



Tunable optical cavities for wavelength Indications in Gas Laser

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ABSTRACT

Explain an all-optical tunable detention in gas laser based on wavelength conversion wavelength reconversion. The use of stable, calibrated optical reference cavities to equipping interferometer users with more exactly. Various resonance wavelengths of cavity were resolved by frequency measurements in a vacuum by use of a gas laser comb followed by corrections to account for atmospheric pressure and cavity temperature. A purpose of a new stable cavity is discussed that allows for the longitudinal mode index to be determined by difference-frequency measurements between the S and P polarized modes. For a wide range of signal pulse interval (ps to 10 ns), an output signal wavelength and bandwidth that are the same as that of the input.

Keywords: gas laser, frequency measurements, interferometer, wavelength standards.

الطول الموجي كمرجع للحصول علي تجويف بصري انضباطي في الليزر الغازي

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المخلص

إثبات وجود تأخير الانضباطي البصري في الليزر الغازي على أساس تحويل الطول الموجي كإعادة التحويل. استخدام مستقرة، معايرة تجاوييف الإشارة الضوئية لتزويد المستخدمين تداخل مع أكثر دقة. وتم تحديد عدة موجات صدى من تجويف بواسطة قياسات التردد في الفراغ عن طريق استخدام مشط ليزر الغاز تليها تصحيحات لحساب الضغط الجوي ودرجة الحرارة تجويف. تصميم من تجويف مستقر الجديد الذي يسمح للمؤشر الوضع الطولي التي تحددتها قياسات الفرق التردد بين أوضاع S و P المستقطب. لمجموعة واسعة من فترات إشارة النبض (١٠ نانوثانية)، والطول الموجي إشارة الى خرج وعرض النطاق الترددي التي هي نفسها كما في المدخلات.

الكلمات الدالة : الليزر الغازي ، مقياس التردد، المدخال، طول الموجي الأساسي.

1. Introduction

Optical interferometers measure length in units of a known optical wavelength. Common interferometric systems use frequency-stable lasers, and the wavelength is a calculated parameter that depends on the local air's refractive index, which varies with air density and composition. Consequently, length measurements performed in air are substantially less accurate than similar measurements utilizing an interferometer operating in vacuum [1]. A different approach that has been suggested is to frequency-lock a tunable laser to a mode of a mechanically stable reference cavity that is open to the air [2,3,4]. Essentially, the frequency of a tunable laser is controlled to fix the wavelength in the medium. The wavelength may be



determined by a calibration of some type, and known correction factors (such as the reference-cavity temperature) applied as necessary. Here, calibrated several modes of a prototype reference cavity by way of frequency measurements with a femtosecond-laser frequency comb [5]. Furthermore, by smoothly tuning between two known resonance wavelengths, swept-wavelength interferometry is possible with no associated refractive index measurements. A wavelength calibration of the cavity at a certain temperature can be accomplished indirectly by an optical frequency measurement. Measured a tunable laser's frequency while it is locked to a resonance of the cavity in a vacuum chamber. The wavelength of the resonance in the vacuum may then be calculated with high precision since the limiting factor is not the refractive index but is instead likely to be the residual error of the temperature monitoring or offsets in the frequency-locking process. As discussed below, when air is re-introduced to the chamber the wavelength of each mode remains nominally the same, apart from several small corrections not related to the air's refractive index [6].

Subsequent frequency-locking of a laser to such a resonance will allow the user to know the laser wavelength in the reference cavity air path which, for instance, may be placed adjacent to a length-measuring interferometer. Monitoring the cavity temperature appears to be preferable to controlling it, since temperature control would unduly heat or cool the air in the cavity relative to the interferometer measurement path. The correction for atmospheric pressure requires knowledge of the barometric pressure, but again not as precisely as the present method of using the Edlen equations [7]. The material aging issue refers to a gradual shrinking at the rate of $\Delta l/l \leq -5 \times 10^{-9} \text{yr}^{-1}$ in the low-expansion material ULE glass [8]. This characterization is the result of long-term measurements of Fabry-Perot resonance frequencies. Another candidate low-expansion glass material, Zerodur-M, exhibits an aging rate larger by an order of magnitude [9]. Direct measurements of optical frequency as described here are to be distinguished from resonance frequency estimates based on measurements of the cavity free spectral range (FSR). Frequency measurements of a cavity's FSR to the level of 10^{-7} have been demonstrated at a single wavelength [10], but the FSR is wavelength dependent since the dielectric-mirror phase shift upon reflection is wavelength dependent. An accurate ($\Delta\nu/\nu \approx 10^{-8}$) measurement of a resonance frequency by way of FSR measurements does not appear to be practical at this point. However the tunable laser must be brought into coincidence and locked to the same longitudinal mode index (m) that was previously calibrated. Several methods of finding the correct mode are discussed.



The choice of which laser to employ in this research has been based on several factors. Traditionally, most metrology systems have been built around the red 633 nm wavelength since frequency-stabilized He-Ne lasers have long been available. For this application we need a tunable laser with a line-width narrow enough to be captured and locked by electronic means. While it is true that the longer wavelength is a negative factor with regard to an interferometric measurement, the DFB characteristics including ruggedness, power, cost, eye-safety, fiber compatibility and component availability are positive factors. For instance, for paths on the order of one meter, a very precise $\Delta\lambda/\lambda \approx 3 \times 10^{-8}$ measurement represents a fractional fringe interpolation of only 1/50 of a wave using the telecom-wavelength lasers.

The actual stability of the laser wavelength in air is a difficult parameter to measure. Monitoring the laser frequency via a heterodyne beat-note will only record changes of the air's refractive index. By building a rigid test interferometer and monitoring the apparent path length using our "stable wavelength," we are likely to measure a changing phase shift at some level [11].

The aim of this study is discussed that allows for the longitudinal mode index to be determined by difference-frequency measurements between the S and P polarized modes. For a wide range of signal pulse interval (ps to 10 ns), an output signal wavelength and bandwidth that are the same as that of the input.

Table (1): Scientific names of abbreviations

No.	Scientific names	Abbreviations
1.	Change rate of length	$\Delta l/l$
2.	Uncertainty wavelength reference	$\Delta\lambda/\lambda$
3.	Calibration wavelength	λ_c
4.	Calibration Temperature	T_c
5.	The error of the polynomial approximation	ϵ
6.	cavity's coefficient of expansion	$\alpha(T)$
7.	Free spectral Range	$\Delta\nu/\nu$
8.	Total phase -shift	Φ_m
9.	Total Gouy phase-shift	Ψ_R
10.	Cavity length	L
11.	Trademark of Coming and Schott Glass, Inc. Trade names are mentioned for reference only and do not imply product endorsement by NIST.	ULE and Zeroudur
12.	Transverse mode indexes	P and q
13.	Merit Figure	Γ

2.Wavelength Indication Cavity Quests

2.1. Stability

The resonance condition of an optical cavity is often approximated as an integer number of wavelengths in the cavity round-trip path length, or $m\lambda = L$. This simplification neglects any phase-shift upon reflection at the mirrors. It also assumes plane-wave propagation, neglecting the phase accumulation that occurs as the optical wave diffracts. We write the resonance condition as [11]

$$\lambda = \frac{L}{m + \frac{\varphi_m(\lambda)\Psi_R}{2\pi}} \dots\dots 1$$

Where L is the physical round-trip path length of the resonator, the integer m is the longitudinal mode index, (Φ_m , is the total phase-shift upon reflection from the dielectric mirrors per round-trip, and Ψ_R is the total Gouy phase shift around the ring cavity. Note that

the index of refraction of the medium does not appear explicitly in Eq. (1). In other words, the resonant wavelength is to first order independent of the air density in the cavity. One may expect a higher-order dependence if the air affects $\Phi_m(\lambda)$, Ψ_R , or L in any indirect manner. Examples would include a change of the cavity length L due to air pressure or mirror contamination. The largest sources of uncertainty appear to come from residuals after correcting for changes of the mechanical length L due to temperature, aging, and atmospheric pressure. Equation (1) defines two distinct sets of modes, s and p polarized, that will in general have different resonance wavelengths since Φ_m is polarization dependent due to the non-zero angle of incidence on the cavity mirrors. The total Gouy shift is the phase difference between a plane wave and the actual cavity mode wave, over a single round trip in the cavity. It is a function of the cavity geometry, i.e., the mirror curvatures and spacing. The shift may be calculated numerically for any cavity geometry, and will be a factor on the order of $\Psi_R \approx 2\pi \sqrt{5}$ for all geometries considered here. For a two-mirror Fabry-Perot cavity, the Gouy term can be written as [12]

$$\Psi_R = 2(1+p+q)\cos^{-1}(\sqrt{g_1 g_2}) \quad g_i = 1 - \frac{L}{R_i} \quad \dots 2$$

Here, p and q are the transverse mode indexes. As we will be interested only in the TEM_{00} modes, $p = q = 0$ for the designs considered in this report. The mechanical length L clearly enters Eq. (1) through the Ψ_R term in the denominator, in addition to appearing explicitly in the numerator. However due to the large factor m (typically $>10^5$) in the denominator of Eq. (1), this indirect contribution of cavity length drift to wavelength shift is quite small, far below the level of $\Delta\lambda/\lambda \approx 10^{-8}$. The Ψ_R term can therefore be considered a constant for each cavity design considered here. The phase shift upon reflection at each mirror is a function of mirror stack design. The coatings considered here are fabricated at elevated temperatures by ion-beam assisted RF deposition, which results in nonporous layers that have virtually the same density as the bulk materials Ta₂O₅ and SiO₂ [13].

A molecular monolayer on each mirror of a ring cavity represents about 1 part in 10^8 of the path length. However, this does not equate to the wavelength instability caused by accumulating a monolayer of contamination. At this point it is worth noting that the initial calibration does not need to be performed in a high-vacuum environment. Indeed, measuring the mode frequency with a background pressure of 0.1 Pa (≈ 1 mTorr) will cause an error (if uncorrected) of only $\Delta\lambda/\lambda \approx 23 \times 10^{-10}$ [14].

To summarize the contributions of the dielectric mirror phase shift $\Phi_m(A)$ and Gouy term Ψ_R to the overall wavelength instability, these terms are significantly less than $\Delta\lambda/\lambda \cong 10^{-8}$. Wavelength uncertainty related to temperature, atmospheric pressure, and material aging are discussed in the following section concerning accuracy.

2.2. Accuracy

Considering stable cavities made entirely of low-expansion glass with optically contacted mirrors. The goal is to construct a resonator with a wavelength uncertainty between calibrations of a few parts in 10^8 or better. The wavelength uncertainty provided to the interferometer user may then largely be a function of how well the refractive index of the air in the cavity matched that of the interferometer path. As discussed in the introduction, candidates for mirror spacer material include ULE glass and Zerodur-M. The initial temperature coefficient at room temperature will be within the range of $\pm 30 \times 10^{-9} \text{ }^\circ\text{C}^{-1}$. The temperature coefficient of each cavity would be measured during the femtosecond comb calibration over a nominal range of temperatures near room temperature. Subsequent use would entail monitoring the cavity temperature and correcting the wavelength as the cavity temperature deviates from the calibration temperature. The temperature calibration will include the effects, if any, of a possible temperature coefficient of the dielectric mirrors. The cavity's coefficient of expansion, $\alpha(T)$, will be approximated by fitting a polynomial to experimental data points derived from frequency measurements over a range of $\pm 5 \text{ }^\circ\text{C}$ from room temperature. Expect to measure the coefficient of expansion $\alpha(T)$ at multiple temperatures over this limited range with an accuracy of $\pm 2 \times 10^{-9} \text{ }^\circ\text{C}^{-1}$. The corrected wavelength would be estimated according to:

$$\lambda(t) = \lambda_c \left(1 + \int_{T_c}^{T(t)} (\alpha(T) + \varepsilon) dT \right) \quad \dots 3$$

Where λ_c and T_c are the calibration wavelength and temperature, respectively, ε is the error of the polynomial approximation with respect to the true coefficient of expansion, and $T(t)$ is the temperature at time t . The error in the estimation of $\lambda(t)$ will have two independent components which will be combined in a root-sum-square (RSS) fashion to determine the total error caused by temperature.

As the wavelength calibration will be performed in vacuum, any change in the resonant wavelength with air pressure must be properly accounted for. There are two known effects

that scale with pressure; the first is a bulk volume decrease due to the finite bulk modulus of the glass, and the second is a slight correction due to the dielectric mirror phase shift. According to theory the change in bulk volume causes a proportional change in length [15] that follows

$$\frac{\Delta l}{l} = \frac{1}{3} \frac{\Delta V}{V} \quad \dots 4$$

The volume change is related to the pressure change by the bulk modulus K:

$$\frac{\Delta V}{V} = \frac{\Delta P}{K} = \frac{\Delta P}{E/[3(1-2\nu)]} \quad \dots 5$$

In Eq. 5 the bulk modulus is written in terms of the modulus of elasticity (E) and Poisson's ratio (ν). Unfortunately for both Zerodur and ULE glass these quantities may vary slightly (by at least $\pm 2\%$, 1σ) from batch to batch. For Zerodur (nominal E = 90.3 GPa and $\nu = 0.243$), the theory indicates a linear contraction of $\Delta l/l = 0.577 \times 10^{-6}$ from vacuum to one Atmosphere. For ULE (nominal E = 67.6 GPa and $\nu = 0.17$), the theory indicates a linear contraction of $\Delta l/l = 0.989 \times 10^{-6}$.

Table (2) Aging rates of several low-expansion glasses from the references shown. All the results were collected over periods of at least 2 years except where noted. In some cases we have converted the reference data to yr^{-1} to facilitate comparison. The negative sign indicates the length change is in all cases a contraction.

Reference	ULE	Zerodur-M	Zerodur
Bergquist [16]	$\leq -2.4 \times 10^{-9} \text{ yr}^{-1}$		
Marmet (1997) [17]	$\leq -3.7 \times 10^{-9} \text{ yr}^{-1}$		
Hils (1989) [15]			$\leq -2 \times 10^{-7} \text{ yr}^{-1}$
Tamm [2000] [18]	$\leq -5.5 \times 10^{-9} \text{ yr}^{-1}$		
Riehle (1998) [19]		$\leq -3.2 \times 10^{-8} \text{ yr}^{-1}$	$\leq -6.3 \times 10^{-8} \text{ yr}^{-1}$

In practice one could employ helium back-filling or simply measure the cavity mode frequency in a known pressure of helium. The refractive index of helium as a function of frequency and temperature is presently known theoretically with an uncertainty of approximately $\pm 3 \times 10^{-9}$ [16]. At near infrared wavelengths the value is approximately an order of magnitude smaller than that of air ($I-n = 2.5 \times 10^{-5}$ at 10^5 Pa). The temperature

coefficient is also smaller than that of air (helium: $-1.1 \times 10^{-7} \text{ }^{\circ}\text{C}^{-1}$ versus air: $-9.4 \times 10^{-7} \text{ }^{\circ}\text{C}^{-1}$, at 1 atmosphere). The uncertainty of the cavity contraction calibration would be limited more or less equally by uncertainty contributions from the helium pressure and temperature measurements.

In subsequent use of the wavelength reference the absolute barometric pressure could be monitored with inexpensive sensors with an uncertainty of $\pm 1.5 \%$. By itself the barometric error results in an uncertainty of approximately $\Delta\lambda/\lambda \leq 0.87 \times 10^{-8}$ (for Zerodur), and $\Delta\lambda/\lambda \leq 1.5 \times 10^{-8}$ (for ULE). Thus combine the uncertainty of the wavelength shift with pressure with the uncertainty of barometric pressure and find the total pressure-related uncertainty terms of $\Delta\lambda/\lambda \leq 2.84 \times 10^{-8}$ (for Zerodur) and $\Delta\lambda/\lambda \leq 3.09 \times 10^{-8}$ (for ULE glass).

Table (3): Uncertainty budget for a wavelength reference constructed from ULE.

Item	$\Delta\lambda/\lambda$
Temperature correction error	$\pm 2.0 \times 10^{-8}$
Aging correction error	$\pm 0.5 \times 10^{-8}$
Bulk volume change correction error	$\pm 3.1 \times 10^{-8}$
Mirror phase shift correction error	$\pm 0.001 \times 10^{-8}$
Mirror contamination uncertainty	$\pm 1.0 \times 10^{-8}$
Wavelength calibration uncertainty	$\pm 0.25 \times 10^{-8}$
Root-Sum-Square Total	$\pm 3.9 \times 10^{-8}$

2.3. Mode Differentiation

A small cavity is appealing since the free spectral range (FSR) would be large, which would facilitate the unambiguous identification of each mode. For instance, the *s* polarized TEM₀₀ modes of a ring cavity with an 8 mm perimeter would be separated by 37.5 GHz. At red wavelengths, a laser frequency repeatability of about 50 ppm would be more than sufficient to return unambiguously to a given mode. However, such a small cavity is more vulnerable to environmental effects such as contamination of the mirror surface.

Due to these uncertainties I have considered longer cavities, on the order of 25cm, in order to reduce the potential wavelength instability caused by possible contamination of the mirrors. However, longer cavities present a challenge in the unambiguous identification of a particular (previously calibrated) mode. There are a number of distinct approaches to accomplish the

mode discrimination in a cavity of this size ($L = 25$ cm round-trip, 1.2 GHz free spectral range). The first is to rely on laser repeatability for a tunable laser to return to the same (previously calibrated) mode. This may be possible with certain types of lasers, for instance solid-state lasers. Secondly, another air-spaced optical reference cavity may be used, with a shorter length and lower resolution, and the coincidences between the two cavities will indicate the correct modes. This vernier approach is introduced in Fig.(1) , below. The shorter cavity must be air spaced since the frequency of the finely-spaced reference cavity modes may shift by more than a FSR with the ambient barometric pressure.

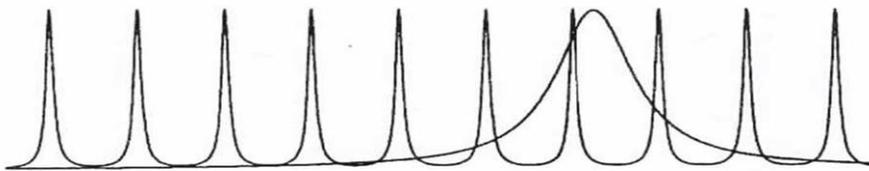


Fig. (1): Mode identification using the two-cavity vernier technique. A short cavity with a large unambiguous free spectral range is used to identify a particular mode of a wavelength reference cavity. The short cavity must also be air-spaced.

There are a number of designs for high-reflectivity dielectric coatings that exhibit different behavior of the phase-shift upon reflection. For this application the best coating design will optimize the s-to-p frequency difference per FSR in relation to the p polarized mode line-width $\Delta\nu_p$. This suggests a figure of merit, which define below as Γ . We let $\Delta\nu_{sp}$ represent the difference in the longitudinal mode frequencies of the two polarizations, and $\Delta(\Delta\nu_{sp})$ is then the change in this mode spacing per free spectral range. Then we write

$$\Gamma = \frac{1}{3} \frac{\Delta(\Delta\nu_{sp})}{\Delta\nu_p} \times 100\% \dots\dots\dots 6$$

This represents the precision that the frequency difference must be measured in relation to the limiting line width.

2.4. Cavity Resolves

It is useful then to explore different designs for the cavity and coating with the figure of merit r in mind. Other aspects to consider include spatial-mode shape, fabrication difficulty, and the number of (expensive) optical coating runs required.

2.4.1. Three - mirror cavity

We start with a three-mirror cavity that has the advantage of being a stigmatically Compensated see Fig. (2). We analyze this using the same coating on all three mirrors, to avoid more than one expensive mirror-deposition run. There are many different coating designs, and we use here $H(LH)^n$ because the s and p polarizations have the same phase shift approximately mid-band (H and L refer respectively to the layers of high and low refractive index). This allows the difference frequency $\Delta\nu_{SP}$ between the two polarization modes to be on the order of a megahertz near the coating band center, which facilitates the measurement of kilohertz differences between cavity FSRs. (For instance, it may allow an inexpensive frequency-to-voltage converter to be used, with no intermediate IF stage). It also allows the cavity to be used as a reference for two relatively close (less than 100 MHz) optical frequencies, allowing the interferometer system designer very long synthetic wavelengths ($c/\Delta\nu > 3$ m). We calculate the loss per pass by multiplying the reflectivity at each mirror.

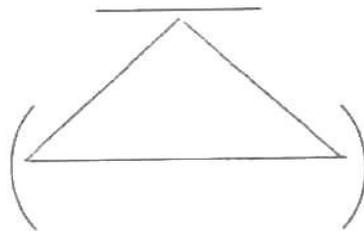


Fig. (2): Three-mirror cavity has two reflections at a 22.5' angle of incidence and one at a 45[□] angle of incidence. The beam waist between the curved mirrors is round and free of astigmatism.

The round-trip reflectivity, along with the round-trip phase shift of each polarization is shown in Fig. (3) for an $H(LH)^n$ coating. (The exponent refers to the number of LH coating pairs). From the Fig. 3 data we calculate the s and p mode line-widths that a three-mirror cavity would have with a $H(LH)^n$ coating, assuming the ring cavity was 25 cm long and the loss was due primarily to the mirrors.

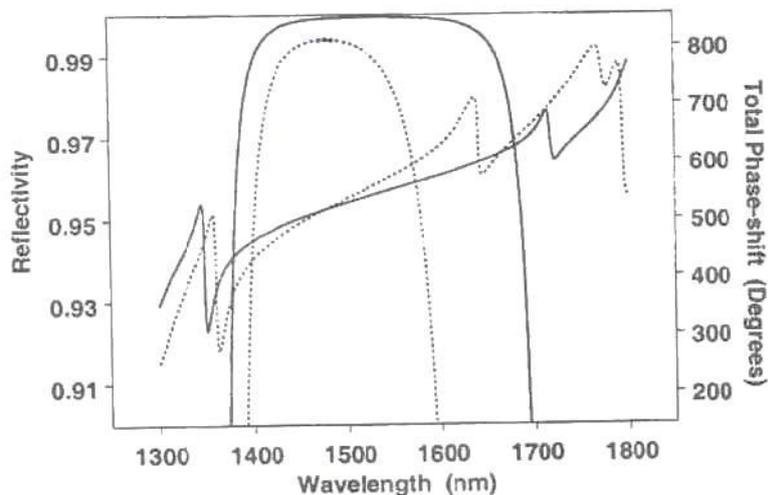


Fig. (3): The solid lines are the s polarized reflectivity and mirror phase-shift per round trip. The dashed lines are the same quantities for the p polarization.

These calculations are shown in Fig. (4) . The figure of merit r is also plotted, and is on the order of 0.2 % near the center of the mirror pass-band. To discriminate modes using this frequency-difference technique would require measuring the center of the cavity mode to approximately ± 0.2 %. In addition to the H(LH)" coating design, it is possible that other designs may offer more s-to-p polarization dispersion, which would increase the figure of merit r by a similar amount.

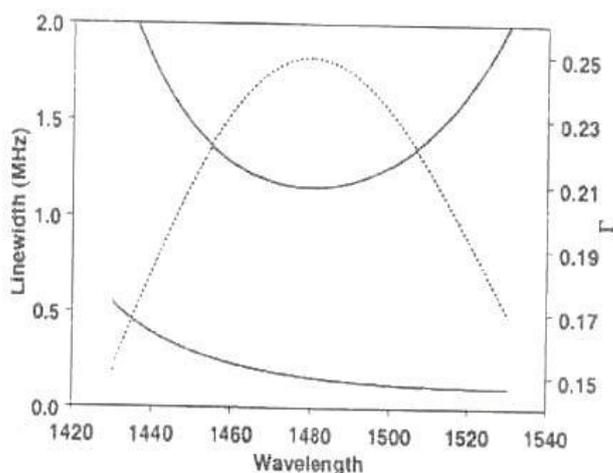


Fig. (4): The solid curves are the p polarized line width (upper) and the s polarized line width (lower) of the three-mirror cavity. The dashed curve is the figure of merit r .

The calculated data is for the same $H(LH)^n$ dielectric coating on all three mirrors of a three mirror cavity see Fig. (2) . The different slopes of the two phase-shift curves allow the discrimination of the longitudinal modes of the cavity by measuring the s-to-p frequency difference.

3. Conclusions

The approach of using stable calibrated resonators to deliver accurate wavelengths in air is technically feasible. We estimate that a total wavelength uncertainty of about $\Delta\lambda/\lambda \leq 3.9 \times 10^{-8}$ could be delivered to interferometer users by such a reference cavity over a +5 °C temperature range, presently limited by the method of accounting for the mechanical contraction from vacuum to atmospheric pressure. It is possible that this particular uncertainty could be greatly reduced by performing measurements (in air) of a length held fixed by a vacuum interferometer. That concept is not explored in this technical report, but is an area of further research. Other areas for further research include exploring the accuracy versus calibration interval trade-off, and the locking of visible (red) DFB lasers should they become commercially available.

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