

Quantification of parasitic etalons in Fabry-Perot cavities and the errors they cause in Pound-Drever-Hall frequency stabilization schemes

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The Pound-Drever-Hall (PDH) scheme is a well-known technique for stabilizing a laser's frequency to a reference length such as an optical cavity. However, if a PDH setup is not carefully designed, one might easily create parasitic etalons, which are caused by back reflections in the optical path. These etalons alter the electric fields being read out and, therefore, decrease the PDH performance. In this paper, we describe these etalons as the amplitude modulation of the nominal PDH signals and identify two different kinds of etalons: internal ones formed within a plane-parallel window and free-space etalons between two interfaces of different optical components. We experimentally probe these two etalons and verify our theory. Furthermore, we employ a dual-modulation scheme that is capable of measuring the optical cavity's Free Spectral Range and discuss the influence of these additional GHz sidebands on the etalons. We conduct this study in the framework of future space-based interferometric laser ranging instruments in DLR/NASA's GRACE-Continuity and ESA's Next-Generation Gravity Mission.

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I. INTRODUCTION

Laser frequency stabilization is a key technique underpinning many scientific disciplines, including gravitational wave detection [1–4], spectroscopy [5,6], optical clocks and timing [7–9], and displacement metrology and navigation [10–12].

Previous studies have identified various limitations of laser frequency stabilization techniques, including residual amplitude modulation, scattered light, thermal noise, and quantum noise [13–17]. Parasitic etalons are a specific contributor to residual amplitude modulation effects, generating an offset due to the interference of scattered light off pairs of surfaces in the light path [18–20].

This paper presents a quantitative and systematic investigation of the effects of parasitic etalons. A tabletop experiment was set up, and the measured parasitic etalon effects are compared with a simulation, providing a potential approach to modeling these effects during the design phase of future space-based laser interferometry missions to minimize the errors induced by parasitic etalons.

The results and findings may help develop intersatellite laser ranging instruments for future missions following the concept of the Gravity Recovery And Climate Experiment (GRACE).

A. Pound-Drever-Hall laser stabilization

The Pound-Drever-Hall (PDH) method is a well-known scheme for stabilizing a laser to an optical reference cavity, typically comprising temperature-stable UltraLow Expansion (ULE) glass in a temperature-controlled vacuum chamber. The scheme employs phase modulation of the incident light and demodulation of the sensed signals in the reflection port [21,22]. It is widely used in a range of applications where a stable length or frequency reference is needed, for example, in precision interferometry for gravitational wave detection [23] or in space-based gravimetry, such as the GRACE Follow-On (GRACE-FO) mission [24–26]. Well-designed cavity setups at room temperature reach a fractional frequency stability of 10^{-16} over 0.1 to tens of seconds averaging time with a small linewidth, and even better stability in cryogenic setups [27–29].

B. Fabry-Perot etalons, parasitic (coupled) cavities, and AM

PDH setups must be well designed to prevent the introduction of parasitic etalons, i.e., coupled low-finesse cavities, into the optical path. We identified two different kinds of these etalons, which differ in their practical creation, but both share the same mathematical description.

Figure 1 depicts these two etalons. The left sketch illustrates an intrasubstrate etalon forming in a plane-parallel glass window with nonzero reflectivity. Such an etalon may form in the cavity mirrors themselves, if not wedged, or within a viewport of a vacuum tank, which typically surrounds a cavity. The second mechanism, sketched on the right-hand side, may form between a reflective surface that is aligned with another optic in the setup, for example, the cavity input mirror and

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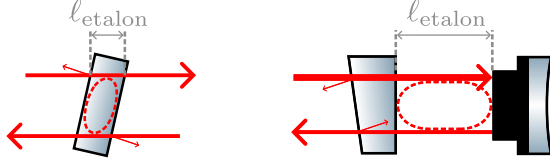


FIG. 1. Intrasubstrate etalons forming in plane-parallel optics (left) and free-space etalon between two well-aligned optics (right). For the free-space etalons, we employ wedged optics to prevent the superposition of the intrasubstrate etalon with the free-space etalon in our measurements. The length of the etalon is named ℓ .

vacuum tank viewports. In the illustration, we used a wedged window to separate the two mechanisms.

The parasitic etalons accrue a round-trip phase before interfering with the primary beam, generating amplitude modulation (AM). The effect of this amplitude modulation on the PDH error signal is shown in Fig. 2. An ideal PDH error signal is shown in blue. This same error signal is then shown in red with 0.1% amplitude modulation added at the same modulation frequency as the phase modulation and with no phase offset. The addition of the amplitude modulation has introduced a DC offset to the error signal.

The inset of Fig. 2 shows a close-up view of the zero-crossing point of the two error signals. Typically, the laser is controlled to remain at the zero-crossing point of the error signal. The ideal error signal (blue) has a zero-crossing point at 0 MHz detuning, whereas the error signal with AM (red) has a zero crossing at $x \neq 0$, which constitutes a frequency offset at the lock point of the control loop. Increasing AM

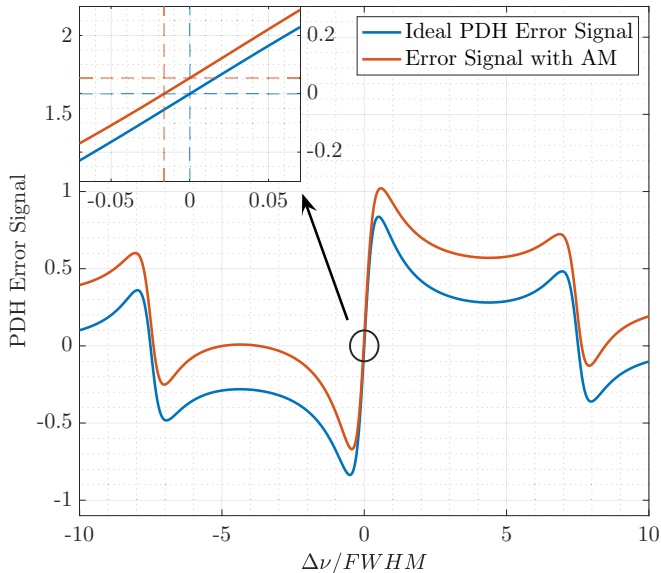


FIG. 2. PDH error signal (blue) compared with a PDH error signal with additional amplitude modulation as a result of a parasitic etalon (red). Amplitude modulation introduces a DC offset in the error signal. Inset: Ideal PDH error signal (blue) with the zero crossing points given by the dashed blue lines. With AM (red), the zero-crossing points are offset as shown by the dashed red lines. The laser stabilization system will feed back to keep the laser at the zero-crossing point, which results in a frequency offset.

levels will result in greater frequency offsets in the system, which are typically in the order of some percent of the full width at half maximum (FWHM). Crucially, these frequency offsets also provide a mechanism whereby other errors can couple into the system.

Given stable environmental conditions, a laser control system will probe a single point of the etalon's error signal. However, if the substrate temperature changes, one might observe length or refractive index changes, which shift the etalon's resonance condition and, hence, the probe point on the sinelike curve resembling the low-Finesse error signal (cf. Ref. [22]). Consequently, the zero crossing of the nominal PDH error signal is further altered, and thus a temperature-dependent frequency offset is introduced.

In a previous study by Shen *et al.* [18], these two effects were identified as well, but were examined only in theory and not experimentally verified.

C. Scale-factor measurement and sensitivity

The PDH method can be extended with a dual-frequency modulation scheme in order to measure the cavity's Free Spectral Range (FSR) and hence infer the absolute optical frequency ν of the circulating light field through $\nu(t) \approx (N + \epsilon) \cdot \text{FSR}(t)$ [30,31], where the longitudinal mode number N is typically in the order of 10^5 . This requires additional phase-modulated subcarriers at ± 1 FSR of the optical carrier frequency, which are also resonant in the cavity and thus produce an additional PDH-like error signal. This error signal can be used in a closed-loop system to maintain the GHz subcarrier at the cavity's neighboring resonances; the subcarrier generator frequency thus acts as an in-loop sensor for the cavity's FSR. Despite well-controllable small offsets $0 \leq \epsilon < 1$, e.g., from Guoy- and coating phase shifts, this scheme is prone to time-varying etalon errors in the FSR measurement. These errors in the FSR estimate are then scaled by the longitudinal mode number N when computing the absolute laser frequency $\nu(t)$. Hence, avoiding parasitic etalons is of utter importance in this application, which requires absolute frequency knowledge on the order of 10 ppb [32]. This readout scheme is called the Scale-Factor Unit (SFU) in the context of future Laser Ranging Interferometer (LRI) developments for GRACE-Continuity (GRACE-C) and the Scale-Factor Measurement System (SFMS) within ESA's Next-Generation Gravity Mission (NGGM).

II. EXPERIMENTAL SETUP

In this study, we aim to quantify etalon-induced errors in a flightlike cavity system. The tabletop experiment is sketched in Fig. 3. We use a Lumentum NPRO 125 Series at 1064 nm with several mW output power, of which 100 μ W are coupled into the cavity. For detection on the rx and tx ports we use Thorlabs DET100A2 large-area Silicon photoreceivers, and an off-the-shelf camera (Thorlabs CS165MU/M). The Electro-optic modulator (EOM) is a (ixblue NIR-MPX-LN-05). A Laser Lock Box implemented on a Moku:Pro was used for the PDH cavity lock [33], while a Rohde & Schwarz SMA100B [34] produced the phase-modulated GHz subcarriers, as described in Refs. [31,32]. A second Moku:Pro was

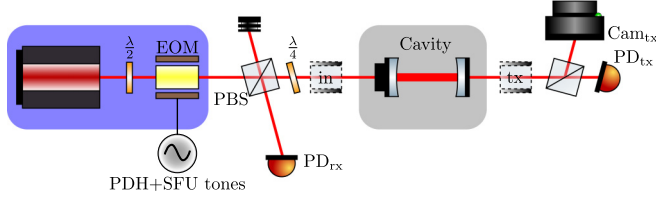


FIG. 3. The experimental setup. All optics in the critical path are intentionally slightly angled to prevent back reflections. The etalon-forming optics inserted subsequently are shown in dashed lines, labeled “in” and “tx.” The gray box marks the thermal vacuum chamber. EOM: Electro-optic modulator. PD: photodiode. PBS: polarizing beam splitter.

used for the FSR readout using the Lock-In Amplifier. Both the PDH and SFU readouts use the same RF photodiode signal but demodulate at different frequencies, effectively separating the measurement principles. Unlike the previous publications by Rees *et al.* [31,32], the optical cavity used in this study was a vertically mounted Fabry-Perot “midplane” cavity (cf. Ref. [27]) with a finesse of $\mathcal{F} \approx 10\,000$, which features wedged cavity mirrors. The cavity was 77.7 mm long, providing a Free Spectral Range of 1.93 GHz. To achieve the cavity finesse of 10 000, the mirror coatings had a reflectivity of approximately 0.9997. Typical coupling achieved with the cavity was between 85% and 90%. The cavity was integrated into a thermal-vacuum chamber with two viewports for the reflected and transmitted beams. A tap-off of the laser was interfered with a second, independent laser stabilized to a second optical reference cavity with a higher finesse ($\sim 100\,000$), and the beat note was recorded using a digital phasemeter implemented on a Moku:Pro. This beat note provided an independent verification of the etalon-driven frequency offsets in the PDH lock of the system under test.

For both etalon types, substrate-internal and intrasubstrate, two optics were used to test the amplitude of the etalon. We used one uncoated and one coated window with an antireflective coating, and a plane-parallel window for the intrasubstrate etalon experiments, and a wedged window for the free-space etalon experiments. The key specifications of these optics are provided in Table I.

Each of the optics were placed in both positions indicated in Fig. 3. At each location and for each optic, the frequency offset induced by the optic was measured using the beat note with the second independently stabilized laser, and by noting the offset to the measured FSR.

TABLE I. Key specifications for the optics used to induce a parasitic etalon. All parts were made of UV Fused Silica.

Part No.	Wedge angle	Coating
WG41050	0 arcmin	Uncoated
WG14050-C	0 arcmin	AR coating: 1050–1700 nm
WW14050	30 ± 10 arcmin	Uncoated
WW14050-C	30 ± 10 arcmin	AR coating: 1050–1700 nm

A. Intrasubstrate etalon

For the intrasubstrate etalons, we varied the temperature, which induced a length change of the etalon, ℓ_{etalon} , due to the temperature dependency of the refractive index, and through thermal expansion of the fused silica substrate. The data analysis then comprises fitting a model of an etalon-induced measurement error to the measured frequency errors of PDH and SFU, which depend on the etalon optic temperature. The model reads

$$\Delta\nu(T) = x_1 \sin[x_2 \cdot T(t - x_3) + x_4] + p_n, \quad (1)$$

where t is the measurement time, T the measured temperature of the substrate, and p_n a polynomial of order n to remove slow differential cavity drifts between the cavity under test and the independent reference. The fit parameters x_i describe the magnitude of the frequency error x_1 , their scaling with temperature x_2 , an empirical time shift of the measured temperature data x_3 (to account for temperature propagation delay from the sensor into the glass), and an initial condition x_4 . For an example measurement, see Sec. III A.

B. Free-beam etalons

For free-beam etalons, it is impractical to change the etalon length by manually moving the optic longitudinally over several wavelengths while maintaining alignment with the cavity. Hence, the optic was first mounted in the beam path, the reflection was aligned into the cavity, and the angular alignment of the window was then slightly varied by manually turning the mount’s alignment screws. The lever-arm effect of the mount translates the small angular adjustment into a longitudinal shift of the window in the beam path over a few wavelengths, which allowed us to sample several fringes of the etalon-induced errors. Since this method does not allow to directly measure the stimulus, i.e., the manual movement of the mirror, we estimate the peak-to-peak (pk-pk) envelope of the measured errors of PDH and SFU (cf. Sec. III B).

III. RESULTS

A. Intrasubstrate etalon

We were able to measure and model etalon-induced frequency variations in both PDH and FSR measurements as shown in Fig. 4. Within the shown data, we increased the temperature of the etalon window by 20 K and measured the beat note of the cavity-locked laser with the reference system, as well as the response of the SFU system. For an uncoated window (WG41050, $R = 5\%$), the measured peak amplitude of the error, x_1 , is 266 and 150 Hz for PDH and FSR, respectively. The temperature coupling of the phase is $x_2 = 0.56 \text{ rad } ^\circ\text{C}^{-1}$ for both models. The temperature propagation delay from the measurement at the heating element to the response of the optical system is approximately $x_3 = 45 \text{ s}$.

For a coated window (WG41050-C, reflectivity $R = 0.25\%$), we observe much smaller errors of about 13 Hz in PDH and 7.4 Hz in the SFU measurements.

This temperature-induced frequency error response is what one might see in a commercial cavity system with no wedged windows. These systems may operate in environments where the temperature can vary by a few Kelvin. If the system

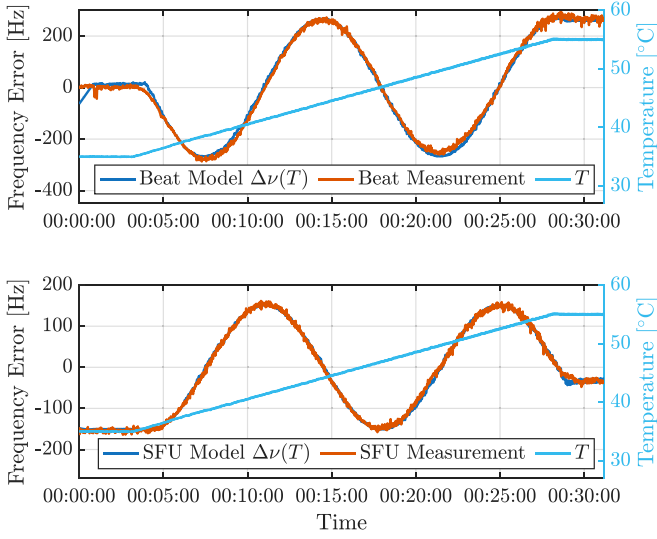


FIG. 4. Intrastubstrate etalon measurement using a flat, uncoated window (WG41050) in the *in* position of the beam path. Top: PDH. Bottom: SFU.

happens to be operating at either the maximum or minimum turning points on these curves, the resultant frequency error would be minimal; however, it is more likely that the system probes some other point along the curve. Any temperature change would therefore result in a frequency error on the order of 100 Hz. For the SFU readout, this is converted to absolute frequency by multiplying by the longitudinal mode number N (here, $N \approx 10^5$), giving absolute frequency errors on the order of tens of MHz.

If only short-term stability is required, or these frequency errors are tolerable, this may not be an issue; however, in the context of interferometric satellite-to-satellite laser ranging as GRACE-like missions, this frequency error would exceed the mission requirement and render the technique infeasible.

B. Free-beam etalon

For the external etalons, we employ the mirror mount lever-arm method as described in Sec. II B. The results for an uncoated, wedged window (WW41050) forming a low-Finesse etalon with the cavity's incoupling mirror are shown in Fig. 5. We observed a pk-pk error of 8.3 kHz for PDH and 1.1 kHz for SFU. As before, the PDH error was obtained by measuring the beat note to an independent cavity and hence directly refers to the frequency error of the laser, while the SFU error refers to the error at the FSR, which again has to be scaled by the longitudinal mode number N for obtaining the error at the laser frequency. An error in the SFU readout of 1.1 kHz is therefore an error of 165 MHz in absolute frequency when scaled by the mode number. A small linear trend stemming from differential cavity drifts of the setup under test and the reference setup was subtracted from the PDH data.

C. Free-beam etalon: Length dependency

During the previous experiment about the Free-Beam etalon (Sec. III B), it was found that the measured pk-pk errors were not reproducible between subsequent runs when the

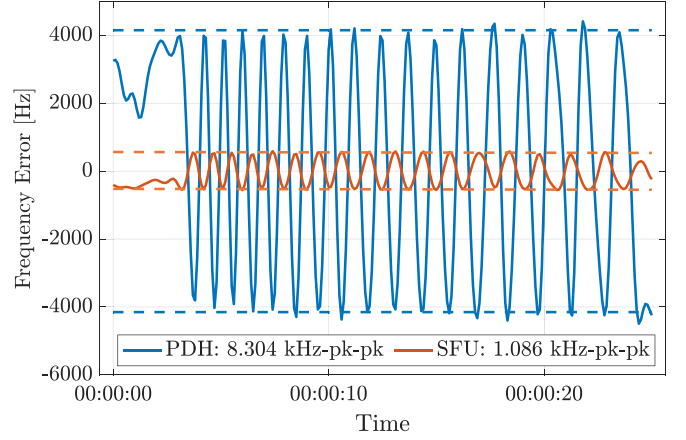


FIG. 5. Free-beam etalon measurement using a wedged, uncoated window (WW41050) in the *in* position of the beam path.

window position was modified. Hence, a measurement campaign was performed in which the mirror was moved relative to the cavity for both window positions, *in* and *tx*.

Figure 6 shows the measured frequency offsets induced by the coated and uncoated wedged optics with the optics placed in the *tx* position. Each measurement point is analyzed as shown in Fig. 5 for the pk-pk errors. The top plot shows the frequency offset measured for the uncoated wedged optic, the middle plot for the coated wedged optic, and the lower plot using the coated wedged optic but with the GHz modulation frequency set to twice the cavity FSR. Similarly, Fig. 7 shows the same measurements for the window inserted into the *in* position. Further, the panel for the uncoated window is omitted. The blue traces show the offset measured using the beat note with the second independently stabilized laser. The observed variations are an offset of the PDH lock point caused by etalon-induced AM, resulting in a change in the laser frequency. The green trace shows the same measurement taken with the SFU readout disabled, i.e., the laser is only modulated with the PDH tone. The orange traces show the

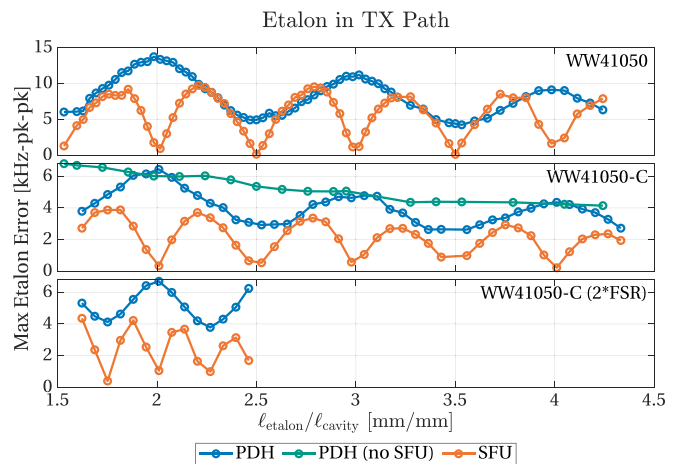


FIG. 6. Etalons in the TX Path. The blue traces show the offset to the PDH lock point induced by the optic. The green trace is the same measurement made with the FSR modulation disabled. The orange trace shows the frequency offset as measured by the FSR readout.

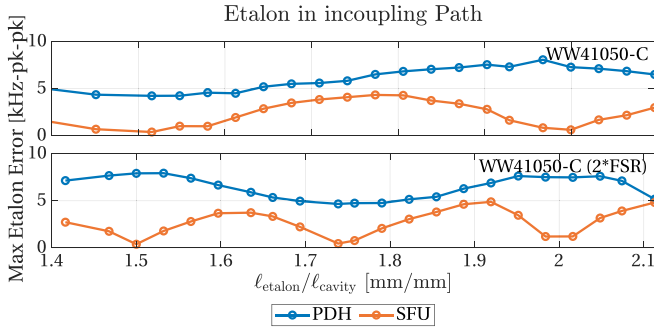


FIG. 7. Etalons in an incoupling path. The blue traces show the offset to the PDH lock point induced by the optic. The orange traces show the frequency offset as measured by the SFU readout.

frequency offset measured by the SFU readout. These offsets change the apparent free spectral range of the cavity, which introduces errors when the SFU measurement is used to compute the absolute laser frequency.

Figure 6 shows a periodic modulation of the errors of both PDH and SFMS systems, which are due to interference of the two phase modulated sidebands of the FSR modulation in the reflection port, whose state is depending on the length of the etalon. The figure also shows that the period of the etalon error in the SFU measurement is double that of the period in the PDH system. This is due to the slightly different readout scheme: in the PDH case, we directly measure the carrier electric field vectors' amplitude at the PDH modulation frequency, while in the SFU case, we measure the difference of the upper and lower subcarrier electric field amplitudes, which counterrotate in the carrier-fixed corotating reference frame. The period of the etalon is directly related to the frequency of the FSR modulation frequency; when this tone is doubled, the period also doubles in both the PDH and the SFU readout.

Comparing the top and middle panels of Fig. 6, the amplitude of the etalon-induced error is significantly reduced by the addition of the antireflection (AR) coating on the optic, as would be expected. The uncoated optic provides a good metric of a worst-case error, where nearly 4% of the light is reflected. The AR-coated optic is a more realistic scenario; however, even with the AR coating, approximately 0.25% of the light is still reflected.

There is also a clear difference between the amplitude of the induced etalon error between the PDH and SFU measurements. The PDH error measurements are approximately 1.5 times larger than those measured by the SFU readout. When the SFU readout is converted into absolute frequency, however, this error is multiplied by the longitudinal mode number and gets amplified by a factor of roughly 10^5 and easily reaches absolute frequency errors in the MHz range.

Figure 6 also plots the error in the PDH measurement when the SFU modulation is disabled (green). It is evident from this trace, and can also be seen in the other PDH traces, that the power in the etalon decays as the length of the etalon cavity (ℓ_{etalon}) increases. In this case, the etalon optic was located in the transmitted path, after the optical cavity. This decay is therefore likely a result of the mode mismatch of the spurious reflected beam compared to the cavity mode.

TABLE II. Parameters of the experimental setup, also used for the simulations.

Parameter	Value
Laser wavelength	1064 nm
Cavity FSR	1.933 568 857 GHz
PDH modulation Freq.	1.38 MHz
PDH modulation depth	0.1 V $\approx$ 70 mrad
Subcarrier modulation Freq.	1 FSR
Subcarrier modulation depth	17 dBm $\approx$ 800 mrad
SFU modulation Freq.	1.89 MHz
SFU modulation depth	0.25 rad with respect to GHz mod
Cavity mirror R	50 ppm
AR coating R	0.25%
Uncoated fused silica R	4%

Placing the etalon-optic in the in and tx positions should, in principle, yield the same results, but differ by the mode matching with respect to the cavity mode.

IV. SIMULATION: COUPLED CAVITIES WITH SFU TONES

For simulating the observed etalon amplitudes, we use the framework for three-mirror cavities published in Chap. 3 in Ref. [35] to compute the electric fields reflected and transmitted by the system.

The formalism allows the effective decomposition of the electric field into its Fourier components, which provides an elegant readout of what could be sensed with a lock-in amplifier. The relevant signals are at the PDH modulation frequency, the subcarrier frequency at 1 FSR, and the subcarrier modulation frequency.

Assuming that a wedged etalon optic is inserted into the in position, one of its surfaces forms a low-Finesse cavity with the cavity incoupling mirror, while the cavity itself is high-Finesse relative to the etalon cavity. In the simulation, we macroscopically vary the length of the etalon, meaning that we move the etalon-optic relative to the cavity. For every mirror position, we then vary the optical frequency of the incident electric field over one full wavelength, which results in the well-known error signal of a low-finesse cavity (see, e.g., Fig. 6 in Ref. [22]). From that error signal, we measure the peak-to-peak amplitude, which provides us with the maximum error envelope due to the parasitic etalon. The conversion into an equivalent frequency error is done through the discriminant of the PDH and SFU readout, respectively (cf. Chap. 3.2 in Ref. [36]). This represents the envelope of the frequency error one could observe in a real experiment with a laser locked to a cavity and a freely drifting etalon. Table II lists the key parameters used in the simulation, which were matched to the values for the equivalent experimental part.

To replicate the experiment, errors due to the etalon were simulated for a PDH only system, a PDH readout with the SFU modulation enabled, and for the SFU readout itself. The simulation results are presented in Fig. 8. Since we do not simulate losses due to imperfect mode matching and coupling losses, which would increase with the distance ℓ_{etalon} , the traces repeat exactly every ℓ_{cavity} and only the first period is shown. These simulation results should be compared with the

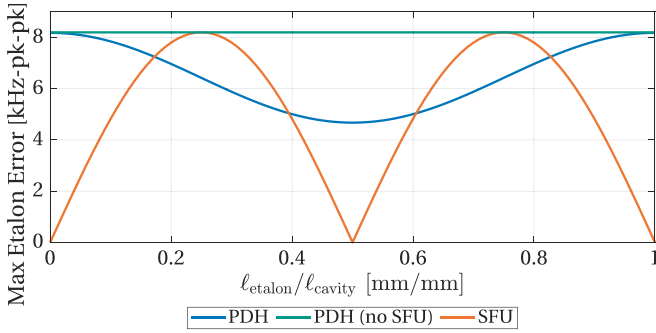


FIG. 8. Simulation of maximum etalon errors in a coupled cavity setup with a spurious low-Finesse and a high-Finesse cavity, for PDH and SFU readout schemes. The etalon cavity window in the in position has a reflectivity of 0.25%, as the WW41050-C window.

middle panel of Fig. 6, which shows an etalon in the transmission path, using similar parameters to those in the experiment. We observe that the traces exhibit the same periodic behavior; our simulation appears to overestimate the SFU error slightly.

It is likely that the discrepancies between the simulation and the measured data are due to several losses in the experiment that are not accounted for in the simulation (optical loss, incoupling loss, and mode-matching losses). Further work could be done to identify and quantify each of these and to incorporate their effects into the simulation.

V. CONCLUSION AND RECOMMENDATIONS

Parasitic etalons are easily formed between any two reflective surfaces in optical setups. The etalon effectively adds amplitude modulation to the PDH-like system, resulting in frequency offsets to the lasers and coupling other errors into the system. For tabletop experiments, the wedging of the optical components is typically sufficient to mitigate these effects. In space systems where the optics are often bonded to an optical bench and are inaccessible after launch, this is more challenging. In such cases, the impacts of parasitic etalons should be well understood such that they can be prevented through design as much as possible.

This paper has quantified the impacts of parasitic etalons in two key locations for a typical optical cavity laser

stabilization system. Further, the frequency offsets induced by parasitic etalons have been studied particularly for a dual-frequency modulation scheme, expected to be included on future geodesy missions, including GRACE-C and NGGM.

Frequency lock offsets caused by parasitic etalon on the order of 10 kHz and 160 MHz (absolute frequency) were measured using a standard Pound-Drever-Hall readout and a dual-frequency modulation readout, respectively. This demonstrates the dual-frequency modulation scheme's particular susceptibility to these types of etalons. A difference in susceptibility to intrasubstrate etalons compared to free-beam etalons is also apparent, with the latter creating significantly larger frequency offsets in both PDH and dual-frequency modulation readouts.

This work has bounded the effects of parasitic etalons for this readout technique, allowing appropriate design considerations to be incorporated into future mission designs.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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