

Optics Letters

High stability laser locking to an optical cavity using tilt locking

NAMISHA CHABBRA,^{1,2,*} ANDREW R. WADE,^{1,2} EMILY ROSE REES,^{1,2} ANDREW J. SUTTON,^{1,2} ALBERTO STOCHINO,¹ ROBERT L. WARD,^{1,2} DANIEL A. SHADDOCK,^{1,2} AND KIRK MCKENZIE^{1,2}

¹Centre for Gravitational Astrophysics (CGA), Research School of Physics, The Australian National University, Canberra ACT 2601, Australia

²ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav), Research School of Physics, The Australian National University, Canberra ACT 2601, Australia

*Corresponding author: namisha.chabbra@anu.edu.au

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This paper describes, to our knowledge, the first demonstration of high performance tilt locking, a method of stabilizing laser frequency to an optical reference cavity using a spatial-mode readout technique. The experiment utilized a traveling wave cavity with a finesse of approximately 10,000, housed in a thermally controlled vacuum chamber. The tilt locking method in a double pass configuration has promising performance in the 100 μHz –1 Hz band, including surpassing the Gravity Recovery and Climate Experiment (GRACE) Follow-On laser ranging interferometer requirement. Tilt locking offers a number of benefits such as high sensitivity, low cost, and simple implementation and therefore should be considered for future applications requiring high performance laser locking, such as future laser-based satellite geodesy missions and the Laser Interferometer Space Antenna. © 2021 Optical Society of America under the terms of the OSA Open Access Publishing Agreement

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Laser frequency stabilization is important for high precision interferometry and optical metrology standards. Tying a laser source to a more stable optical frequency reference ensures that intrinsic noises and environmentally induced drifts in lasers are actively suppressed. Laser stabilization has applications as diverse as narrow linewidth spectroscopy [1], optical communication [2], inter-spacecraft laser ranging [3], gravitational wave astronomy [4], and optical frequency standards [5]. A key part of any stabilization scheme is the readout method that measures the detuning of a laser away from the reference to enable feedback control. This paper details an experiment that uses a “tilt locking” method [6] to read out an optical cavity mode without the use of radio-frequency (RF) modulation. It shows tilt locking’s comparative performance against standard RF locking methods and discusses its advantages in the context of laser ranging applications in space missions.

The state of the art in optical frequency references are optical cavities, typically constructed from ultra-low-expansion (ULE) glass or crystalline devices with reflective surfaces. The cavities are operated about resonance where a light experiences many

round trips over the cavity’s length, amplifying the effect of detuning from the ideal resonance frequency. A high precision measurement of the frequency detuning is enabled by interfering the cavity’s circulating field with an external reference. Typically, the reference light is provided by RF sidebands that are offset from resonance and therefore promptly reflected from an optical cavity. However, any non-resonant modes of light can be used. The industry “gold standard” of frequency locking, the Pound–Drever–Hall (PDH) method [7], measures the phase shift between imposed modulated sidebands and the carrier signal to generate an error signal using heterodyne readout. Tilt locking, on the other hand, generates an error signal by measuring the phase difference between a resonant fundamental cavity spatial mode and higher order spatial modes produced by an intentional tilt of the input beam. Tilt locking has been demonstrated in a number of applications, such as frequency stabilization [8], injection locking [9], control of a continuous-wave second-harmonic generator [10], measurement of Gouy phase evolution [11], and pulsed laser locking [12]. In theory, tilt locking and PDH have similar fundamental quantum noise limits [13].

Tilt locking is an elegant approach and offers a number of benefits over PDH, such as simpler implementation and the absence of RF modulation [6]. The question that this paper seeks to answer is: *can tilt locking achieve levels of laser stabilization performance similar to PDH locking?* If it can approach frequency noise performance similar to PDH at frequency bands pertinent to ground and space applications, such as gravitational wave detectors and satellite geodesy missions {Gravity Recovery and Climate Experiment (GRACE) Follow-On [3] and Laser Interferometer Space Antenna (LISA) [4]}, then it may be considered as a viable alternative. This paper builds on previous work on the tilt locking method [8], providing the first test of laser frequency noise performance of a double pass tilt locked cavity for high stability applications, using a specialized traveling-wave cavity design of the optical cavity reference. The results presented here demonstrate that tilt locking is a competitive alternative to PDH. The tilt locking noise performance is

comparable to PDH and within a factor of three of the calculated thermal noise for the key Fourier frequencies for LISA- and GRACE-FO-like missions (100 μHz –1 Hz).

A brief overview of tilt locking and how it generates an error signal is provided here; however, further theory on the method can be found in [6].

Frequency stabilization techniques such as PDH and tilt locking utilize the near-linear phase response of a field interacting with an optical cavity near its resonance. This phase shift interaction is compared against reference light provided by off-resonance phase-modulation sidebands in the case of PDH, and off-resonance phase-front tilt in the case of tilt locking. Tilt locking introduces a deliberate tilt of the input beam, such that the cavity decomposes light into multiple higher order spatial modes. To first order, a small beam tilt into the cavity will transfer power out of the cavity's fundamental Hermite–Gaussian optical TEM₀₀ mode and into a tilted TEM₁₀ mode [14]. The TEM₁₀ component is non-resonant in the cavity, due to the different Gouy phase accumulation, and is reflected from the input coupler. As the mode is strictly a phase-front tilt, the excited TEM₁₀ can be used as a phase reference for detection of phase changes in the TEM₀₀ as it passes through resonance. The TEM₁₀ has a relative phase shift of $\frac{\pi}{2}$ to TEM₀₀ on reflection, as seen in Fig. 1(b). To generate an error signal for the control loop, a vertically split detector is used to measure the interference of the two modes. By taking the difference of the two vertical halves, as seen in Fig. 1(a), the change in phase of the resonant TEM₀₀ light about the cavity fringe is converted into a relative shift in power on the horizontal axis. When the beam is on resonance, seen in Fig. 1(c), the two halves are symmetric, giving an error signal of zero: the photodetector will detect equal intensity on both halves. As the laser detunes from resonance, it accumulates a leading or lagging phase shift (depending on red or blue detuning from resonance). Due to the inverted polarity of the two TEM₁₀ lobes, this results in differential constructive and destructive interference. The net effect of the interference is a lateral beam displacement, which can be detected by a split photodetector. Figure 1(d) shows when the beam is displaced due to being off resonance. The two halves are anti-symmetric, giving a non-zero error signal, as the photodetector will detect different intensities on each half. An example of the tilt locking error signal and the sum signal of both halves can be seen in Fig. 2.

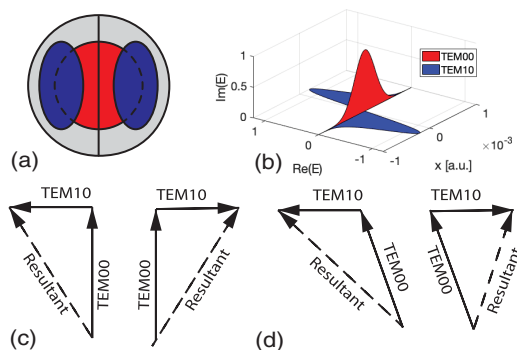


Fig. 1. (a) A vertically split photodetector is used to measure interference of (b) TEM₀₀ and TEM₁₀ modes. The vector sum of the electric fields on each half of the photodetector when (c) on resonance and (d) slightly off resonance show the change in the balance of power in the two halves as the TEM₀₀ light frequency shifts from resonance.

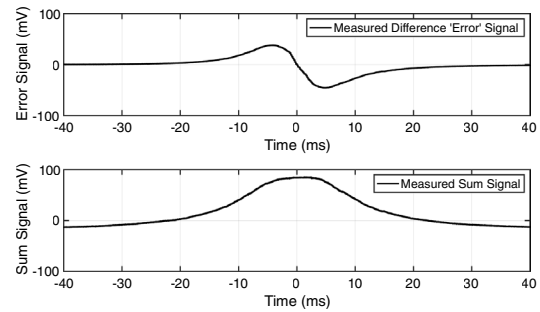


Fig. 2. Measured difference “error” and sum tilt signals using double pass tilt locking, at the resonances of TEM₀₀ and TEM₁₀ modes.

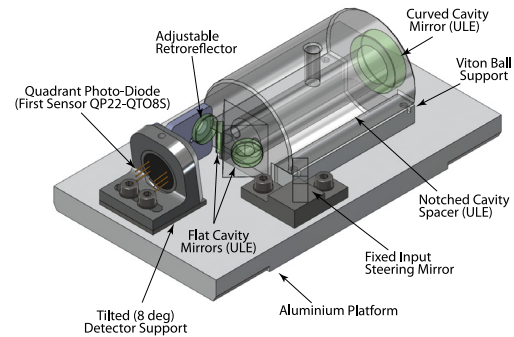


Fig. 3. CAD rendering of the cavity, tilt, and readout assembly, configured for double pass tilt locking. A custom made cavity was designed to be thermally stable using a vacuum chamber and spacer and mirrors made of ULE glass. The whole platform is placed inside a thermally controlled vacuum chamber. The laser beam enters the cavity through the fixed input steering mirror.

Double pass tilt locking was utilized, where the error signal is derived from the counterpropagating mode after being first passed through the cavity [6]. This allows for mode cleaning of the first pass of the incoming light using the forward propagating mode, reducing the effects of beam jitter, lock point error offsets due to misalignment, and unwanted higher order spatial modes. Double pass tilt locking is possible only in a traveling wave cavity, such as the triangle cavity seen in Fig. 3, due to the non-degenerate modes between clockwise and counterclockwise propagation.

A custom traveling-wave cavity and vacuum enclosure were sourced from Stable Laser Systems [15]. The full in-vacuum assembly is illustrated in Fig. 3. The cavity frequency discriminant was measured to have an optical gain of $G_{\text{cav}} = 8.9 \cdot 10^{-13} \frac{\text{W}}{\text{Hz}}$, which defines the slope of the error signal about resonance. The cavity had a finesse of approximately 10,000 with a free spectral range (FSR) of 1.78 GHz. The cavity spacer and mirrors were made of ULE glass to minimize the sensitivity of cavity length to temperature of the order of 10 ppb/K. The cavity was placed in a vacuum chamber to further isolate it from acoustic pickup and thermal variations due to air flow. Special care was taken to use high quality, low loss mirrors to reduce intra-cavity scatter effects that might scatter light between forward and reverse propagating modes of the cavity. A silicon quadrant photodiode (First Sensor QP22-QTO8S) was used in a vertically split mode by electrically connecting the right and left quadrants. An 8° vertical tilt was introduced in the design of the detector mount to deflect residual backreflections

normal to the incident beam. A zero-drift precision instrument amplifier chip (Analog Devices AD8230) was built into the front end of a photo-current amplifying and differencing circuit to minimize low frequency electronic offset drift, though it limited the control bandwidth to below 500 Hz due to the sample-and-hold requirement of the zero-drift operation. A possible source of noise for tilt locking is the lateral displacement of the photodetector. To first order, by using an impedance matched cavity, tilt locking is insensitive to this lateral jitter, as the TEM₁₀ local oscillator has a null in power in the center of the beam.

Figure 4 shows the setup for this experiment. The laser used is a Lightwave 125 non-planar ring oscillator (NPRO) operating at 1064 nm. The laser beam is transmitted through the cavity in the forward (counterclockwise) propagating mode. The transmitted field is spatially filtered into only the TEM₀₀ mode, then retro-reflected with a partial horizontal tilt at a distance of 25 mm from the output. With an approximate Rayleigh range of 280 mm, this ensures the returned beam predominantly couples into an angular tilt of the TEM₁₀ mode, rather than a translation offset. Resonant light passes through the cavity for a second time on the reverse propagating (clockwise) path. The tilt detection is implemented on the reflected field for the second pass through the cavity using the split photodetector. As shown in Fig. 2, an error signal is produced by electronically differencing the intensity between two halves on the photodetector. This signal is used by the controller to actuate and suppress the laser's frequency excursions from cavity resonance. Scatter of the counterpropagating modes was not observed to induce etalon-like effects. A Moku:Lab instrument [16] was used as a digital cascaded controller and fed back to both the laser thermal actuator and high speed piezo-electric transducer (PZT) actuator, while a "pre"-amplifier and a "post"-amplifier with a low pass filter (Stanford Research Systems, SR560) were used to overcome the analog-to-digital converter (ADC) noise of the digital controller servo and boost low frequency gain, respectively.

A second cavity with independent thermal isolation and control but a common vacuum envelope pump was used to pre-stabilize a second laser using a conventional PDH technique. To characterize the performance of tilt locking, the stability of the beatnote frequency between the tilt locking stabilized beam and the independent pre-stabilized reference beam was measured. This was of the order of 800 MHz, equal to the difference in the resonant frequencies of the two closest modes of the two optical reference cavities. This beatnote encodes relative frequency fluctuations between the two laser systems over time, allowing for the observation of relative frequency fluctuations. The output of the photodetector was mixed with a high stability signal generator to downconvert the beatnote frequency to less than 100 MHz for readout using a digital phasemeter. Here the phasemeter was implemented using a Liquid Instruments Moku:Lab phasemeter. Residual noise of this readout was of the order of 10 $\mu\text{Hz}/\sqrt{\text{Hz}}$ with a sensing bandwidth of 10 kHz.

Figure 5 shows the relative frequency noise spectral density measured between the tilt locked and PDH locked lasers (orange curve), as well as a measurement of the dark noise in the tilt locking system (gray curve). The models of total electronic noise, total input referred noise, and expected noise suppression are also plotted (solid and dotted lines), and the space application requirement curves for the LISA and GRACE-FO missions

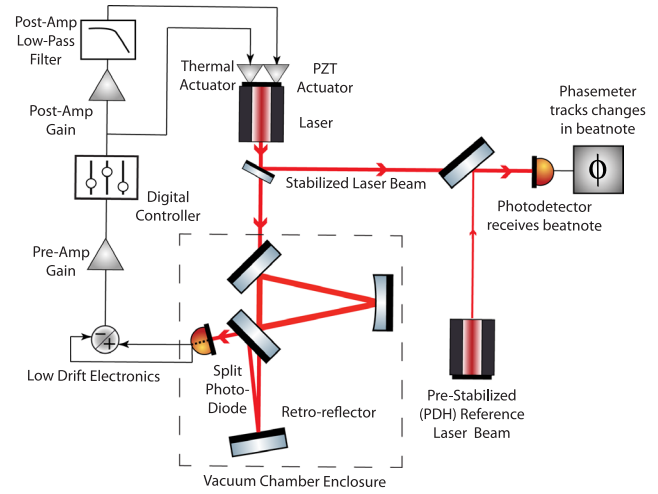


Fig. 4. Experimental setup for digitally controlled tilt locking with a beatnote measurement against a PDH pre-stabilized reference beam. The laser beam is transmitted through the cavity in the forward propagating mode then retro-reflected with a small tilt. Resonant light passes through the cavity for a second time on the counterpropagation path. The non-resonant "tilt" light is reflected off a cavity mirror and received by the split photodetector. The tilt locking stabilized beam is mixed with a PDH stabilized beam and tracked with a phasemeter to measure the relative frequency noise obtained.

Table 1. Summary of Input Referred Noise Contributions in the Tilt Locking Experiment (Cavity Optical Gain $G_{\text{cav}} = 8.9 \cdot 10^{-13} \frac{\text{W}}{\text{Hz}}$)

Component	Noise Contribution
Laser frequency noise	$\eta_{\text{freq}} = \frac{10^4}{f} \frac{\text{Hz}}{\sqrt{\text{Hz}}}$
Cavity thermal coating noise	$\eta_{\text{cav}} = \frac{0.3}{\sqrt{f}} \frac{\text{Hz}}{\sqrt{\text{Hz}}} [18]$
Shot noise	$\frac{\eta_{\text{shot}}}{G_{\text{cav}}} = 1.3 \frac{\text{Hz}}{\sqrt{\text{Hz}}} [13]$
Photodetector noise	$\frac{\eta_{\text{PD}}}{G_{\text{cav}}} = 0.45 \frac{\text{Hz}}{\sqrt{\text{Hz}}}$
Pre-amplifier noise	$\frac{\eta_{\text{preamp}}}{G_{\text{cav}} G_{\text{PD}}} = 5.4 \cdot 10^7 \cdot \sqrt{\frac{1+100}{f}} \frac{\text{Hz}}{\sqrt{\text{Hz}}}$
ADC noise	$\frac{\eta_{\text{ADC}}}{G_{\text{cav}} G_{\text{PD}} G_{\text{preamp}}} = 3.8 \cdot 10^6 \cdot \sqrt{\frac{1+220 \cdot 10^3}{f}} \frac{\text{Hz}}{\sqrt{\text{Hz}}}$
Phasemeter noise	$\eta_{\text{PM}} = 10 \frac{\mu\text{Hz}}{\sqrt{\text{Hz}}}$

are included for reference (dotted green and yellow lines). A summary of the tilt locking noise sources, gains, and their contributions in input referred units ($\frac{\text{Hz}}{\sqrt{\text{Hz}}}$) is provided in Table 1. The phasemeter noise is not considered in input referred noise calculations, as it is considerably lower than all the other noise sources.

Tilt lock was maintained for 18 h using a controller with a $\frac{1}{f^2}$ shape (two cascaded integrators) from low frequencies up to approximately 50 mHz, and then a $\frac{1}{f}$ shape (one integrator) from 50 mHz to unity gain at approximately 230 Hz. The beatnote has an Allan deviation of the fractional differential laser frequency fluctuations of $1.1 \cdot 10^{-14}$ for a 1 s interval, $2.8 \cdot 10^{-14}$ for a 10 s interval, $8.7 \cdot 10^{-14}$ for a 100 s interval, and $2.8 \cdot 10^{-13}$ for a 1000 s interval. The beatnote has clearance from the GRACE-FO requirement and is close to meeting the LISA requirement curve. However, it should be noted that as the measurement is a beatnote of two independent systems,

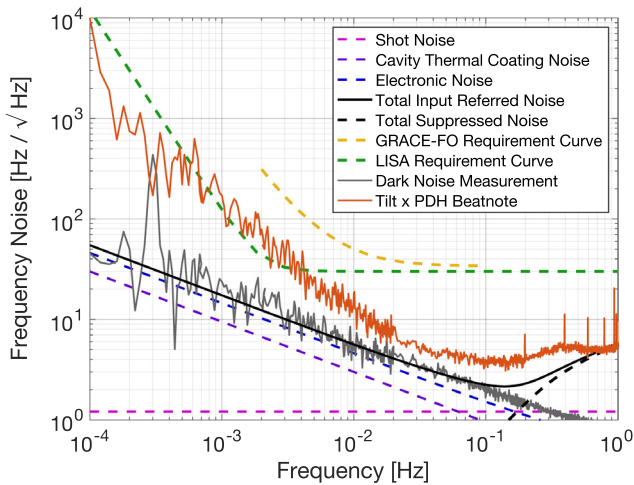


Fig. 5. Experimental results for the residual laser frequency noise measured between independent tilt locked and PDH locked cavity systems. Shot noise, cavity thermal coating noise, and electronic noise are plotted. The electronic noise is a sum of the amplifier, ADC, and PD noise contributions. LISA and GRACE-FO space application requirement curves are also plotted:

$$\eta_{\text{LISA}} \leq 30 \cdot \sqrt{1 + \left(\frac{2 \text{ mHz}}{f}\right)^4} \frac{H_z}{\sqrt{H_z}} \text{ for } f = 0.1 \text{ mHz} - 1 \text{ Hz} \quad [17]$$

$$\text{and } \eta_{\text{GRACE}} \leq 34 \cdot \sqrt{1 + \left(\frac{3 \text{ mHz}}{f}\right)^2} \cdot \sqrt{1 + \left(\frac{10 \text{ mHz}}{f}\right)^2} \frac{H_z}{\sqrt{H_z}} \text{ for } f = 2 \text{ mHz} - 100 \text{ mHz} \quad [3].$$

it is sensitive to the drift of two cavities. Below 10 mHz, the comparison of performance may be limited by differential cavity length drift due to thermal fluctuations. Between approximately 10 and 100 mHz, the tilt locking method is limited by cavity coating thermal noise and amplifier electronic noise. Above 100 mHz, the level of noise suppression is constrained by the feedback gain limitations due to the low bandwidth of the photodiode transimpedance amplifier circuit. This constrains the feedback servo unity gain frequency setting for stable feedback. Higher frequency noise may be further improved by redesign of the photodiode transimpedance amplifier to allow for greater loop bandwidth and additional gain at 100 mHz and above. It is worth remarking that tilt locking may have reduced sensitivity to scatter and stray optical paths in the input optical chain, before the tilted mirror, where the phase reference is generated. Therefore, tilt locking is primarily sensitive to etalon effects in the short path between the tilt mirror and photodiode.

Tilt locking offers an elegant configuration for cavity frequency readout and feedback control by replacing the signal generator, modulator, high speed photodetector, and mixer in equivalent PDH schemes with a split photodetector and low drift photodetector amplifier stages. The tilt locking method, with careful engineering, robust cavity design, and control loop optimization, can approach fundamental noise limits and is suitable for space missions or in applications demanding high stability and low noise over time scales of a second or more.

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Data Availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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