Pound-Drever-Hall locking of an optical cavity for use in an Ultra-Cold Strontium Experiment

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Abstract. A novel electro-optic technique was successfully implemented to lock a confocal Fabry-Perot cavity to the frequency of the input laser beam at 689nm. This required the electronic locking system based on the Pound-Drever-Hall (PDH) stabilization electronics, in addition to the feedback control electronics of a proportional-integral PI control servo lock. An electro-optic modulator, driven by a helical resonator, was employed to create sidebands on the laser locking beam which were essential to PDH lock. The system was designed to later be utilized as part of a larger experiment which aims to stabilize the lock of a high finesse ring cavity to the narrow atomic transition of ultra-cold strontium atoms. These atoms will serve as the basis for non-destructive gravimetric measurement and result in wider application of atomic interferometric sensors.

1. Introduction

A gravimeter can be simply be described an instrument for measuring the local gravitational field. It is a very particular type of accelerometer, measuring only the downwards acceleration of gravity and is more sensitive to fractional changes of the Earth's gravity. These changes can be due to temporal tidal variations or geological structures [1]. In recent years, it has proven to be of fundamental research interest for the precise measurement of Casimir forces but also in tests of general relativity [2]. Additionally, gravity sensors have proven to be indispensable in terms of their industrial applications. For instance they have allowed for gravity surveying along seismic lines in addition to inertial navigation and mineral prospecting.

Other forms of gravimeters which have proven to have unprecedented precision for gravitational field, magnetic and time-frequency measurements are atom interferometric sensors. Despite the precision with which measurements can be made, the application of this technology experiences limitations in size and complexity. This is particularly prominent in existing experiments which are based on ultra-cold atoms [3]. An alternative approach which has been explored is the trapping of ultra-cold atoms in a periodic potential, such that the atoms are forced to exhibit Bloch oscillations. These atoms have an oscillation frequency which is dependent on an external force: gravity. In doing so, any shift in the oscillation frequency relates to a change in gravitational field, resulting in a high precision gravity probe[3]. Although recent gravimeters have been developed using this technique, they suffer from the limitations of rapid repeatability of measurements which arises from the imaging technique used to monitor the atoms trapped within the potential.

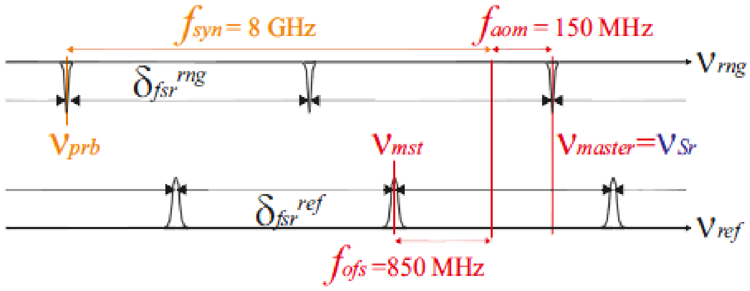

Figure 1. The transition lines of the cavity and the reference laser are shown here. The reference laser has to be offset from its normal resonance through use of the aom (f_{aom}). The resonance of the cavity are shown to coincide with the atomic resonance of the strontium atoms but also with another longitudinal mode which the ECDL will lock the cavity at. Figure used from [3].

The Strontium group based at Institute de Fisica de Sao Carlos (IFSC) aim to circumvent these problems through a novel approach which involves a high-finesse ring cavity. The group is currently developing a continuous precision sensor for gravity with additional applications, such a creating a new time standard. This non-destructive measurement process relies on discerning the magnitude of the impact on the confining light as a result of atomic motion. The oscillations of the atoms moving in the standing wave (which here acts as the periodic potential) will have a measurable effect on the phase and amplitude of the output [3]. This is achieved by allowing the standing wave to form inside a high-finesse ring cavity. The intensity and phase of the light transmitted by the cavity is modulated by the back action of the atoms inside the resonator. The transmitted light permits continuous observation of changes to the oscillation frequency, of a small ultra-cold cloud of atoms, in real time and with high precision.

To achieve this, a new technique locking a high finesse ring cavity to a narrow transition needs to be implemented. The cavity needs to be the correct length such that a standing wave can form inside it and therefore needs to be locked at a particular resonance. This proves problematic as any movement which is resonant with the ultra-cold atoms will result in thermal heating of the cloud. It is for this reason that a more complex locking system has to be employed. The cavity is instead locked to at resonance to a separate input laser beam: the extended cavity diode laser (ECDL). The frequency at which the ECDL operates is detuned from the atomic resonance of the ultra-cold atoms to be stored in the cavity by an integer number of free spectral ranges. The ECDL laser behaves as a slave to the DL Pro laser (which is otherwise referred to as the master laser) which locks to the atomic transition. The frequency at which the ECDL operates is represented by the transmission line labeled v_{prb} in figure 1. The result is that another longitudinal mode of the cavity is automatically at the correct frequency for the atomic resonance of the atom, v_{sr} (which here represents the atomic resonance of strontium atoms). This is shown in figure 1 to be two free spectral ranges away (δ_{fsr}^{rng}) from v_{prb}. The frequency of the master laser (v_{master}) is tuned such that it is at the same frequency as that of the atomic resonance of the strontium atoms (v_{sr}). The beam from the master laser also passes into the cavity to create the standing wave. This schematically illustrated in figure 2.

The DL Pro, shown in figure 2 [3], represents the 'master laser'. This is tuned to the frequency of the atomic transition and as such is able to trap the atoms in an optical lattice by forming a standing wave in the ring cavity – hence produces a periodic potential for trapping. A phase lock loop (labeled PLL in figure 2) is then employed between the DL Pro laser and the ECDL. The PLL allows the phase between the two lasers to remain constant whilst maintaining the ECDL's frequency one free spectral range away from the atomic resonance, such that it is non-resonant with the atoms. The ECDL can therefore be used to lock the cavity.

This approach has not been explored before as it would typically require the use of two longitudinal modes which are many free spectral ranges apart to avoid thermal heating of the cold atom cloud which is stored in the cavity. Rubidium which is most commonly used in cold atom experiments of this kind, for example, would require a phase lock over a distance which is of the order of terahertz as the linewidth of the transition one FSR away would overlap with the atomic resonance. The feasibility of doing this over such a range is technologically not possible. Strontium, on the other hand, is an ideal

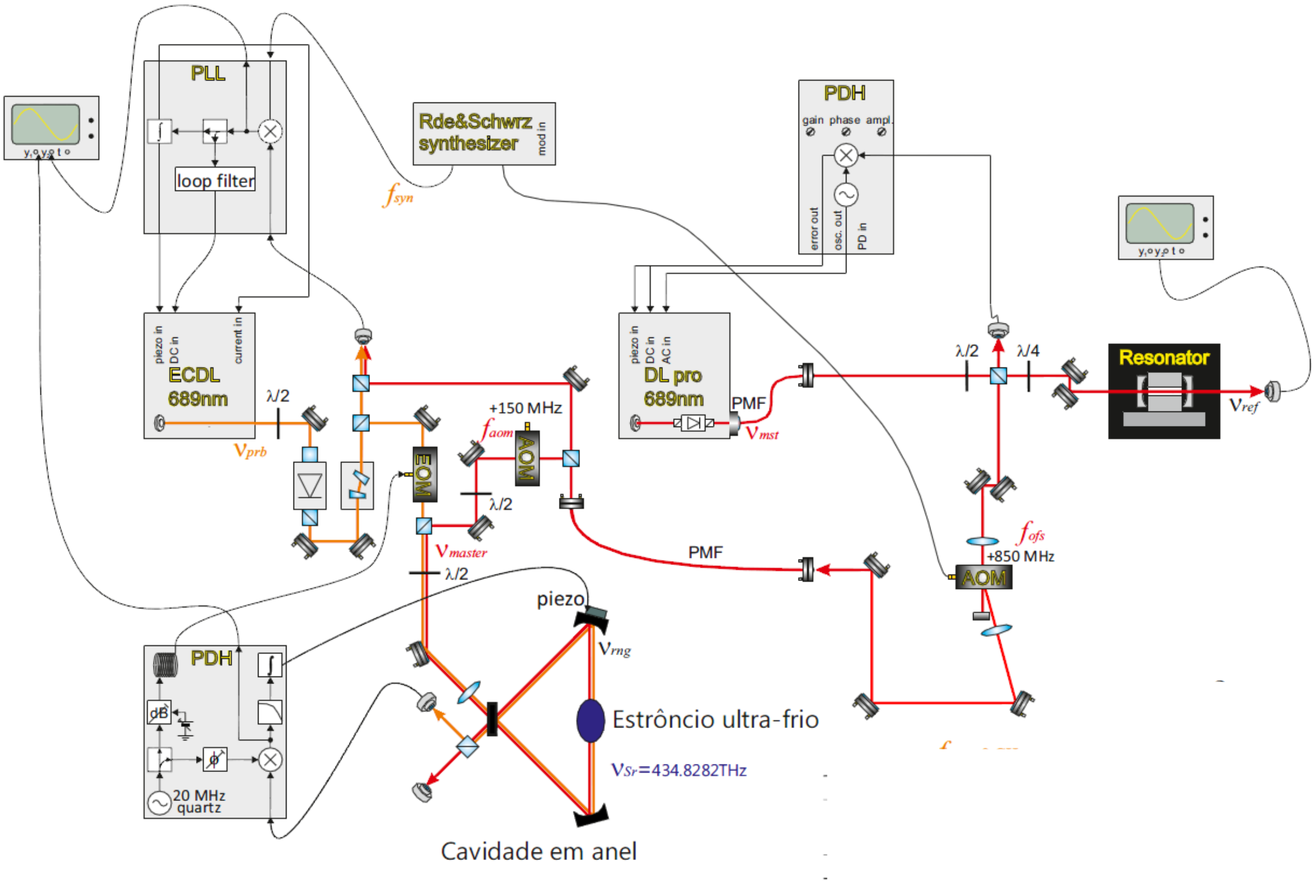

Figure 2. Schematic diagram of both the optical and electronic systems to be p finesse cavity to the ECDL via Pound-Drever-Hall technique. The ECDL is in turn shown to be kept locked to the DL Pro laser via the PLL. The cavidade em anel represents the the ring cavity and Estronico ultra-frio represents the the ultra-cold stontium closd to be stored witing the ring cavity

candidate for this scheme. It has a narrow linewidth transition (see figure 1 again) such that the distance over which the phase lock loop needs to be produced is of the order of gigahertz and only one free spectral range away. It is far away enough that it does not cause thermal heating of the ultra-cold atom cloud but close enough to be realistic to current electronic limitations.

A fundamental part of the locking scheme which this report concerns itself with, is the frequency stabilization electronics which will lock the ECDL laser to the high finesse ring cavity. The ECDL laser operating at 689nm acts as a probe laser to the cavity. The cavity is kept resonant with the ECDL using Pound-Drever-Hall locking scheme. The probe beam passes through an electro-optic modulator (EOM) which was driven by a helical resonator. The beam then passes into an optical cavity. The reflected signal is detected by a fast photodiode detector. This becomes an electrical signal which is passes through the PDH electronics such that the output error signal accounts for any frequency drifts of the laser. A proportional-integral-differential (PID) controller converts the signal into a high voltage output which drives the mirror mounted piezo-electric transducer (PZT). This allows the piezo mounted mirror to adjust accordingly by changing the length of the cavity and hence keeping it constantly in resonance with the probe laser. In this experiment, a Fabry-Perot interferometer was used in place of the high finesse ring cavity and an existing slave laser was used as the probe beam in place of the ECDL which had not yet been constructed.

2. Background

There are three fundamental areas which need to be brought together to achieve a successful locking system. The first was the Fabry-Perot cavity which was used in place of a high finesse ring cavity to test the locking system. The second was the purpose of the EOM and the helical resonator which generated the sidebands on the beam which were essential for the PDH electronics. The final aspect which is paramount to the success of the locking system is the PDH locking electronics

2.1. Optical cavities

A set of two or more mirrors which are arranged such that light is forced to propagate in a closed path is called an optical resonator or optical cavity. There are two basic types of optical resonators: a standing wave resonator and traveling wave (or ring) resonator[3]. A Fabre-Perot interferometer is a very simple device which relies on the multiple-beam interference of a monochromatic light source which falls incident upon the input mirror of the cavity. If the frequency of light is non-resonant with the cavity then destructive interference occurs resulting in little or no transmission. Another condition for this is that light can only be transmitted through the cavity if the twice the length of the cavity is equivalent to an integer number of half wavelengths.

A simple Fabry-Perot cavity consists of two partially reflective cavities which are aligned precisely parallel form the reflective cavity. The simplest of Fabry-Perot cavities which we are interested in is the scanning confocal etalon which requires that the two partially transmitting mirrors or partially reflective surfaces are arranged at a separation which is equal to the radius of curvature of the two mirrors[3].

Interferometers of this kind can then be scanned by varying the optical separation piezoelectrically. In doing so, different resonant modes of the cavity can be seen in the transmission as peaks. An important characteristic to consider is the linewidth of the peaks, Otherwise known as the full width half maximum (FWHM). It is important to note here that it is only when a standing wave forms within the cavity that a longitudinal mode is excited. Each mode has a characteristic profile which is shown in figure 3. These are known as the transverse- electromagnetic modes of the cavity (TEM), of which the fundamental mode is referred to as TEM_{00} [3].

The spacing in optical frequency between two successive transmission peaks of the same mode is defined as the free spectral range (FSR). It can also be given by the equation below as a function of the physical separation between the reflective surfaces,*d* [3]. The denominator of equation (1) therefore represents the *round-trip* length of the light beam inside the cavity.

$$FSR = \frac{c}{2 \cdot d} \tag{1}$$

The free spectral range, FSR of the cavity heavily impacts another characteristic of interest: the finesse. The finesse essentially quantifies the resolution of the interferometer [3]. It is measured as a ratio of the FSR and half the FWHM, or as it is known, the half-width-half-maximum (HWHM). It is also important to note that for a given FSR, the resolution of the cavity will only increase if the reflectivity of the mirrors is improved. At very high reflectivity, the surface quality of the mirrors comes into play as a limiter of the finesse.

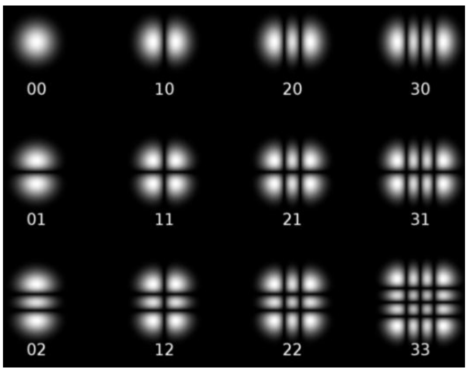

Figure 3: Presented here are the Hermite- Gaussian modes of a confcal mirror cavity [4].

2.2 Electro-optic modulator and Helical Resonator

An EOM is a device which can be used to modulate the input beam of light. The modulation can be imposed on the intensity, phase, amplitude, frequency or polarization of the input laser beam using an electric signal to control the magnitude of the change on these particular characteristics. EOM's, in general, contain one or two Pockell cells, this is usually accompanied by other optical elements, such as a polarizer[5]. The principle method of operation of an electro-optic modulator relies on the linear electro-optic effect (or Pockell's effect). This effect describes how the refractive index of the non-linear crystal (the Pockell's cell) is modified by an electric field which is proportional to the field strength that is supplied across it. This occurs due to forces distorting the structure of the material at molecular level or it position, shape and orientation [5].

The simplest kind of EOM is a phase modulator. In this instance, usually only one Pockell's cell is required and an electric field is supplied to the crystal via electrodes. The field changes the phase delay of the laser beam passing through it [5]. It is important that the polarization of the beam is aligned with an optical axis of the crystal such that the polarization of the beam is unchanged [5].

A common application of phase modulation is the creation of sidebands on a monochromatic laser beam. The advantage of this is that you get three beams that overlap themselves i.e. they are co-propagating. The additional beams are separated from the carrier frequency by a given phase shift and have a smaller amplitude. Mathematically, it is also simpler to describe the phase modulation of a monochromatic beam than its frequency modulation, despite producing essentially the same resultant beam [6]. Let us consider the case that the strength of a monochromatic laser beam, of frequency ω,amplitude A, enters the EOM is given by expression

$$Ae^{i\omega t}. \tag{2}$$

$$\Phi(t) = \gamma\, sin(\Omega \cdot t) \tag{3}$$

$$Ae^{(i\omega t+\, \Phi(t))} = \; Ae^{(i\omega t+i\gamma \sin(\Omega \cdot t))} \tag{4}$$

If a sinusoidally varying potential, $\phi(t)$, is then supplied across the EOM of frequency, Ω, which has a small amplitude, γ, given by the expression given in equation (3), then the beam described in equation (2) can now be described by the expression in equation (4).

By using a Taylor expansion for the exponential given in the RHS of equation 4, the first expression takes the form

$$Ae^{i\omega t}\big(1 + \gamma\, \sin(\Omega \cdot t)\big). \tag{5}$$

By substituting the identity for sine and tidying up the expression we find

$$A\left(e^{i\omega t} + \frac{\gamma}{2}e^{i(\omega+\Omega)t} - \frac{\gamma}{2}e^{i(\omega-\Omega)t}\right). \tag{6}$$

It is clear to interpret from this final expression that the original carrier frequency is still present with the addition of two small side bands at $\omega + \Omega$ and $\omega - \Omega$. The number of sidebands with noticeable power depends on the modulation strength (or modulation depth). A more mathematically rigorous analysis in which the other terms of the Taylor expansion are included can be found in [4].

In order to drive the EOM and create the sidebands, a high voltage power supply is required. This is often bulky and expensive. An alternative solution, which is cheap and easy to make is a step-up helical resonator which was used as an alternative to high voltage power source. This essentially functions by stepping up the voltage supplied to it (much like a step up transformer) when supplied a signal which is at the resonant frequency of the resonator[7].

2.3Pound-Drever-Hall locking technique

The scheme for stabilising the input light field to the length of the cavity and vice versa is known as Pound-Drever-Hall technique and is heavily based on much older techniques [3]. An effective method to measure the frequency of a laser beam is to pass it through a Fabry-Perot cavity and analyse the transmitted (or reflected signal). The Fabry-cavity behaves much like a filter in this sense. The transmissions (or resonances) of the cavity are evenly spaced in terms of frequency every FSR as a longitudinal mode only occurs when a standing wave is allowed to form between the reflective surfaces of the cavity. However, if the system is operated such that the cavity is not perfectly resonant with the incident light beam (e.g. operating to one side of the resonance such that only some of the light is transmitted), then it can be seen that a small drift in the laser frequency would produce a proportional change in the transmitted intensity. The intensity of the transmitted light can be fed back to laser via the tuning port and the laser can be held at this intensity, hence keeping the frequency of the laser constant.

One of the disadvantages of these previous techniques was that the system could not differentiate between the fluctuations in the laser's frequency to those variations of the laser's own intensity fluctuations. Both the reflected and transmitted beams are symmetric about the resonance and so another problem arises. If the frequency drifts away from the resonance, the output intensity measurement does not provide any information about which side of the resonance the beam is now operating on. The solution to this, upon which the Pound-Drever-Hall frequency stabilization methods are based, is by looking at the derivative of the reflected signal. This is instead asymmetric about the resonance. A measurement of the derivative signal would provide the missing information since any drift of the laser above resonance gives a positive output intensity value. Below resonance, however, the derivative signal is entirely negative. This is due to the reflected intensity being 180 degrees out of phase with the frequency [6]. If the laser beam is at resonance the derivative signal is at zero. It is the comparison of the variations on the reflected intensity according to the phase modulation that determines which side of the resonance the beam is operating at.

3. Method

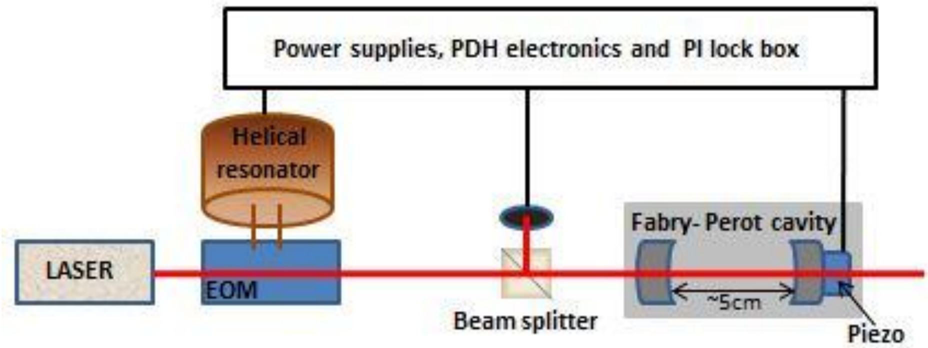

Figure 4. Simplified schematic of the optical system which was fixed to the optical bread board. It is important to note that all the fine adjustment mirror that were used to guide the light through the EOM and injected into the F-P cavity have been, as well as the lens which were used for beam shaping and quarter-wave plates have omitted. The laser presented here was in reality the output of the fiber. The electronic side of the experiment (here Power supplies, PDH and PI) is presented later in figure 5.

Light passes from the fiber output through an electro-optic modulator which is driven by a helical resonator. The EOM imposes a phase modulation on the beam, creating side bands on the beam which are essential for locking the cavity length to the laser. The beam (with its side bands) is then injected into the Fabre Perot cavity. This is then ´tuned´ such that the FSRof the output is optimized to the fundamental mode of the cavity. The back reflection falls incident upon the fast photodiode detector where it measures the optical bet frequency between the carrier frequency and phase modulated side bands. This carries the information of the phase difference between the two and is the PDH signal. This signal which carries information about how far the cavity is from resonance is PI feedback loop which can then allow the cavity is kept in resonance with the incident probe beam. A simplified version of the optical system used to achieve this is presented in figure 4. In order to create the locking system there were four main areas which had to be constructed and optimized before they could be placed in the set up and be operational and are presented in the following subsections.

3.1 Coupling the existing probe laser to a single mode fibre

To begin the experiment, an input laser beam is required. As the ECDL laser had not yet been constructed an existing probe laser was used. This required that the light from the slave laser in one laboratory be coupled to a 5m single mode fiber allowing the light from one lab to be transferred to another. A single mode fiber was chosen since it only allows a single mode of light to propagate through the core. As a result the number of light reflections created as the light passes through the core decreases. This lowers attenuation of the beam as it passes along the fiber, allowing it to travel further.

In order to do this, light had to be coupled into the fiber without misaligning the optical system which was already in place. A beam splitter was used to split a fraction of the light away from the setup with was already in place. A quarter-waveplate was used in conjunction with the beam-splitter such that the intensity ratio of the split beams could be controlled. This ensured that the experiment in one lab could go on unheeded by the other. A minimum of two mirrors with fine adjustment screws for the horizontal and vertical axes were required such that the laser light could be ‘beam walked’ to couple with the fiber.

Beam walking is essentially the process of adjusting the mirror such that they reach a specified point in space at a specific angle. Since light travels in straight lines, it is the equivalent of saying that the beam passes through two consecutive apertures. It is essential skill to have when working with optics as it can be used to make two beams precisely collinear for spectroscopy or interferometric purposes, or, as in this instance, for coupling into a fiber. There is a specified procedure which can be followed to successfully beam walk the laser light. The first mirror upon which the beam is incident controls the position of the mirror in the near field, whilst the second mirror controls the position of the beam in the far field, but affects the angle of the beam in the near field.

In order to achieve better coupling efficiency, such that the maximum amount of power is transmitted out of the other side of the fiber, another aspect has to be considered: mode-matching. This essentially requires that the modes of one structure match the mode of the other. When mode matching two beams, this requires good spatial overlap of the intensity and phase profiles of each. Provided that the complex amplitude of the two beams are matched in a given plane then it follows that they should remain well matched through further propagation [5]. In the case of coupling light into an optical fiber or a Fabry-Perot cavity good mode matching is achieved when structure of the laser beam is transformed into a Gaussian beam profile. This is readily attained through use of a thin film. Although more complex systems can be used, in this instance, only a one lens with a 40mm focal was required and sufficient to achieve good coupling. The optical system used is presented in figure 4.

3.2 Constructing and tuning the Fabry-Perot Cavity

A Fabry-Perot cavity was used in place of a high-finesse ring cavity. The cavity was constructed using two small confocal mirrors for 689nm wavelength. One of the mirrors was piezo-actuated such that its movement could be controlled using a high stability signal generator or synthesizer. In order to this the confocality of the mirrors was tested. It was found that the mirrors were not perfectly confocal and a skew or slant existed across the confocal surface as shown in figure 6. The mirrors therefore had to be arranged as also shown in figure 6.

Once the Fabry-Perot was constructed, it was then placed in the optical system shown in figure 5. The Fabry-Perot cavity has to be aligned with the output beam of the fiber. Just as was described for coupling the light into the single mode fiber, the beam had to be mode-matched with the Fabry-Perot cavity. For perfect matching to the cavity mode complete transmission of the fundamental mode of resonator has to be observed and no other modes should be excited in the FSR. There are two ways in which this can be observed; by eye, but is more precisely achieved by letting the transmission fall upon a fast photodiode detector (FPDD) and looking at the excited modes in one FSR on an oscilloscope. The purest output intensity of the cavity is given by the Hermite-Gausssian modes which are presented in figure 3.

In order to tune the Fabry Perot cavity to the fundamental resonant mode (i.e. the TEM_{00} mode exhibited in figure 3), the piezo was connected to a function synthesizer and set to sweep the cavity length. The function synthesizer was set to output a saw-tooth wave at frequency of 1Hz. In doing so, the output could be observed to change between the different resonant modes which were excited. By setting the frequency at a value of 40Hz instead, the observed output would instead exhibit the average output intensity, therefore exhibiting a single mode to which the cavity is best aligned. Improving the alignment to the fundamental mode is first achieved by walking the beam with the two fine adjust mirrors which 'fed' the laser beam into the cavity simply by watching the effect this had on the average output intensity and trying to tune the cavity to the fundamental mode. It was then optimized by changing the cavity length and angle of the mirror on one side of the cavity by adjusting the tautness of the affixing screws. These steps are iteratively repeated until the best possible transmission of the fundamental mode is achieved.

Once this has been tuned as best as is possible, the cavity transmission is the allowed to fall incident upon the FPDD (the electronics and construction of which is described in the next section). Both the function synthesizer and FPDD were connected to an oscilloscope such that the longitudinal modes per sweep could be seen visually. Provided that the initial rough optimization of the cavity to the fundamental mode by eye had successfully been achieved, per sweep of the cavity by the piezo should yield a FPDD intensity spectrum. Two of the modes in the sweep would have a much higher intensity than any of the other excited modes. These would represent the fundamental mode whilst the other smaller peaks would represent the other excited modes. The aim would now be to minimize the other peaks such that only the peaks of the fundamental modes remain through optimization techniques of beam walking and changing the cavity length just as before.

Just as before with coupling the light into the fiber, tuning the Fabry-Perot cavity to the fundamental TEM_{00} mode requires good mode matching. Again only a thin lens was used at a focal length of 25mm and is labeled in figure 3. An optical isolator was used in order to keep the reflected beam from getting back into the cavity and destabilizing it. Conceptually, an isolator need not be considered, but its use is essential in a real system.

3.3 Constructing a Fast Photodiode Detector (FPDD)

A fast photodiode diode was created using a FDS010 silicon photodiode from Thor Labs. This particular diode was chosen through a process of elimination of the available materials and was best suited to the task at hand. The wavelength range encompassed the wavelength of laser beam and the peak wavelength of 730nm was again the closest to the wavelength of the laser beam. The diode then had to be integrated into an electrical system. In order to minimize connections such that a fast response was achieved SMD electronic parts were used. A load resistor of 1.3kΩ was used such that current produced by the anode, which is a function of the incident light power and wavelength, was converted to a voltage signal. The resistor was placed between the photodiode anode and the circuit ground. Once constructed comparative testing to another fast photodiode detector was carried out to ensure a good response was achieved.

3.4 Pound-Drever-Hall electronics and PI lock box

The simplified layout of the optical scheme used to achieve the PDH is presented in figure 5. The laser beam is shown to pass through an EOM, which applies a periodic phase modulation at a fixed frequency. The phase modulated beam is then injected into the Fabry-Perot cavity. The FPDD then measures the reflected light from the cavity and will see an optical beat between the carrier field and the phase modulated sidebands. This also carries information at the modulation frequency. The modulation frequency is a measure of the phase difference between the carrier field and the sidebands [4]. Any slight changes in cavity length, or drifts in frequency would incur a proportional change in the phase of the carrier field.

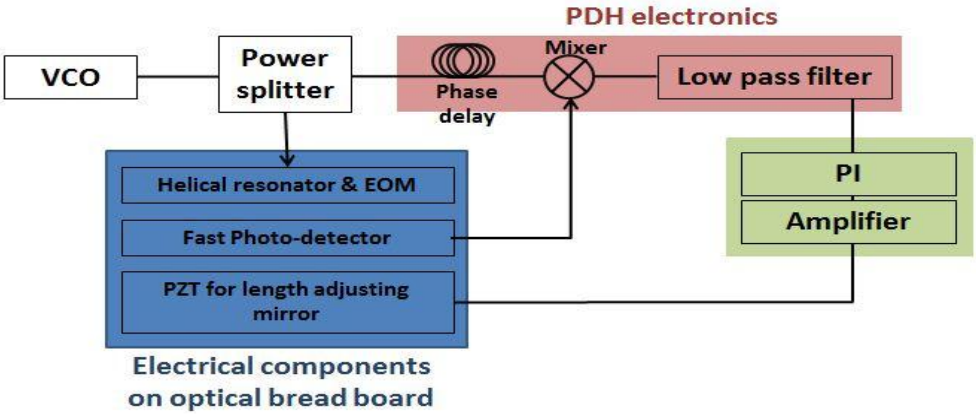

Figure 5. The electronics for the optical feedback locking are presented in simplified form. A voltage controlled oscillator was used to drive the helical resonator and PDH side of the electronics. PDH technique was used to tune the phase of the feedback from the FPDD which carried the beat frequency of the reflected signal from the cavity into the mixer of the PDH. The output PDH was passed through a low pass filter to pick out the error signal and then sent through the PI controller. The PI controller then generated an electrical corrective signal which was amplified to drive the PZT inside the cavity. A 10 meter BNC cable was used as the phase delay.

Figure 5 instead presents the electronic setup of the Pound-Drever-Hall technique. The EOM which is driven by the helical resonator is powered via a voltage controlled oscillator (VCO). The reflected beam is picked off by a polarized beam splitter and a quarter-waveplate before falling incident upon the FPDD, the output of which is compared with the local oscillator's signal via a mixer. A mixer can be thought of a device whose output is the product of its inputs. This will output two signals: one at a low frequency signal and the other at twice the modulation frequency. It is the low frequency signal that is of interest as it gives the derivative of the reflected intensity. The use of a low-pass filter on the output of the mixer isolates the low frequency signal. This was first connected to an oscilloscope to ensure that PDH signal is visible before being connected straight to the PI lock box.

A PI servo lock was used to lock the cavity length to the incoming laser light. This essentially took the signal from the FPDD and converted it into the appropriate electronic signal to control the PZT report. In order to do this, the set point (i.e. the zero of the derivative signal) had to be found and locked to. The PI then conducted an iterative process through which a high voltage response was created, in response to the signal fed to it by the PDH derivative signal of the reflection, to correct the cavity's length by driving the PZT accordingly.

4. Results

Overall, the aim of the experiment was achieved and a Pound-Drever-Hall locking system was implemented and the laser was locked to cavity resonance.

4.1 Coupling efficiency of the fiber

The introduction of a lens system resulted in better mode matching as the diameter of the beam was too large for the fiber interface. Prior to addition of the lens, the coupling efficiency was at ~30%± 3%. This was doubled with the introduction of the lens to 60%. Further working of the beam resulted in a 67%±3% efficiency. Percentages were used as opposed to actual power input and output values since these would vary according with dependence on the quarter-waveplate and the ratio of power across the beam splitter.

4.2 Tuning the Fabry-Perot cavity

The next step was to tune the Fabry-Perot cavity. Figure 6 shows the free spectral range of the cavity when it is not tuned to the fundamental mode and when the cavity is very well aligned to the TEM_{00} mode. As can be seen it was difficult to achieve good coupling to the TEM_{00} mode only. The other excited mode in the spectrum corresponds to the TEM_{01} mode to which the cavity was also quite well aligned.

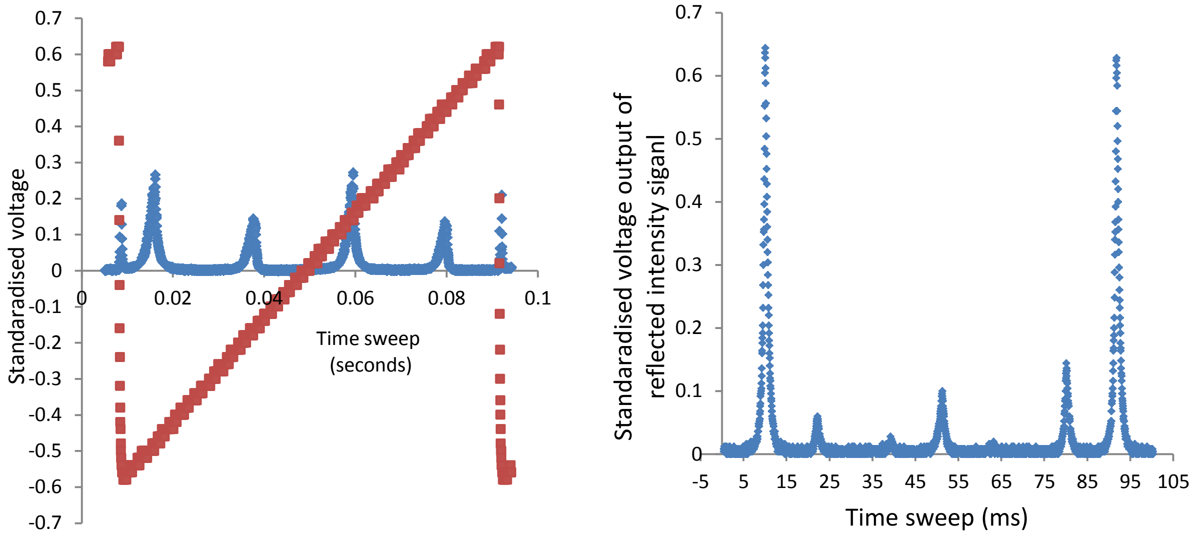

Figure 6. (Left) The plot shows the saw-tooth signal (red) over which the PZT mounted mirror was swept in order to scan for the longitudinal modes of the cavity which is presented by the blue plot. It is clear to see that some of the peaks are high then these others. This is because the cavity had already been roughly aligned by eye to the TEM_{00} mode. **(Right)** This presents instead the full alignment of the cavity to the fundamental mode. Although some other peaks representing other modes still show, their coupling to the cavity is negligible when compared to the amplitude of the peaks of the 00 mode.

4.3 Resolving the sidebands

Once good coupling had been achieved such that the peaks of the TEM_{00} mode were higher than those of the other cavity modes, the peaks of the fundamental were improved. As seen in fig 7, the peak needed to have a small linewidth as little noise on the signal could be achieved. Figure 7 shows that even when the central peak had large amplitude and small FWHM there was still some noise to contend with on the ascending side of the central peak. This was minimized by further walking of the beam. The EOM, driven by the helical resonator, was then switched on and tuned to run at 18.4MHz and produced the sidebands, shown in figure 7 (right), which are paramount in achieving a good PDH signal.

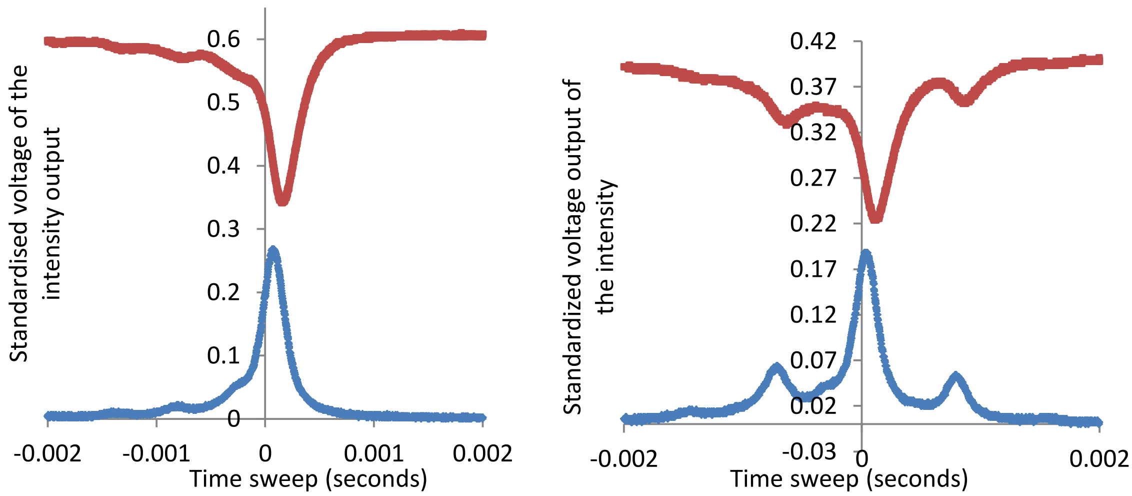

Figure 7. In the graphs above both the transmitted (blue) and the reflected (red) signal are shown. The difference between the two is the sidebands. **(Left)** represents the signals without the phase modulation of the EOM and the (right) presents the signal with the phase modulation. **(Right)** The three distinct peaks can be seen, and it is important to note that the amplitude of the carrier frequency has also decreased.

4.4 Obtaining the derivative Pound-Drever-Hall signal

The reflected signal with sidebands was allowed to fall incident upon the fast photodiode detector and yielded the result shown in figure 8. The left hand plot of figure 8 is particularly interesting as the peaks and troughs of the PDH signal can be showed to correspond to the intensity profile of the transmission (which is one minus the reflected signal). The figure on the right on the other hand shows only the PDH signal at its best. It is clear that there is a lot of noise in the system possible reasons for which are discussed in section 5.

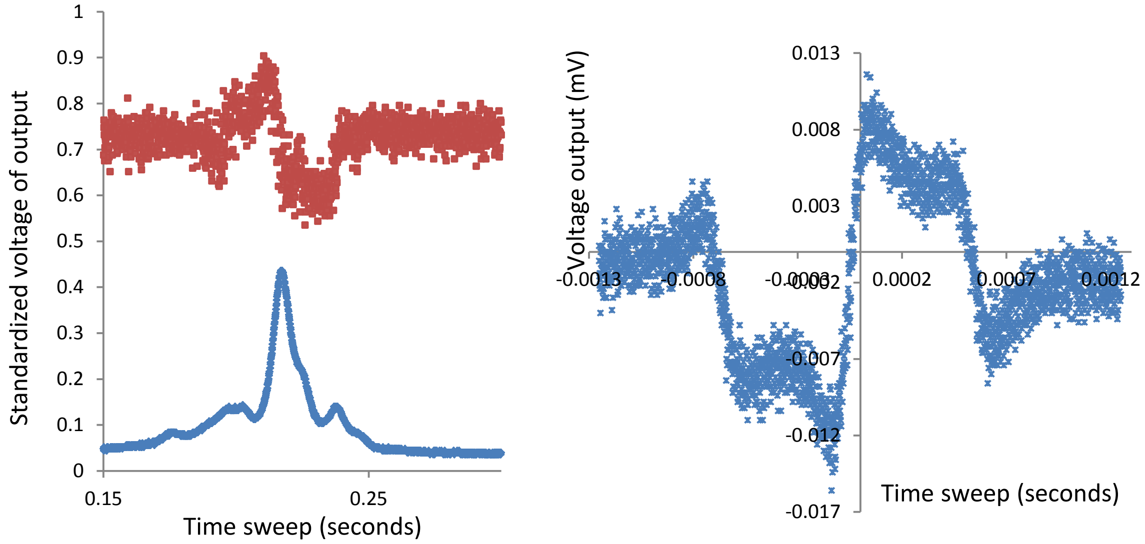

Figure 8. (Left) This shows the PDH signal as well as the transmission such that the contribution of the sidebands to the signal can be seen. The PDH signal in this instance is noisy whereas **(right)** presents a smoother PDH signal. This however is an example of a PDH signal produced by modulating the frequency instead of the phase.

4.5 Locking the cavity

The cavity was locked and maintained the lock to frequency up to and just over an hour at any one time, shown in figure 9. This was heavily reliant on how well the set point had been determined to begin with.

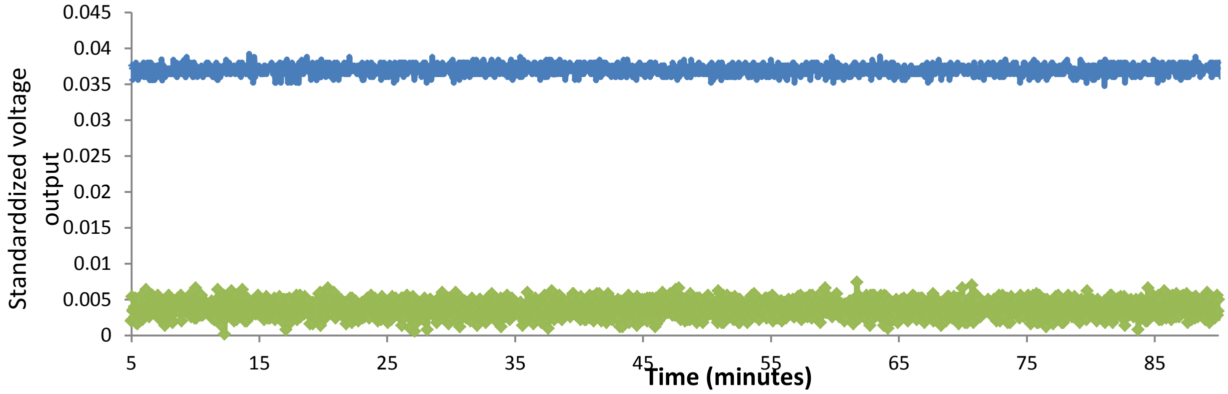

Figure 9. Demonstrates the lock achieved of the cavity to the frequency of the probe beam. The green plot shows the frequency of the laser changing a standardized voltage reading, whilst the blue line present the driving voltage of the PZT (as produced by the PI) to keep the cavity at resonance.

5. Discussion

The main limiting factor to a good locking scheme here was heavily based on the quality of the apparatus. This however was to be expected, particularly with respect to the Fabry-Perot cavity. Unlike the high-finesse ring cavity to be used in the final experiment, the F-P cavity only had a finesse of ~ 900. In addition to this, the mirrors of the cavity were not perfectly confocal, therefore aligning the beam through the centre of their combined focal points proved difficult.

The main areas which were most likely to malfunction were the helical resonator and EOM system. Although the EOM produced sidebands and was easily controllable, in being an EOM it suffered from requiring a huge amount of power to modulate the phase of the cavity probe beam. This was due mainly to the helical resonator needing improvement. When functioning the helical resonator worked beautifully at driving the EOM to produce sidebands. It was, however, a very temperamental piece of equipment and prone to malfunctioning. This was due mainly to the step-up coils contained within. The functionality of which relied on the diameter of the wire used, the diameter of the coil that was made with the wire, the spacing between each wind of the coil but also to the dimensions of the housing case. In particular the connections were an issue, as the coils were soldered into place, creating additional capacitance which affected the magnitude to which the voltage could be stepped up.

The final area to discuss is the Pound-Drever hall signal itself. As can be seen from the results it was extremely noisy and this had a direct effect of the quality of the lock. Although the PI system was able to lock on the zero of the PDH signal and maintain lock for over an hour, better accuracy and precision could have been achieved with a 'cleaner' PDH signal. Possible sources of noise could have been the back reflection of the reflected beam destabilizing the cavity. Another source of noise was the back reflection of light coupling back into the fiber. This would cause interference to occur within the fiber. Other problems include damage to the fiber itself again causing interference within the fiber and affecting the beam shape of the transmission. As previously mentioned the finesse of the cavity was very low and this would have had a direct effect on the quality of the PDH derivative signal which was produced.

6. Conclusions

A successful system for locking the cavity length to the input beam of the laser was achieved. Further study however is required in discerning the limitations of the equipment used. Further investigation into the PI servo- lock in particular would be beneficial. In doing, so the order to which corrections to the cavity length could be obtained. This provides information on the sensitivity of the lock i.e. the smallest variation which the PDH and PI lock can produce a corrective electrical signal to drive the piezo mounted mirror. The maximum jump in frequency that the PDH and PI lock can account for could also be determined. Another area for improvement would have been the helical resonator, because of its sensitivity to its own resonance at which it is driven; it was very easy to control the modulation depth of the sidebands simply by changing the frequency driving the helical resonator. However, revision of its design and the materials used needs to be seriously considered.

Acknowledgements

I would like to thank Prof. Philippe Courteille for giving me the opportunity to work on this fantastic and challenging project. I would also like to thank Mike Holynski and Paulo Hisao Moriya for their daily guidance. I would also like to acknowledge **Djeylan Ehktas** for his work on the helical resonator, **Jair** and **Joao Marcello** from LIEPO who constructed the PI servo lock and introduced me to the Zigler-Nichols method.

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