

Simple pressure-tuned Fabry–Pérot interferometer

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A simple, compact and inexpensive pressure-tuned Fabry–Pérot interferometer is presented. It is used as a laser locking reference for optical frequencies where the use of an atomic reference is impractical. The scanning range is several GHz. Absolute positioning of the interferometer with an accuracy of 7 MHz rms over a range of 2 GHz is possible. The instrument is temperature stabilized and shows long-term drift of 16 MHz rms over 48 h.

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I. INTRODUCTION

Tunable Fabry–Pérot interferometers (FPIs) have been used since the 1960s as locking references for lasers or spectrometers (see, e.g., Ref. 1 and references therein). Interferometers are often used as locking references when atomic reference lines are not available or have too large a linewidth. In one of the experiments in our laboratory, a laser has to be tuned and stabilized to an atomic transition that is frequency shifted by tens of GHz due to the Zeeman effect in a strong, variable magnetic field.² In another experiment, an infrared laser has to be stabilized in a frequency range where there exists no suitable atomic reference.³ For these applications a locking reference with tunability of several GHz and long-term stability on the order of a few MHz is needed.

Tuning of FPIs is often achieved by changing the cavity length mechanically⁴ or with piezo actuators (as in many commercially available units). However, due to drift, hysteresis, and piezo creep, these interferometers are unsuitable for our applications. Another way to tune the interferometer is to change the gas density and thereby the refractive index inside the cavity. Here the cavity itself is fixed, which greatly improves the stability and accuracy of the instrument. We present a new setup for such a “pressure-tuned” interferometer. It differs from earlier setups (e.g., in Rockwell *et al.*⁵, Mack *et al.*⁶) and commercially available units in its compact size, accurate tuning and good stability at low cost.

II. PRINCIPLE OF OPERATION

Light of vacuum wavelength λ will be transmitted through a confocal FPI^{1,7,8} in the N th order if the relation $4nd=N\lambda$ is fulfilled, where n is the index of refraction inside the cavity and d is the cavity length. Phase shifts that might occur in the mirrors are neglected. If the index of refraction inside the interferometer cavity is changed by δn , the wavelength transmitted in the N th order transmission peak changes by $\delta\lambda$ according to $\delta\lambda/\lambda=\delta n/n$. A change of the refractive index can be achieved by changing the gas density ρ inside the cavity. A density change $\delta\rho$ causes a change of

refractive index $\delta n=(n-1)\delta\rho/\rho$. The gas density inside the cavity varies inversely with the length l of the pressure tube that contains the cavity. By varying the tube length by δl the transmitted wavelength and frequency are varied according to

$$\frac{\delta\nu}{\nu} = -\frac{\delta\lambda}{\lambda} = \frac{(n-1)}{n} \frac{\delta l}{l}. \quad (1)$$

A laser locked to a transmission peak of fixed order N will follow the frequency change and can be tuned to the required wavelength. Interferometers operating by this principle are commonly called “pressure tuned.” They offer some major advantages over interferometers with piezo-electric actuators directly integrated into their cavities. In pressure-tuned interferometers, a differential drive and a suitable geometry of the pressure tube can be employed to translate macroscopic actuator steps into very small frequency steps of the interferometer. Also, in pressure-tuned interferometers the actuator is mechanically decoupled from the interferometer cavity, leading to a reduced effect of actuator vibrations on the transmission resonances of the interferometer.

III. INSTRUMENT SETUP

Figure 1 shows a sketch of the instrument setup and a photograph of the instrument mounted in its enclosure. The confocal interferometer cavity consists of two partially reflecting (at 780 nm) plano-concave mirrors attached with a very thin layer of glue to the ends of a 14.94 cm long ultra-low expansion glass rod (custom made by Advanced Glass Industries, Rochester, NY). The mirrors have a reflectivity of 0.98 and 15 cm radius of curvature (CVI Laser Corp, Albuquerque, NM; Part No. PRI-780-98-0737-0.15CC). The free spectral range (FSR) of the cavity is 500 MHz, the transmission peaks are measured to have 13 MHz full width at half maximum, corresponding to a finesse of 39. The cavity was designed to have a relatively small finesse to allow for a soft, stable laser lock.

The cavity is housed in a Kwik Flange (KF) enclosure near atmospheric pressure. In order to increase the scanning range we introduced the high-index of refraction gas SF₆ [$n=1.00078$ at 589 nm, standard temperature and pressure (STP)⁹] such that the enclosure is filled with $\approx 70\%$ SF₆ and

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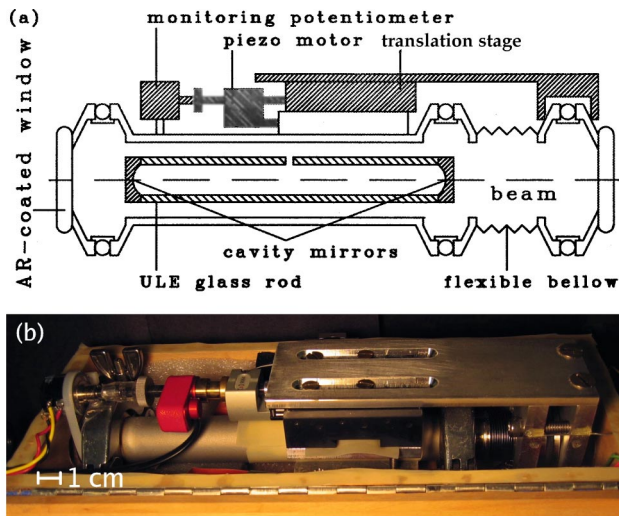


FIG. 1. (Color online) Instrument setup. (a) The translation stage is driven by a piezo motor and mounted to the pressure tube such that it extends or contracts the flexible bellow, changing the gas density inside the cavity. A potentiometer is attached to the rear end of the actuator to monitor the position of the motor and the translation stage. (b) Photograph of the instrument mounted in a temperature stabilized box.

30% air. As seen through Eq. (1), this approximately doubles the tuning range compared to air (for air $n=1.00029$ at 589 nm, STP).⁹ As seen in Fig. 1(a), the ends of the enclosure are sealed with antireflection (AR) coated windows. The length of the enclosure is comprised of a fixed tube and a variable-length bellow with ≈ 6 mm travel for stretching. The bellow can be stretched by moving a translation stage which is attached to the far end of the bellow. The base of the translation stage is attached to the pressure tube [see Fig. 1(a)]. The interferometer is automated by driving the translation stage actuator with a motor. We chose a small piezo driven stepper motor which would fit in the thermally stabilized enclosure. Driving the piezo motor results in a change of the KF enclosure volume and thus a change in the density of the gas which is proportional to the change in bellow length. A hole in the side of the cavity ULE rod ensures that the cavity rapidly follows this density change.

An absolute reference for the linear travel of the translation stage (and thus the stretching of the bellow) was realized by monitoring the angular travel of the actuating screw. A ten-turn precision wirewound potentiometer was attached between the box and the rotating actuator such that its resistance was correlated with the rotation of the screw. This resistance was used as feedback to tune the interferometer in an absolute fashion. Using the FSR as a reference, the correspondence between the potentiometer readout and the frequency change of the transmission peaks was calibrated. The maximum of ten revolutions of the potentiometer together with the thread of the actuator (1/4 in.-80 thread) limits the usable travel of the bellow to 3.2 mm. This configuration results in a tuning range of about 2 GHz. We can scan across this range in 90 s.

The instrument is mounted inside a small wooden box ($9 \times 12 \times 30$ cm³), which is sealed to minimize heat exchange with the outside. The laser beam to be analyzed travels through holes closed with AR-coated windows. For tem-

perature stabilization a commercial temperature control unit (Wavelength electronics HTC-3000) is used, resulting in a stability of 20 mK rms over 24 h.

We have built an additional tunable interferometer. It has a different mechanical setup and is built for operation at 980 nm (mirrors: CVI Part No. PRI-980-98-0737-0.15CC). The total cost of each interferometer setup, including motors and driver modules, was \approx \$2500.00. To our knowledge, there is no instrument commercially available at this price with qualities as described in the following section.

IV. TUNING PRECISION AND STABILITY

In principle, the Fabry-Pérot can be driven deterministically with very small step sizes. The small piezo motor employed in our design, however, operates with a slip-stick mechanism which is sensitive to the applied load. Since the load in our system depends on the direction of travel and the length of the bellow, the travel of the actuator is not deterministic and we have observed variable amounts of travel for a given number of steps. Overall, the frequency change per step varied by up to 30%. We also measured different amounts of travel depending on how often the motor was scanned back and forth over roughly the same range. In order to achieve satisfactory absolute positioning accuracy and reproducibility, we measured the motor travel with the potentiometer described in Sec. III.

In all measurements presented in this article, the interferometer tuning frequency is derived from the potentiometer readout. At a given interferometer tuning frequency, the transmission spectrum of the interferometer is obtained by scanning an external-cavity diode laser linearly over a well-defined frequency range. The spectra can be evaluated with an accuracy of a few MHz using simultaneously recorded saturated spectra of ⁸⁵Rb as a reference. As an example, Fig. 2(a) shows five superimposed FPI transmission spectra over identical ranges of 600 MHz. The interferometer tuning frequency was varied in steps of 100 MHz. The first and last transmission peak in Fig. 2(a) are from the same spectrum and separated by the FSR of 500 MHz.

We have used measurements such as the ones displayed in Fig. 2(a) in order to quantitatively characterize the tuning accuracy and the drift behavior of the FPI. First, the long-term stability of the interferometer was evaluated at a fixed position of the piezo motor drive, i.e., FPI transmission spectra were acquired without any tuning action of the interferometer between the scans. The FPI transmission spectra were taken by scanning the external cavity diode laser. As described, the FPI transmission spectra were evaluated using simultaneously recorded saturated spectra of ⁸⁵Rb as references. The FPI transmission spectra were recorded in 10 min intervals over 48 h. The frequencies of the transmission peaks were then extracted from the spectra. The rms drift of a typical transmission peak from its mean value was found to be 16 MHz over 48 h. The maximum full drift range of any peak over that time was 80 MHz.

The accuracy and reproducibility of the interferometer tuning mechanism are of particular interest. The short- and long-term accuracy and reproducibility were determined by

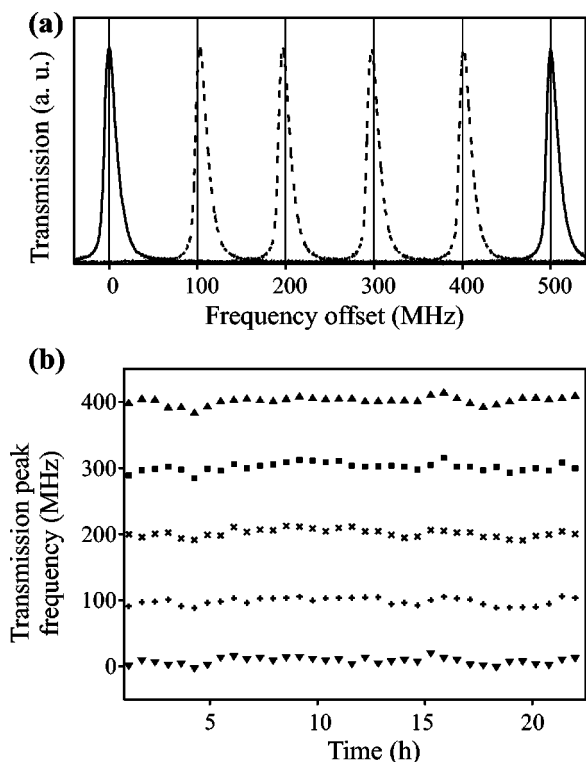


FIG. 2. Instrument performance. (a) Superimposed transmission spectra of the FPI over a 600 MHz wide range, taken for five values of the interferometer tuning frequency. The tuning frequency is varied in steps of 100 MHz using the potentiometer resistance as an indicator for the FPI tuning. One spectrum (solid line) shows two transmission peaks separated by 500 MHz, i.e., the free spectral range of the instrument. The other spectra exhibit only a single transmission peak within the displayed range. (b) Frequencies of FPI transmission peaks with respect to an atomic reference for five different values of the interferometer tuning frequency as a function of time. The transmission frequencies were determined 35 times over a time interval of 22 h by periodically tuning the interferometer to different positions and evaluating the FPI transmission spectra at these positions. The displayed transmission frequencies were expected to have 100 MHz separation. The deviations from the expected frequency values reflect FPI positioning uncertainties and drifts.

repeatedly driving the interferometer to 31 different tuning frequencies using the potentiometer readout. The tuning frequencies had 50 MHz intervals and covered a range of 1.5 GHz. At each tuning frequency, the interferometer transmission spectrum and a ^{85}Rb saturated spectrum, used as a reference, were recorded by scanning the external cavity diode laser. Using this method, each of the 31 tuning frequencies was tested 35 times, resulting in 1085 FPI transmission spectra acquired over 22 h. From the recorded FPI transmission and saturation spectra, the actual frequencies of the FPI transmission peaks were extracted. As an example, Fig. 2(b) shows the actual frequencies of FPI transmission peaks observed for 5 out of the 31 interferometer tuning frequencies as a function of time. Those 5 tuning frequencies were such

that under perfect instrument performance the transmission frequencies displayed in Fig. 2(b) would have fixed intervals of 100 MHz. Deviations of the actual frequencies of the transmission peaks from their expected values are attributed to slow thermal drifts and to fast, measurement-to-measurement positioning uncertainties caused by the FPI tuning mechanism. Evaluating the FPI transmission peak frequencies in all of the described 1085 spectra, we determined that short-time-scale deviations caused by the tuning mechanism lead to a rms tuning accuracy of 7 MHz, with a maximum deviation of 26 MHz. The observed thermal drifts were not larger than those found in the measurement without tuning action, which shows that the tuning mechanism does not cause significant additional drifts.

V. POSSIBLE IMPROVEMENTS

In the current setup, a higher precision potentiometer as positioning reference would enhance the tuning accuracy. Alternatively, a stepper motor with load-independent angular travel could be used to move the translation stage. This would remove the need for the potentiometer reference, but it would probably increase the minimum tuning step size and result in a bigger instrument. If larger tuning ranges were needed, one could introduce a gas with higher index of refraction than that of SF_6 into the FPI enclosure. However, this may degrade the instrument's stability. A suitable, readily available substance would be difluoroethane, which is, e.g., used in Falcon Dust-Off sprays. At 314 K and standard pressure it has a refractive index of 1.0083 at 545 nm,¹⁰ which would result in a tuning range of tens of GHz, about ten times as much as with SF_6 .

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