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Long-term wavelength stabilisation of widely modulated lasers

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ABSTRACT

In this paper, we present a novel technique for stabilisation of widely wavelength modulated lasers (>100pm) over long time scales, where modulation depths exceed the spectral width of standard reference features, such as gas absorption lines, by over an order of magnitude. The technique operates by controlling the temporal separation between successive appearances of a gas absorption line on the up and down sweeps of a sinusoidal laser wavelength modulation waveform. The influence of the signal distortions introduced by the laser intensity modulation that are associated with laser diode injection current modulation are also addressed. The technique is applied to a range-resolved interferometric system interrogating a Mach-Zehnder interferometer operating in thermally stable conditions, using an absorption feature from a fibre-coupled gas cell as a reference. Proof-of-principle measurement results achieved using this technique are presented, demonstrating a notional fractional stability of 3.9×10^{-7} without further correction.

Keywords: Frequency, Wavelength, Stabilisation, Modulation, Interferometry

1. INTRODUCTION

Laser-based metrological approaches have become significantly prevalent in the past half century and as technology improves, so does the resolution at which laser-based techniques can operate. Laser interferometry for example is constantly pushing the boundaries of high-resolution measurements, whilst simultaneously decreasing in cost as better laser and manufacturing technologies become available. A problem that plagues all laser-based techniques however is the stability of the laser emission wavelength, particularly in laser interferometry, where measurements are intrinsically linked to the laser emission wavelength.

This has led to the development of a large variety of techniques for long term laser wavelength stabilisation, with typical timescales greater than 1 second, usually applied to reduce laser drift over longer operational periods, such as in precision range-Doppler imaging,[1] laser frequency spectroscopy,[2] optical frequency combs for telecommunications[3] or laser cooling.[4,5] Interferometric measurements for example, require stabilisation over the entire measurement period, which could be during a complex stage motion, long assembly procedure or long-term observation measurements. An extensive range of techniques have been developed for these purposes, such as polarisation spectroscopy of atomic vapour,[6] the Pound-Drever-Hall technique,[7,8] self-injection locking to external cavities[9,10] among others.

For precision techniques such as range-resolved interferometry (RRI)[11,12] that typically use very large wavelength modulation amplitudes of many 10s of Gigahertz, far exceeding atomic or molecular linewidths that are on the order of 1 GHz, there are a number of constraints that limit the performance of existing techniques, requiring the development of new approaches for long-term laser stabilisation in these conditions. These constraints arise from the magnitude of the wavelength modulation depth, comparative to the linewidth of typical references, and the phase offset between the intensity and wavelength modulations in injection-current modulated techniques such as RRI.

In this paper, a novel technique for stabilisation of widely wavelength modulated lasers (sinusoidal modulation, amplitudes >100 pm) over long time scales is presented. The influence of the signal distortions introduced by the laser intensity modulation that is associated with laser diode injection current modulation is also addressed.

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2. THEORY

In RRI, a laser diode is modulated using sinusoidal injection current modulation, typically spanning most of the available current modulation range. This results in both a sinusoidal wavelength modulation of up to 1-2 nanometers, as well as a sinusoidal intensity modulation. Both are considered in the first order to scale proportionally to the injection current modulation, within the lasing current thresholds of the laser diode. While the intensity modulation is an important factor that will be discussed later, the intended output from this modulation is the wavelength modulation used in pseudo-heterodyne signal processing.

In a single period of the laser modulation, the wavelength emission of a laser diode modulated with a sinusoidal injection current will "sweep" through a range $\lambda_c \pm \delta\lambda$, where λ_c is the central laser emission wavelength, and $\delta\lambda$ is the wavelength modulation depth of the laser. This sinusoidal waveform has a modulation period the same as that of the injection current modulation waveform, but typically has a phase offset θ_λ determined by the laser diode and driver characteristics.

The laser is passed through an atomic gas cell and is directly incident on a photodetector, with the measured intensity I given by the Beer-Lambert Law;[13]

$$I(t) = 10^{-A} I_0(t) \tag{1}$$

where I_0 is the original intensity, and A is the absorbance, calculated as the product of the molar absorption coefficient ε, the interaction length l of the optical beam and the absorbing medium, and the molar concentration c. The molar absorption coefficient of the medium is wavelength dependent, which in turn is time-dependent, so Eqn. 1 can be re-expressed as:

$$I(\lambda_t, t) = 10^{-[\varepsilon(\lambda_t).c.l]} I_0(t) \tag{2}$$

where λ_t is the time-dependent wavelength modulation function. As expressed by Eqn. 2, as the injection current is modulated, there are changes to the intensity at the detector caused by both changes in $I_0(t)$ and the changes in the wavelength modulation, which results in changes to the absorption coefficient $\varepsilon(\lambda_t)$.

The result of the interaction with the gas cell is that for a single modulation period, an absorption feature within the wavelength range $\lambda_c \pm \delta\lambda$, where ε increases in value, will cause two significant dips in the measured intensity as the absorption feature at λ_n indicative of the forward and reverse sweep of the wavelength modulation over the absorption line. An example of this is shown in Fig. 1 for a single sweep through an acetylene gas cell ($^{12}C_2H_2$).

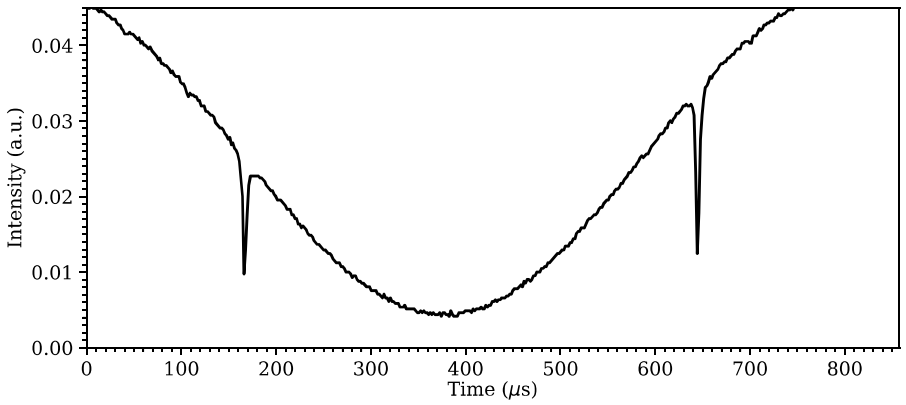

Figure 1. Photodetector reading for a single modulation period of a laser sinusoidally modulated across a single absorption line of an acetylene ($^{12}C_2H_2$) gas cell.

Whilst the intensity modulation of the laser is directly visible in the photodetector signal, the wavelength modulation is not and has a phase offset from the intensity modulation which results in the absorbance features, seen in Fig. 1 being skewed by the intensity modulation and offset from one another on the sinusoidal waveform. As a result, simply locking the absorption line to a fixed location on the visible modulation sweep, which is dominated by the intensity modulation, is inaccurate. Instead in the method presented here, the intensity modulation is first corrected using a fitted waveform of the same period and shape as the laser diode current modulation. This is achieved by application of the Beer-Lambert law re-arranged for absorbance, A, using the fitted waveform as the incident intensity I_0 and the photodetector signal as the transmitted intensity I.

The result is the calculated absorption which, once the intensity is accounted for, consists of two clear peaks, per gas line, on an approximately flat baseline. Using standard peak fitting techniques such as the Levenberg-Marquardt algorithm,[14,15] a Voigt or Lorentzian function, dependent on the pressure of the gas cell, can be fitted to both peaks.

To stabilise the laser emission wavelength, the laser junction temperature can then be tuned such that the two peaks, corresponding to the forward and reverse sweep over the same gas absorption line, are temporally separated by half the modulation period. Adjusting the laser temperature setpoint results in the peaks shifting either towards, or away from, the turning point of the modulated intensity signal. This concept is illustrated in Fig.2 where experimental data of a 1521 nm laser diode being sinusoidally modulated through an acetylene ($^{12}C_2H_2$) cell is shown for a range of laser temperature setpoints.

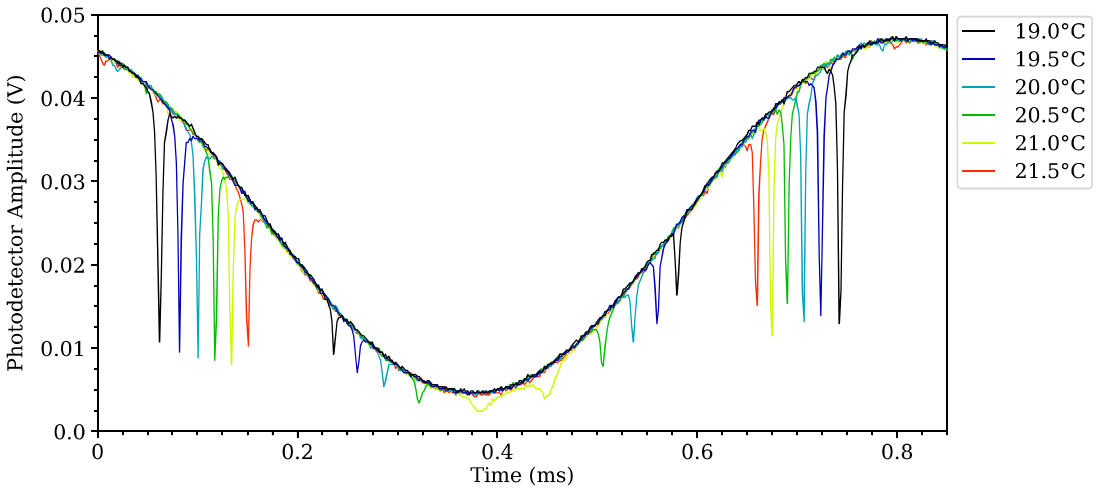

Figure 2. Photodetector signals for a sinusoidally modulated laser passing through a sealed gas cell over a pair of gas absorption line for a range of laser temperature setpoints.

Fig.2 shows a series of photodetector signals for a single sinusoidal modulation period through an acetylene gas cell. As the laser emission wavelength sweeps past the absorption wavelength of a gas line, an absorption trough is seen in the photodetector signal in both the forward and reverse sweeps of the laser. If multiple gas lines are within the laser wavelength modulation range, multiple pairs of gas lines will be visible within a single laser sweep. Here it can be seen how tuning the central laser emission wavelength, by changing the temperature setpoint of the laser temperature controller, alters the position of the absorption troughs on the intensity modulation signal, shifting the absorption troughs "up" or "down" the modulation waveform. As a direct result of this, for a given absorption line there is a wavelength, and hence temperature setpoint at which the time period between the forward and reverse sweeps over the gas line is exactly equal to half the time period of the laser modulation. To a first order, at this temperature, the central wavelength of the laser modulation is exactly equal to the absorbance line wavelength.

By comparing the difference in the times at which the two peaks occur, τ_δ to half the modulation period $\tau_{1/2}$, an error value can be calculated and a temperature setpoint adjustment can be applied. The error amplitude $\tau_{1/2} - \tau_\delta$ is a bidirectional value, and can be positive or negative as necessary, which makes it suitable for use in a control circuit as the error amplitude signal. This process, and the resultant absorbance for two different temperature set points are shown in Fig. 3, demonstrating conditions where the central emission wavelength is offset from the absorption line, and where the central emission wavelength is locked to the absorption line. Here, the fitting results for both the intensity modulation sine waveform and the Voigt fits of the absorption peaks are also shown. Fig. 3 illustrates two examples of the locking process using photodiode data from a wavelength modulated 1520 nm laser diode passed through an acetylene gas cell with a pair of absorption peaks for each single absorption line within the range of the wavelength modulation.

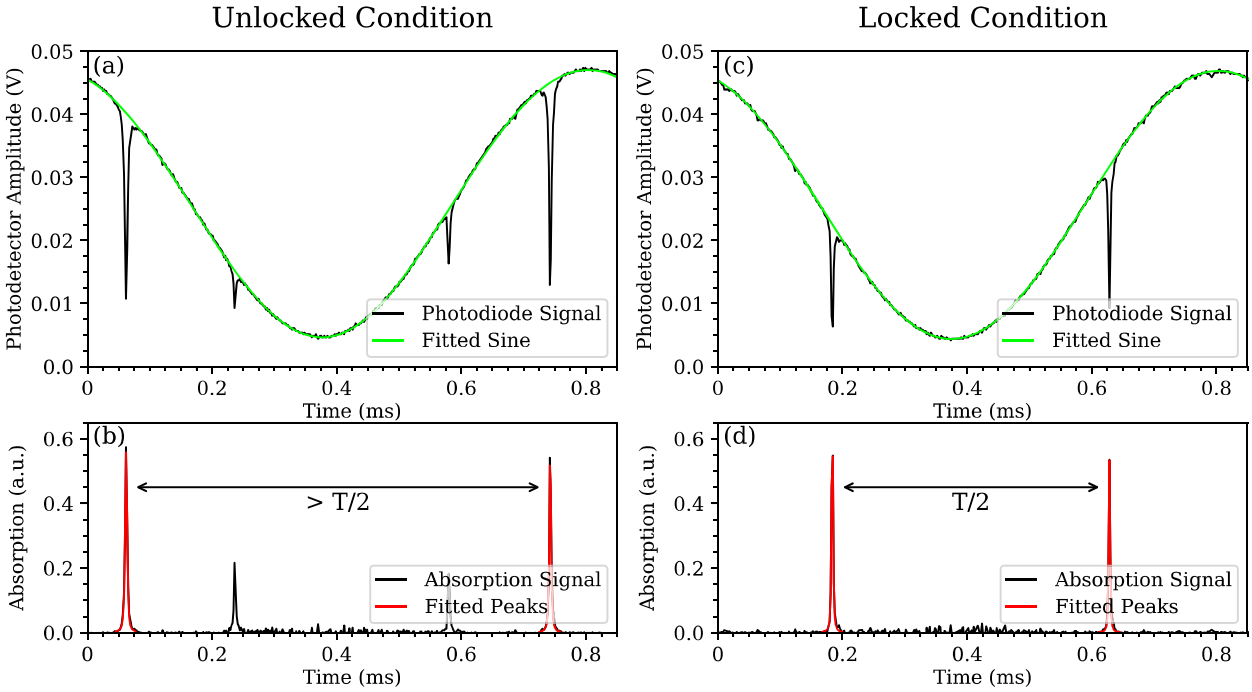

Figure 3. (a) Photodetector signal for a wavelength modulated laser diode passing through a gas cell with fitted intensity correction in the case where the stabilisation system is unlocked (b) Resultant absorption signal for the unlocked condition showing Voigt fits applied to the relevant peaks (c) Photodetector signal for a wavelength modulated laser diode passing through a gas cell with fitted intensity correction in the case where the stabilisation system is locked (d) Resultant absorption signal for the locked condition showing Voigt fits applied to the relevant peaks

Figs. 3(a) and (b) illustrate an unlocked example, where the temporal separation of the two peaks is greater than half the laser modulation period. In this case, a temperature setpoint correction would be applied to bring the peaks closer together. In addition, a second pair of peaks with a lower amplitude can be seen, indicating that the laser emission wavelength is being modulated across a second gas absorption line wavelength. In the locked case shown in Figs. 3(c) and (d) the temporal separation is exactly half the laser modulation period so no temperature correction needs to be applied to the laser diode. Notably, in the uncorrected signals shown in Figs. 3(a) and (c), the position of the peaks appear at different "heights" in the intensity modulation in the forward and reverse sweeps. This is a result of the phase offset between the intensity modulation which is the visible sine wave in the photodiode waveform, and the wavelength modulation which is not visible, discussed earlier. Once the sinusoidal correction has been applied, as in Figs. 3(b) and (d), the intensity modulation becomes irrelevant, and only the wavelength modulation defines the peak positions.

To determine the temperature setpoint change required to adjust the central laser emission wavelength to equal the absorption line wavelength, a secondary control loop, independent of the laser TEC control loop, is applied to the output of the process shown in Fig.3. Using a standard proportional-integral controller, the temperature setpoint is adjusted in discrete steps. In order to avoid competition with the laser TEC which operates at a bandwidth of 20 Hz, this stability control loop operates on a much slower time-scale of 0.05 Hz which is appropriate for the intended application of long-term stabilisation.

3. METHODOLOGY

The typical procedure for demonstrating stability of a laser emission wavelength or frequency stabilisation scheme is to interfere the laser emission locked using the stability technique under test, with the emission from a highly-stabilised and well calibrated laser source. In this case however, lasers with a wide wavelength modulation regime such as those targeted by this stabilisation technique, cannot be easily compared directly with a static wavelength emission source, as the modulation frequency of the modulated laser diode dominates the beat note frequency spectrum. Instead, in these experiments, an interferometric setup is interrogated and the phase change as measured by the interferometer is used as a measure of stability.

In order to test the stabilisation technique, a setup was devised that uses range-resolved interferometry (RRI) to interrogate a simple Mach-Zehnder interferometer with a notional path length imbalance. Using a 1521 nm discrete mode laser diode (Eblana EP1512-DM-B, linewidth ∼2 MHz), the light is split into two separate paths, one arm of which is passed through a fibre-coupled gas cell and is incident on a photodetector. The other arm is guided through a fibre-based Mach-Zehnder interferometer with an optical path length difference between arms of ∼6 cm, and is incident on a separate photodetector. The outputs of both photodetectors are sampled by electronic signal processing hardware which also controls the laser modulation and TEC temperature setpoint.

To reduce the effect of thermal instability between the interferometer arms, which would contribute to measured phase changes, both arms of the interferometer are fixed within an ice bath. In addition, two water pumps are used to create circulation in the ice bath, and the entire ice bath is placed within a thermal chamber. This setup is shown in Fig. 4.

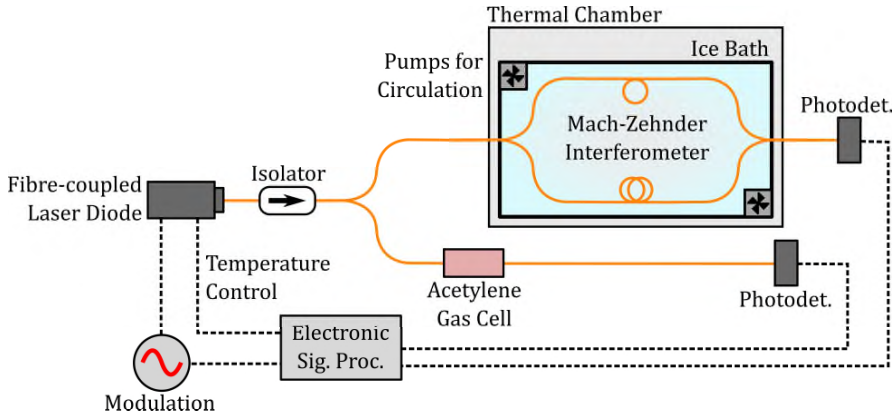

Figure 4. A diagram of the setup used in these experiments. The interferometer arms within the ice bath are affixed to an aluminium plate which is not shown.

Fig. 4 shows a schematic of the experimental setup used in this paper. Notably, the sensitive region of the interferometer is affixed entirely in the ice bath. The thermal chamber temperature is set as close to the water freezing point as possible so that fluctuations of the thermal chamber temperature, due to the heating and cooling cycles of the thermal chamber control loop, fluctuate either side of the freezing point. Here the goal is that the temperature of the ice bath remains as stable as possible, making use of the latent heat of the phase change between water and ice to reduce the effect of fluctuations of the thermal chamber. The water pumps in

the ice bath create circulation of the water, which helps to homogenize the temperature of the water throughout, reducing any temperature differential between the two arms of the interferometer. This is aided by an aluminium plate, with high thermal conductivity, to which the interferometer within the ice bath is affixed, to reduce any motion effects of the water on the interferometric measurements.

In this application of the swept absorption line locking technique, a single-mode fibre-coupled acetylene gas cell (Wavelength References $^{12}C_2H_2$ at 50 Torr[16]) with a path length of 3 cm is used. Acetylene has multiple absorption lines present in the wavelength emission range of the modulated laser diode used in this experiment which can be swept past through temperature tuning of the laser diode however the absorption line of interest is at 1521.06 nm (free space).

4. RESULTS

To demonstrate the effect of the stability control loop, a temperature gradient was applied across the laser diode via a radiant heat source positioned above the laser diode, such that the emission wavelength of the laser diode was slowly altered. During this, the phase change in the Mach-Zehnder interferometer due to the wavelength drift is calculated and recorded.

After a period of 15 mins, the power supply to the heat source is switched on and slowly heats up over a period of 1 hour. After this time, the power supply is switched off and the source begins to cool. This is repeated for both a free-running and stabilised laser diode. Fig. 5 shows the measured phase changes in the Mach-Zehnder interferometer over the total measurement time and the laser TEC setpoint temperatures during this period.

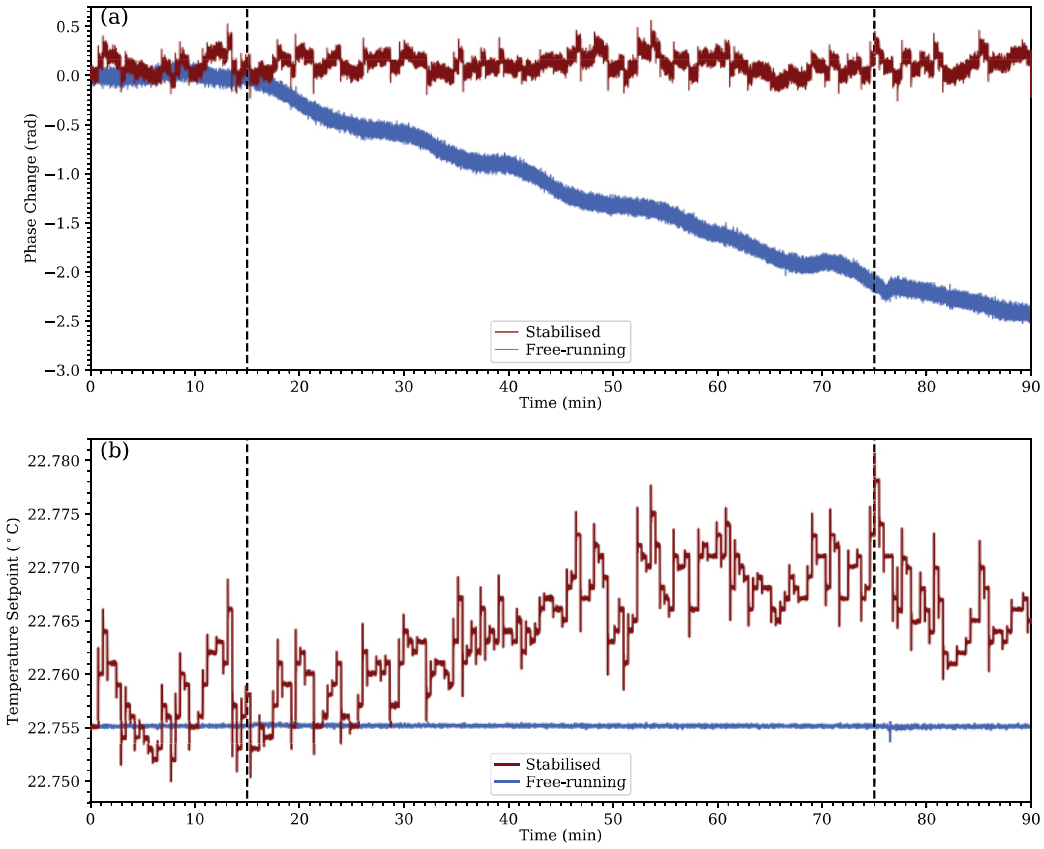

Figure 5. Direct disturbance of a laser diode by a continuous, radiant heat source between the indicated 15 and 75 minute marker showing (a) the phase change in a Mach-Zehnder interferometer (b) the thermistor reading from the laser TEC.

From the phase change measurements shown in Fig. 5(a), there is a clear phase drift in the free-running case of up to 2.14 rad over the 1-hour period of the disturbance being applied, and 2.5 rad over the full measurement period, caused by the temperature gradient across the laser diode. In the stabilised case, while there is no visible drift, the discreet temperature setpoint changes caused by the stabilisation loop are evident, causing an uncertainty of up to ± 0.096 rad over the total measurement period corresponding to a fractional uncertainty of 3.9×10^{-7}.

Fig. 5(b) shows how the temperature of the thermistor as measured by the laser TEC changes over the measurement periods of the stabilised and free-running disturbance measurements. Notably, in the free-running case the temperature of the thermistor is largely unchanged, whereas in the stabilised case, the thermistor registers the change in temperature setpoint that the stabilisation loop has enforced to counter-act the change in wavelength caused by the thermal gradient. It can also be seen that significant overshoot of the temperature setpoint is occurring in the laser TEC, which is directly contributing to instability of the laser emission wavelength when new setpoints are applied.

5. CONCLUSIONS

The results presented in this paper demonstrate a preliminary assessment of the stabilisation achievable with a novel swept absorption line locking technique. For a widely-wavelength modulated laser diode, modulated over an order of magnitude greater than the linewidth of typical references, the results presented indicate improved stabilisation over longer timescales, with a demonstrated stability of $\sim3.9\times10^{-7}$. In the current iteration of the presented technique, the short-term stability is dominated by the laser TEC control loop, which introduces instability into the measurements. To reduce this short term instability, optimisation of the internal TEC PID loop in addition to better optimisation of the external stabilisation control loop timing, to avoid unnecessary temperature setpoint changes, could be performed.

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