CLEARING THE FOG FOR BEST IN THE WORLD AIR-WAVELENGTH

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INTRODUCTION

Laser interferometry is the basis for modern length metrology and achieves very high accuracies as a consequence of the stable, well-known frequencies of laser sources. However, length measurements in air also require corrections based on precise knowledge of the air refractive index. This uncertainty in the refractive index of air sets the fundamental limitation for practical measurements, preventing us from fully utilizing the inherent high accuracy of the laser. Some years ago we developed a refractometer which used a Fabry–Perot (FP) cavity to measure the absolute refractive index of a gas [1]. The device was accurate to 3×10^{-9} ($k = 2$) for dry gas, but showed humidity-related errors of 49×10^{-9} when measuring moist (lab) air. When two cavities were compared side-by-side, one 143 mm in length and the second 329 mm, the error scaled inversely with length, which can be interpreted as a 7 nm shortening in the length of both cavities when exposed to humidity. We believe the change in length was due to water penetrating into the mirror coatings, which caused their apparent positions to change—even though the coatings were ion-beam sputter (IBS)—and we present evidence which supports this theory. We aim to quantify humidity errors of the FP cavity and provide a correction mechanism so that the FP cavity can achieve good results for moist gas, comparable to what is achieved for dry gas.

To correct this humidity phenomenon—to clear the fog—we have been developing a wavelength-tracker based on a gas-cell integrated into a heterodyne interferometer. This gas-cell is placed side-by-side with the FP cavity to monitor how each device tracks wavelength as humidity is changed (from 0 %RH to 45 %RH). We aim to correct the humidity error in the FP cavity to better than 3×10^{-9}: so with a 25 cm gas-cell, the heterodyne interferometer must be stable to 0.5 nm over the 10 h duration of the measurement (or fractional length stability $10^{-11}\,\mathrm{Hz}^{-1/2}$). A successful correction at this level would allow the FP cavity to realize air-wavelength an order-of-magnitude more accurate than state-of-the-art.

METHODS AND RESULTS

We first investigated the influence of humidity on IBS-coated mirrors. We had an ultralow expansion (ULE) glass [2] substrate IBS-coated, such that a 6 mm diameter central region was coated while the surrounding substrate was uncoated. We placed the substrate inside a sealed enclosure and used a Fizeau interferometer to measure the change in "height" of the mirror coating as the humidity of air inside the enclosure was changed from dry to moist and back again; desiccant dried the air to less than 10 %RH and saline solution brought it to 70 %RH. The mirror height was defined as the phase difference between the uncoated and coated regions of the substrate, as shown in Figs. 1(a) and (b): the *actual* height of the mirror stack is several micrometers and can only be determined if the fringe order is known; our interest was *change* in mirror height and not

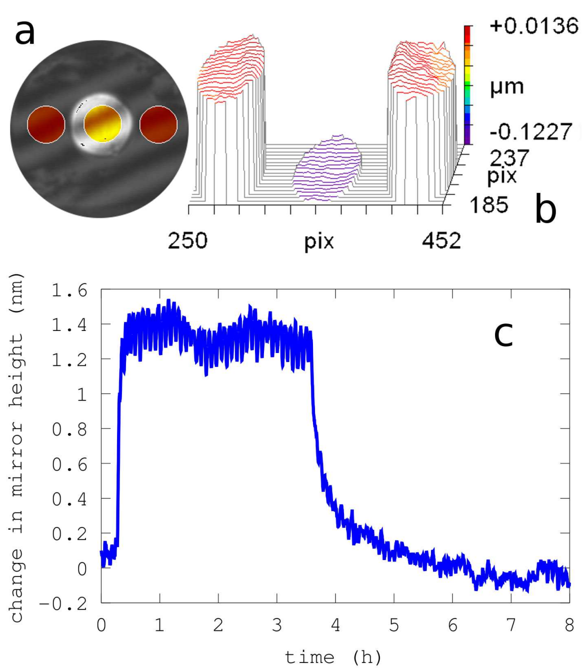


FIGURE 1. (a) Fringes on an IBS-coated mirror with high-reflectivity from the central coated region; (b) mirror height, modulo-2π with order unknown; (c) change in mirror height as humidity was changed from less than 10 %RH to 70 %RH and back again.

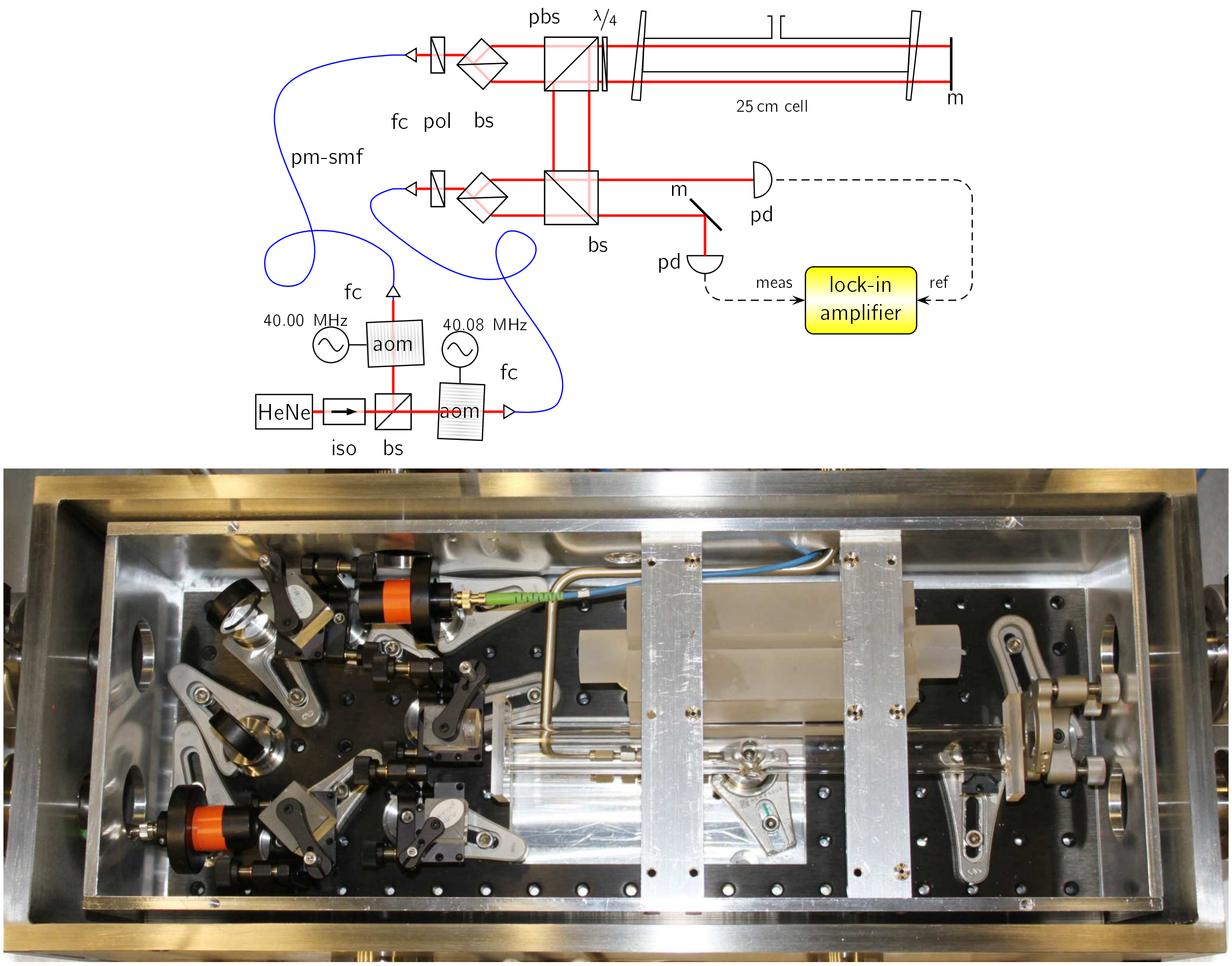


FIGURE 2. Setup of gas-cell heterodyne interferometer. Components include: stabilized helium–neon laser (HeNe), isolator (iso), beamsplitters (bs), acoustooptic modulators (aom), fiber couplers/collimators (fc), polarization-maintaining single-mode fiber (pm-smf), Glan-Taylor polarizers (pol), mirrors (m), and photodetectors (pd). Photograph shows the gas-cell and optics beside the FP cavity in the temperature-stabilized enclosure.

actual height. The change in mirror height as humidity was cycled is shown in Fig. 1(c). Several observations can be made from this test: (1) IBS coatings are obviously sensitive to changes in humidity, (2) the apparent mirror position increases in height as humidity is increased, which is consistent with an FP cavity shortening as humidity is increased, and (3) the response of the coating to moisture is quite rapid. The one incongruous feature of this test was that Fig. 1(c) shows a change in mirror height of about 1.4 nm; our previous experiments with FP cavities showed a change in mirror height of 3.5 nm (per mirror) when the cavities were brought from vacuum to humid lab air [1]. However, a quantitative comparison of the two results is complicated by the fact that the mirror coatings were not identical in the two experiments.

In order to attempt a humidity correction for the mirrors in our actual FP cavity refractometer we developed a heterodyne interferometer into which a gas-cell was integrated. The setup shown in Fig. 2 is based on the well-known spatially-separated design of Tanaka *et al.* [3] and follows the fiber-fed adaption of Wu *et al.* [4]. The gas-cell interferometer measures the change in path-length between one laser beam passing through the cell interior (reference path) and the beam on its exterior (measurement path). When the cell interior is pumped to high-vacuum, the interferometer tracks changes in the refractive index of air around the cell exterior (such as arise due to changes in humidity). Since the cell windows are uncoated, this interferometer should not suffer from the same water penetration errors that affect our FP cavity; coated surfaces in the interferometer (such as mirrors and beamsplitters) are common to both reference and measurement paths. Also note that correcting the FP cavity only requires the cell interferometer to be stable (and precise) as humidity is changed; the errors due to window thickening that usually preclude a cell from measuring absolute refractive index are not a problem.

The gas-cell is made of fused silica and consists of wedged, uncoated windows frit-bonded onto a tube; the tube has a 2.5 cm outer diameter and is 25 cm long; a short stub teed at the middle of the tube serves as a vacuum port. Off-the-shelf optical components were used throughout, and everything from the output of the fibers was placed on a 10 cm × 40 cm breadboard. The breadboard was placed beside the FP cavity inside a sealed, temperature-stabilized enclosure, where temperature variations are known to be sub-millikelvin. Our first point of interest was the stability of the interferometer. To test this, we temporarily removed the gas-cell and monitored the stability of the measurement and reference paths in air: the variations in pathlength were less than ±0.3 nm over 20 h  (min: −0.24 nm, max: 0.17 nm). This stability performance is an order-of-magnitude worse than the phase resolution of the lock-in amplifier, but it nevertheless represents a fractional stability better than 10^{-9} because the cell is configured doublepass. As mentioned above, the goal was to correct the FP cavity to better than 3×10^{-9}.

A more pertinent diagnostic was how well the gas-cell would track changes in the refractive index of lab air when compared to the FP cavity. We know from previous experiments that two FP cavities track one another to better than 1×10^{-9} in normal lab air where humidity is stable to 5 %RH. For this tracking comparison, the gas-cell was placed in the interferometer and its interior was pumped to high-vacuum to serve as the reference path. To compare the cell and cavity we relate both to changes in fractional length, which is equivalent to fractional changes in refractive index $\frac{dn}{n} = \frac{dL}{L}$. Length changes in the FP cavity are related to its resonance frequency via $\frac{dL}{L}|_{\text{cavity}} = -\frac{d\nu}{\nu}$. The resonance frequency was measured by

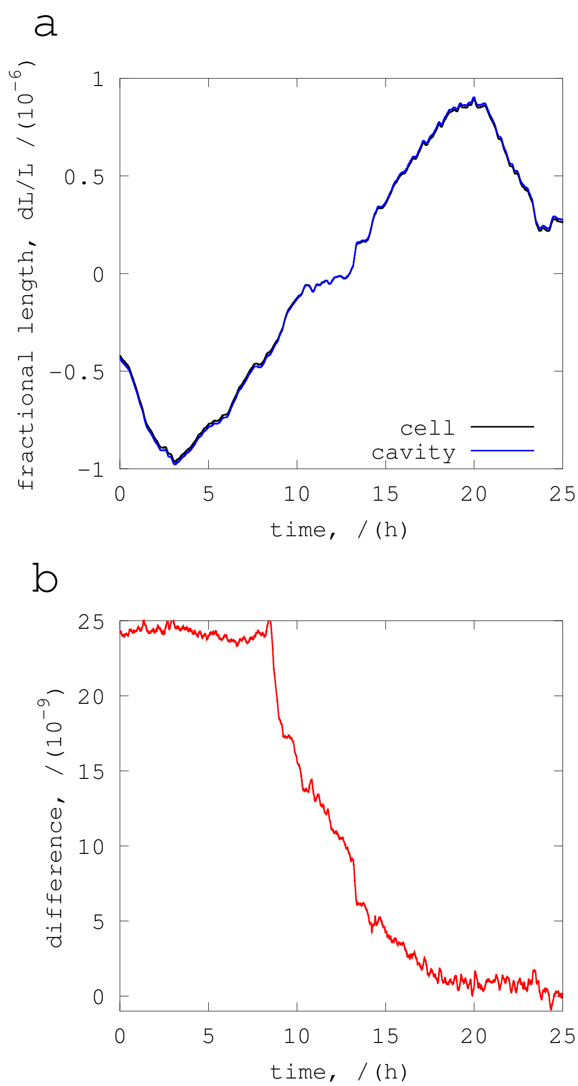
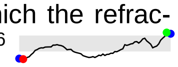


FIGURE 3. (a) Change in fractional length of gas-cell and FP cavity in atmospheric air. (b) The difference between the two: dessicant added at t = 8 h.

beating the cavity resonance against an iodine-stabilized laser and using a counter to record the beat frequency. Length changes in the gas-cell are related to phase via $\frac{dL}{L}|_{\text{cell}} = \frac{d\phi}{\Phi}$, where $\Phi = \frac{4\pi L}{\lambda}$ and λ is wavelength. The changes in phase between the reference and measurement paths was measured with a lock-in amplifier. We performed a test over 25 h during which the refractive index of air changed by 10^{-6}  (min: 1.00027102, max: 1.00027191) and observed that the gas-cell tracked the FP cavity to $\pm 3 \times 10^{-9}$  (min: -2.1×10^{-9}, max: 2.9×10^{-9}). Most of this disagreement in tracking can be attributed to the gas-cell interferometer. Also note that cell length must be known to 0.25 mm in order to accurately track 10^{-9} changes in the refractive index of air during typical 10^{-6} daily fluctuations. Thus far we only have a caliper measurement of cell length (accurate to about 1 mm), and we plan to soon measure it more accurately with a coordinate-measuring machine.

We attempted to correct the humidity error in the FP cavity, once again using desiccant to dry the air inside the enclosure to less than 10 %RH. We observed tracking performance of the gas-cell and FP cavity as shown in Fig. 3. The 2×10^{-6} change in fractional length in Fig. 3(a) is predominantly due to changes in atmospheric pressure (400 Pa changes refractive index by 10^{-6}), and the addition of desiccant at $t = 8$ h barely contributes to the overall change in refractive index. However, the addition of desiccant is clearly visible in the difference in tracking between the cell and cavity plotted in Fig. 3(b). (Also note the aforementioned typical $\pm 3 \times 10^{-9}$ agreement in tracking between the two in normal lab conditions up until $t = 8$ h.) The difference plotted in Fig. 3(b) is $\frac{dL}{L}|_{\text{cell}} - \frac{dL}{L}|_{\text{cavity}}$, so one interpretation of the test is that the cavity gets longer as the mirror coatings are dried out. This relation between mirror position and humidity is consistent with the mirror height test described above. But as with the mirror height test, we are only seeing about half the expected change: we believe the $L = 143$ mm FP cavity shortens by 7 nm ($\frac{dL}{L} = 49 \times 10^{-9}$) when brought from zero humidity to moist air, but our desiccant test only shows 25×10^{-9} disagreement between the FP cavity and gas-cell.

We do not fully understand why our attempts to correct the humidity error in the FP cavity are showing half the expected error. Our best theory at present is that desiccant does not fully remove moisture from the mirror coating. This theory would also account for the fact that Fig. 4 in Ref. [1] does not pass through zero at zero-humidity: in that test, the measure of refractive index by two FP cavities disagreed by 2×10^{-8} in moist air, and still showed 1×10^{-8} disagreement when dried with desiccant; whereas when filled from vacuum with dry air the cavities agreed to 10^{-9}. In order to test this theory we are in the process of making the gas-cell interferometer vacuum-compatible: in addition to some design improvements, the next-generation gas-cell interferometer will feature silicate-bonds to form a quasi-monolithic structure that should deliver the highest stability. We will report on this apparatus in the near future.

CONCLUSION

The most accurate realization of air-wavelength is currently limited by a humidity error in our FP cavity refractometer. We have reported some tests that confirm the error arises due to water penetration into the IBS-coated mirrors. We built a heterodyne gas-cell interferometer to correct this error: in normal lab air, the gas-cell interferometer tracked the FP cavity to $\pm 3 \times 10^{-9}$ over 25 h. Our attempt to use this gas-cell interferometer to correct the humidity error in the FP cavity has only been semi-successful: the disagreement between cell and cavity is half what is expected when air is dried with desiccant. We believe this shortfall is due to residual moisture in the mirror coatings that can not be removed by desiccant. To test this hypothesis we are in the process of transitioning to a vacuum-compatible gas-cell interferometer that will allow us to compare the cell and cavity from moist air to a perfectly dry state (i.e., vacuum).

REFERENCES

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[2] Any mention of commercial products is for information only; it does not imply recommendation or endorsement by NIST nor does it imply that the products mentioned are necessarily the best available for the purpose.

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