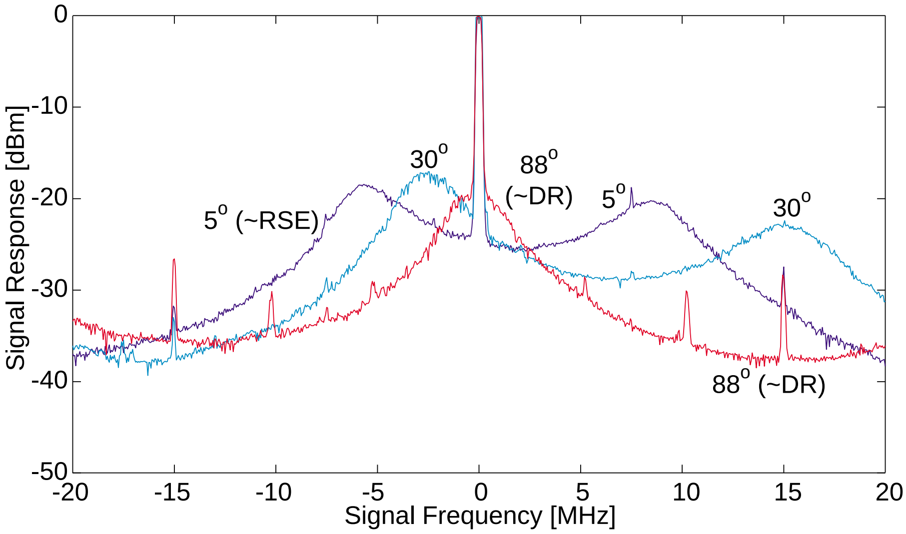

Figure 7. Measured frequency response (both positive and negative frequencies) of the signal transfer from one arm cavity to the Φ_- error signal for RSE Michelson system. The signal cavity detunings are indicated on the responses.

The number in degrees on each of the curves represents the detuning of the signal cavity where 0^o is broadband RSE and 90^o corresponds to dual recycling. Unfortunately, this control system could not be easily configured to lock the system without the signal mirror, and so a direct comparison with the frequency response of a power recycled Michelson with arm cavities was not possible. One other point to note is that this technique is not capable of measuring the increase in sensitivity achieved via power recycling or increased laser power. Both these techniques increase the sensitivity of the device by increasing the absolute size of the sidebands for a given gravitational wave strength. As this technique generates sidebands by the use of an auxiliary laser only the auxiliary laser power and the transmissivity of the end mirror will influence the signal sideband amplitude and is not determined by the carrier power in the interferometer arms.

4. Conclusion

We have shown that an interferometer made up of a Michelson VRSM allows orthogonal control of the peak signal frequency and signal bandwidth. This has potential advantages when designing a control system compared to the cavity VRSM configuration. A system for the measurement of signal responses for gravitational wave detectors was introduced. We presented experimental results for the signal responses of a power recycled Michelson interferometer with resonant sideband extraction.

References

[1] "LSC White Paper on Detector Research and Development", LIGO Internal Report, T990080-00-D (1999) "LIGO II Conceptual Project Book", LIGO Internal Report M990288-A-M (1999) http://www.ligo.caltech.edu/ ligo2/scripts/docs.html

[2] J. Mizuno, *et. al.*, *Resonant sideband extraction: a new configuration for interferometric gravitational wave detectors*, Physics Letters A **175**, 273-276 (1993)

[3] B. J. Meers, *Recycling in laser-interferometric gravitational-wave detectors* Physical Review D, 38 2317 (1988)

[4] H. Luck, *et al.*, *The status of GEO600, Gravitational Waves: Third Edoardo Amaldi Conference, Pasadena.* ed S. Meshkov , 119 (2000)

[5] K. A. Strain and J Hough, *Experimental demonstration of the use of a Fabry-Perot cavity as a mirror of variable reflectivity* Rev. Sci. Instr. 65, (1994)

[6] D. A. Shaddock, PhD Dissertation Thesis, Australian National University, (2000)

[7] D. A. Shaddock, M. B. Gray, C. Mow-Lowry and D. E. McClelland, *A power recycled Michelson interferometer with resonant sideband extraction*, to appear in Appl. Opt. (2001)

[8] D. A. Shaddock, M. B. Gray, and D. E. McClelland, *Experimental demonstration of resonant sideband extraction in a Sagnac interferometer*, Applied Optics. 37(34):7995-8001, (1998)