Published in final edited form as:

Rev Sci Instrum. 2016 November ; 87(11): 115102. doi:10.1063/1.4964622.

Highly Compact Fiber Fabry-Perot Interferometer: A New Instrument Design

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Abstract

This paper presents the design, construction and characterization of a new optical-fiber-based, low-finesse Fabry-Perot interferometer with a simple cavity formed by two reflecting surfaces (the end of a cleaved optical fiber and a plane, reflecting counter-surface), for the continuous measurement of displacements of several nanometers to several tens of millimeters. No beam collimation or focusing optics are required, resulting in a displacement sensor that is extremely compact (optical fiber diameter 125 μm), is surprisingly tolerant of misalignment (more than 5°), and can be used over a very wide range of temperatures and environmental conditions, including ultra-high-vacuum. The displacement measurement is derived from interferometric phase measurements using an infrared laser source whose wavelength is modulated sinusoidally at a frequency f . The phase signal is in turn derived from changes in the amplitudes of demodulated signals, at both the modulation frequency, f , and its harmonic at, $2f$ coming from a photodetector that is monitoring light intensity reflected back from the cavity as the cavity length changes. Simple quadrature detection results in phase errors corresponding to displacement errors of up to 25 nm, but by using compensation algorithms discussed in this paper, these inherent non-linearities can be reduced to below 3 nm. In addition, wavelength sweep capability enables measurement of the absolute surface separation. This experimental design creates a unique set of displacement measuring capabilities not previously combined in a single interferometer.

1.0 Introduction

The plane external fiber, Fabry-Perot interferometer (EFPI) represents the simplest, and probably the most compact, method for interferometric measurement. In its simplest embodiment, this comprises a cleaved, or polished, optical fiber end (typically single mode) opposing a plane, reflecting counter-surface, hereafter referred to as a plane EFPI. The focus of this study is the use of EFPI for position or displacement sensors. Applications of this sensing method include atomic force probes [1, 2, 3], accelerometers [4], and, more recently, longer-range displacement interferometry for measuring motion of translation stages [5, 6, 7]. In the absence of focusing or collimating optics, the beam emerging from the fiber will diffract, resulting in angular dispersion of the optical beam with distance from the end of the fiber. When the reflecting faces of the EFPI are nearly parallel, multiple reflections will take place, with attenuation of the multiply reflected beams being a function both of the reflectivity of the cavity surfaces and the cavity length. When one or both of the cavity surfaces have low reflectivity, few reflections occur, and the cavity is said to have low

finesse. While this type of interferometer has been used for a variety of optical sensing applications [8], the focus of this paper is the presentation of a new experimental low-finesse EFPI with a unique set of features.

The instrument presented in this paper utilizes a tunable infrared laser source operating in one of two modes: either fixed wavelength, or wavelength modulation about a known center wavelength. Phase measurement is achieved by sinusoidally modulating the wavelength of the laser source at frequency f (typically on the order of 1 kHz) and monitoring the strength of interference response at both the modulation frequency and its second harmonic. Wavelength modulation for interferometric studies using diode lasers was first demonstrated in the early 1980's [8]. Pivotal to this development was the realization that the laser diode wavelength could be modulated by changing the drive current through the diode [9]. The theoretical framework for separation of phase components by the harmonics of the modulated signal to measure time of flight for absolute distance measurement appears to have first been discussed by den Boel, [10]. However, a year before this, Beheim and Fritsch had implemented absolute distance measurement using wavelength scanning [11] and, in a further study, Beheim utilized interferometric phase measurement using the intensity beat signals at both the modulated frequency and the second harmonic [12]. A review of developments by these and other researchers is provided in a book by Zhang [13]. This work appears to have received little attention within the dimensional metrology community until this current decade.

Interferometers that utilize external collimating optics from the fiber to produce a plane wave represent the classical homodyne and heterodyne interferometers that have been available commercially for many decades. More recently, a number of designs have emerged that utilize gradient index optics (commonly referred to as GRIN lenses) to collimate the beam from a fiber [5, 14]. GRIN lenses typically come in the form of cylinders of around 1.8 mm diameter and 10 mm long. These will often couple to the optical fiber using a cylindrical guide so that the overall assemblies are around 2 mm to 3 mm in diameter and 20 mm long. Collimation of the optical beam has some considerable advantages, most importantly the ability to use very long cavities; the relative merits of these non-collimated interferometer designs have been theoretically studied in the paper of Thurner et al. [5]. However, the addition of these optical components leads to a less compact sensor. Our focus in this work was to develop an EFPI with a very small sensor volume, so only those designs without external optical components (beam splitters, cube corner reflectors, collimating optics, etc.) were considered. A theoretical model developed by Wilkinson and Pratt [15] for the non-collimated plane interferometer predicts the cavity response as a function of separation and alignment. This model was, in turn, adapted from theory developed by Nemoto and Nakimoto [16] for predicting beam coupling between two fibers based on the assumption of a Gaussian beam profile. While it is demonstrated that this model captures the essential physics of the cavity response, there remain deviations that are significant at nanometer levels over separation changes that are comparable or greater than the source wavelength.

2.0 Instrument design and performance

As part of ongoing research in our laboratory, a plane EFPI interferometer was developed for measurement of displacement in situations where there is less control of the external counter-surface, or its alignment. Applications span cavity separations from a few micrometers to tens of millimeters. The purpose of this study was to assess the performance of the new EFPI as a function of external counter-surface material and for a variety of cavity separations and angular misalignments. Additionally, some measurements take place over many minutes to days. Consequently, the stability of both laser wavelength and cavity separation were also studied.

2.1 Interferometer system

The interferometer developed for these studies is a fiber-optic, homodyne, single-detector system using a low finesse, Fabry-Perot (FP) cavity that is operated in reflectance mode between the cleaved end of an optical fiber and a reflecting counter-surface. A block diagram of the major components of this system are shown in Figure 1. The optical source is a rapidly tunable diode laser (Optilab RTL 1550-30) with wavelength tuning range from 1520 nm to 1575 nm. The wavelength can be controlled by an external voltage; this control voltage can be used either to ramp the laser wavelength over the full tuning range, or to modulate the laser wavelength about a center value. After passing through an optical isolator (ISO) (providing a blocking of return transmission to the laser of better than -55 dB), the laser output is split equally by an evanescent-wave fiber coupler. Half of the laser output exiting the 50:50 coupler is fed to the FP cavity; the other half is dumped using an angle-polished connector (APC). Light reflecting back from the FP cavity returns through the 50:50 coupler. Half is blocked from returning to the laser source by the ISO; the intensity of the other half is monitored by the InGaAs amplified photodiode detector (Optiphase V-600).

For a symmetric FP cavity of length h , where the reflectivity R of the two surfaces is equal, the intensity I_{refl} of the reflected light, normalized by the intensity I_{inc} of the incident light, is given by [3]:

$$\frac{I_{refl}}{I_{inc}} = \frac{(1+R)^2}{2} \frac{1 - \cos\left(\frac{4\pi}{\lambda}h\right)}{1 + R^2 - 2R\cos\left(\frac{4\pi}{\lambda}h\right)}, \quad (1)$$

where λ is the laser wavelength. As h changes, interference fringes are observed as varying light intensity at the photodetector. The fringe shape is described by an Airy function, but appears approximately sinusoidal for low values of R ($<10\%$), as shown schematically in Figure 2. The fringes are periodic in cavity length change, with the distance from one maximum to the next representing a change in cavity length of $\lambda/2$. For small changes in cavity length, the interferometer can be used near a quadrature point, *i.e.*, the mid-point between an interference maximum and an adjacent minimum. At or near that point, the intensity-displacement relation is linear to within a 1 % error for displacements on the order of 100 nm for wavelengths near 1550 nm, but displacements larger than this cannot be tracked accurately, due both to large nonlinearities and to the fact that the sensitivity, which

is proportional to slope of the interference fringe, approaches zero at interference maxima and minima.

To overcome this limitation and extend the working range of our interferometer, the laser wavelength is modulated sinusoidally at a frequency of $f = 1.2$ kHz, which was chosen based on the upper modulation frequency limit of the rapidly tunable laser (RTL). By modulating the wavelength, the AC signal measured by the detector has a spectrum consisting of responses at the modulation frequency f and its harmonics. The optimal wavelength modulation amplitude, or width, depends on the cavity length, and typically is around 0.5 nm (peak-to-peak) for cavities on the order of a few millimeters. To determine both the laser center wavelength and modulation width, a small fraction of the RTL output is fed to an optical spectrum analyzer (OSA, Yokogawa AQ6370C), which has a wavelength accuracy of ± 0.01 nm. In addition to monitoring the RTL wavelength, the OSA is also used to actively stabilize the wavelength; this technique is described in section 3.3.2.

When modulation width is optimized, the intensity of the FP response at f , designated I_f , is greatest when the cavity is near a quadrature point (*i.e.*, where the interference fringe is approximately linear), and approaches zero at fringe maxima and minima. Conversely, the response at $2f$, designated I_{2f} , approaches zero at quadrature points and is greatest at fringe maxima and minima, where the interference fringe is approximately parabolic. I_f and I_{2f} are detected using standard lock-in amplifier methodology; the electrical output from photodiode detector (a signal between 0 V and 5 V) is sent to two lock-in amplifiers, one set to detect responses phase-locked to the 1.2 kHz modulation source, the other set to detect the response at twice the modulation frequency. In our case, the lock-in amplifier functionality was implemented with field-programmable gate arrays (FPGA), but conventional, stand-alone lock-ins could also be used. Typical behavior of the interference fringe measured as reflected intensity (in blue) and I_f and I_{2f} (in red and green, respectively), with arbitrary amplitudes, for a change in cavity length of slightly over one fringe (*i.e.*, approximately 775 nm), is shown in Figure 3a. From this, it can be seen that I_f is greatest (both positive and negative) near fringe quadrature points, and I_{2f} is greatest (again, both positive and negative) near fringe maxima and minima. As a result, use of both I_f and I_{2f} information allows the tracking of cavity length changes over large distances without loss of sensitivity or “blind spots” at fringe maxima and minima. To the extent that I_f and I_{2f} vary approximately sinusoidally with cavity length change, after amplitude normalization they will form an approximate circle in polar coordinates, as shown in Figure 3b, where change in angle is linearly proportional to change in cavity length, and one revolution corresponds to change in cavity length of $\lambda/2$. These signals can therefore be combined into a rotating vector created between point (0,0) and point (I_f, I_{2f}) . Changes in cavity length, h , caused by motion of the polished surface can then be approximated from:

$$\Delta h = \frac{\lambda}{2} \left(\frac{\alpha}{2\pi} + n \right), \alpha = \tan^{-1} \left(\frac{I_f}{I_{2f}} \right), \quad (2)$$

where λ is the wavelength, n is the number of times the vector completes a full revolution, and α is the angle in radians formed between the vector and the positive horizontal axis.

In reality, I_f and I_{2f} are not perfectly sinusoidal functions of cavity length, which creates errors in measurements of h that are periodic in $\lambda/2$. Section 2.2 presents a strategy for addressing this issue.

2.1.1 Dynamic tracking—The dynamic performance of the system is limited primarily by the wavelength modulation frequency. Using the Nyquist criterion, our system's maximum theoretical tracking speed is approximately 450 $\mu\text{m/s}$. To evaluate the system's actual ability to track a moving target, an experiment was performed in which the target was moved at progressively higher speeds at an average distance of approximately 0.5 mm. As predicted, after crossing a speed of 450 $\mu\text{m/s}$, the ability to count fringes diminished and the reported displacement became inaccurate. Measured displacement from the fastest recorded run can be seen in Figure 4.

2.2 Automated error compensation strategies

The error compensation strategy in this work is based on the measurement of, and subsequent correction for, the non-sinusoidal components of I_f and I_{2f} .

2.2.1 Post process error compensation with look up table—One inherent problem related to using a FP cavity in this extended mode is the non-linear characteristic of the displacement, as determined from Eqn. 2, with cavity separation. One strategy to reduce measurement uncertainties is to post-process measurement data. In this method, cavity length is continuously ramped by an open-loop piezoelectric-based nano-positioner capable of smooth and continuous motion with a maximum displacement of approximately 35 μm . During a 35 μm cavity ramp with 1550 nm laser wavelength, the rotating vector completes a maximum of 45 full revolutions. Because all these data can be stored and overlapped, they can be averaged in post-processing to reveal periodic nonlinearities, as shown in Figure 5. In this figure (top), the idealized angle is reconstructed; that is, the angle that the vector should have for ideal sinusoidal response is plotted against the actual measured angle. In the bottom figure, multiple overlapped cycles are presented with angular errors extracted. A bi-cubic spline function is then used to fit the data to average all overlapping cycles into one monotonic data set. These data form a base for creating a 7200 point lookup table with linear interpolation between points. By using this method alone, it was possible to reduce the amplitude of the periodic errors from approximately 50 nm down to the single-nanometer level, as shown in Figure 6.

2.2.2 Amplitude normalization technique and offset removal—Other sources of periodic errors include differences in the maximum values of I_f and I_{2f} , as well as small DC voltage offsets present in signals. Since basic trigonometry is used to compute angle from I_f and I_{2f} it is assumed that their corresponding maximum amplitudes are equal (i.e. the rotating vector has constant length) and is centered at the point (0,0). Any deviation from this condition creates periodic errors.

Maximum values of I_f and I_{2f} depend strongly on laser wavelength modulation width, the optimal amplitude of which is dependent on cavity length: the longer the cavity, the smaller the modulation width required. This is somewhat complicated by the fact that the interfering

beam comprises the sum of reflected beams with optical path lengths of even integer multiples of the cavity separation, with each of these successive beams having an attenuated amplitude. However, at large separations the Gouy phase effects are negligible and it might reasonably be considered that the first reflected intensity will dominate. In this case, the predicted optimal modulation width, A , becomes

$$A = \frac{\lambda^2 \delta}{\pi h}, \quad (3)$$

where $\delta = 2.63$ corresponds to the value for which the Bessel functions of the first kind, of orders 1 and 2, produce the same value [17]. For separations of greater than 3 mm, this provides a reasonable estimate of the modulation width. At smaller separations the hyperbolic dependency on the path length results in considerable deviation from this model. This relationship is plotted in Figure 7 for cavity lengths from approximately 100 μm to 100 mm. Due to a maximum tuning range of 55 nm for our laser, our smallest working cavity length is on the order of 20 μm , but in our applications the interferometer is rarely used with cavities smaller than 1 mm.

To maintain a constant ratio of I_f and I_{2f} maximum values, a closed-loop proportional-integral-derivative (PID) system was incorporated; it is presented schematically in Figure 8. The signal from the detector is separated into f and $2f$ components, as described above. Amplitudes and residual offsets of the f and $2f$ signals are measured individually for every interference cycle. Offsets are then removed by subtracting the measured values from corresponding f and $2f$ signals. The amplitude ratio of I_f/I_{2f} is sent to the PID controller, which changes wavelength modulation width to keep the ratio at unity. In Table 1, we show experimental values of dither width for cavity lengths of 3.72 mm and 13.65 mm, and compare those to the values predicted by Eqn. 3. These experimental points are also plotted in Figure 7. Good agreement is observed.

2.3 Measurement performance

2.3.1 Absolute cavity length measurement—Because the laser wavelength can be changed easily by applying an input voltage to the laser control module, the absolute cavity length can be measured by sweeping wavelength and counting the number of times the interferometer signal I_f or I_{2f} crosses zero in predefined direction to reduce errors due to fringe asymmetry. Knowing the wavelength at the first zero-crossing (λ_1) and last (λ_2) and the number of interference cycles (m) in between, the absolute cavity length h can be computed from the equation:

$$h = \frac{m}{2} \left(\frac{\lambda_1 \lambda_2}{\lambda_2 - \lambda_1} \right). \quad (4)$$

The biggest contributor to uncertainty in this cavity length determination method is how accurately wavelengths at zero-crossings can be determined. Therefore, the implementation of a PID control loop maintains the I_f signal for the time necessary for OSA to accurately

determine wavelength. For an OSA uncertainty u_λ , the corresponding uncertainty in the separation, u_h , is linear with the number of interference cycles and is given by:

$$u_h = \left(\left(\frac{m}{2} \frac{\lambda_2^2}{(\lambda_2 - \lambda_1)^2} \right)^2 u_{\lambda_1}^2 + \left(\frac{m}{2} \frac{-\lambda_1^2}{(\lambda_2 - \lambda_1)^2} \right)^2 u_{\lambda_2}^2 \right)^{\frac{1}{2}}. \quad (5)$$

As an example, for a cavity separation of 2.5 mm, a wavelength change of 0.5 nm, a typical wavelength uncertainty of 2 pm, and a single fringe ($m=1$), an uncertainty of 30 μm in cavity separation (or about 1 %) is predicted.

2.3.2 Stability and noise—There are various methods of stabilizing the laser wavelength in interferometry applications. Many systems have been developed using a reference gas absorption cell or a reference Fabry-Perot cavity. In this work, laser stability is achieved by monitoring wavelength with an optical spectrum analyzer (OSA). The OSA continuously sends wavelength and modulation width information to a real-time control module used as a PID controller. This method allows low-picometer wavelength stability while maintaining the flexibility to choose the operating wavelength.

To test how stable the displacement measurement is in a fully operational instrument deployed in its working environment, a test setup was built (see Figure 9). A glass ferrule holding an optical fiber was mounted with a dab of glue to a glass substrate having a very low coefficient of thermal expansion. An optical cavity was formed between a cleaved fiber end and an optically polished glass wedge attached to the substrate. Care was taken to assure that the metrology loop was as short as feasible. The assembly was then placed in a temperature-controlled chamber capable of maintaining a temperature set-point to approximately 0.01 °C.

Data obtained during the logging of displacement are shown in Figure 10. Data were recorded over 66 h at a rate of 10 samples per minute. The combined average instability of the cavity and interferometer system during this experiment was measured to be approximately 1 nm per 24 h. The initial exponential drift is likely caused by handling the assembly prior to recording data. Higher-frequency variations in displacement are caused primarily by the dynamics of the environmental chamber PID temperature control system. The noise performance of the system at higher frequencies can be seen in Figure 11. Here data were recorded at the rate of 74 Hz. The data obtained follow a normal distribution with 6σ of 0.914 nm and noise amplitude 0.106 nm/ $\sqrt{\text{Hz}}$.

2.3.3 Wavelength tracking—As noted above, feedback from the OSA could be used to monitor and stabilize the RTL wavelength. Figure 12 demonstrates the effectiveness of this mode of operation by plotting the measured RTL wavelength over a period of 60 h. Active wavelength control was enabled for the first 17 h, and disabled thereafter. While the wavelength was under servo-control, its 2σ deviation was 0.002 nm. When servo-control was removed, the maximum change in wavelength reached 0.5 nm.

2.3.4 Maximum range for a mirror-polished target—The maximum working range of our system was determined by moving the cleaved fiber end away from the counter-surface until nanometer-level displacement resolution was no longer possible. When using a polished Al target as the counter-surface, the maximum distance at which the signal is indistinguishable from noise was determined to be approximately 25 mm. This eventual extinction is to be expected, since no light collimation is used and dispersion reduces the amount of return light from the counter-surface coupling back into the fiber core.

2.3.5 Angular misalignment and target roughness—One major advantage of using a non-collimated beam from a simple cleaved fiber end is that careful fiber-target alignment using focusing lenses is not required. When tested on an optically polished aluminum target, the maximum possible misalignment at which the interferometer would still work was $\pm 10^\circ$. The setup and misalignment can be seen in Figure 13. This feature greatly reduces set-up time, as precise alignment is not required for the fiber-target pair during assembly. However, although the system can function with high degrees of misalignment, it is not advised to operate at those limits without careful consideration of the beam path, to reduce displacement uncertainty. In our experimental arrangement, achieving good alignment is accomplished by moving the target perpendicular to fiber axis and adjusting target angular orientation to minimize changes in cavity length. The system aligned in this way will show only surface waviness without any distinct slope present in monitored signal.

Typical laser interferometer systems require an optically polished target surface to operate properly. Because the immediate application for our interferometer is the tracking of specimen surfaces during nanomechanical testing, we tested how our system behaves when the target surface is of significantly poorer optical quality using a set of targets made from common nanoindentation specimens. They are presented in Figure 14. In order, they are: 1) a cured epoxy resin, 2) poly (methyl methacrylate), 3) a polished polycrystalline ceramic, 4) a silicon wafer, and 5) high-density polyethylene. The results are summarized in Table 2.

Although there were large differences in the surface roughness and in the magnitude of the detector signal across the set of tested target surfaces, with the exception of the cured epoxy resin there was no distinguishable difference between any of those samples and a polished aluminum mirror in the performance of the system, *i.e.*, in the reliability or speed of the motion tracking. The interferometer system was stable and the noise level remained constant at $0.71 \text{ nm Hz}^{-1/2}$.

3.0 Conclusions

It has been demonstrated that the new EFPI can provide sub-nanometer resolution displacement measurement in a very compact and unobtrusive sensing volume. Utilizing wavelength modulation, it is shown that this sensitivity can extend to ranges of up to tens of millimeters. However, it is necessary to implement empirical corrections to the modulation response to extract the correct displacement. The strategy adopted in this paper analyzes data from each fringe and updates the modulation width and photodetector offsets as needed. Additional compensation is necessary to take into account the deviation from sinusoidal shape with each fringe; this is achieved by sweeping over the full range of motion to create a

look-up table, followed by post-processing of the data to reduce errors to within a few nanometers.

Notwithstanding the complexities of implementing this interferometer, it is surprisingly insensitive to misalignment, as well as to the composition and the roughness of the external counter-surface. Typically, for the simplest of experimental set-ups, misalignments would be less than a few degrees, while even for extreme misalignments of up to 10° fringe contrast was affected very little. Its performance, in terms of displacement accuracy and stability, is comparable to some commercially available interferometers [18], but with a much more compact and versatile sensor. In its current form, it is however limited to a maximum cavity length of approximately 25 mm.

Acknowledgments

This work was supported in part by Cooperative Research Agreement 70NANB13H195 between the National Institute of Standards and technology and the University of North Carolina, Charlotte. Certain commercial equipment, instruments, or materials are identified in this paper to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

References

1. Rugar D, Mamin HJ, Guethner P. Appl Phys Lett. 1989; 55:2588.
2. Rasool HI, Wilkinson PR, Steig AZ, Gimzewski JK. Rev Sci Instrum. 2010; 81:023703. [PubMed: 20192498]
3. Smith DT, Pratt JR, Howard LP. Rev Sci Instrum. 2009; 80:035105. [PubMed: 19334950]
4. Cervantes FG, Kumanchik L, Pratt JR, Taylor JM. Physics Archive. 2013 arXIV:1303.1188v1.
5. Thurner K, Braun PF, Karrai K. Rev Sci Instrum. 2013; 84:095005. [PubMed: 24089856]
6. Thurner K, Braun PF, Karrai K. Rev Sci Instrum. 2013; 84:115002. [PubMed: 24289429]
7. Nowakowski, BK., Smith, DT., Smith, ST. Proceedings of the American Society of Precision Engineering. Vol. 59. Elsevier; 2014. p. 167
8. Saito S, Yamamoto Y, Kimura T. Electron Lett. 1980; 16(22):826.
9. Dandridge A, Tveton AB. Electron Lett. 1982; 18:302.
10. en Boel AJ. Applied Optics. 1987; 26(21):4545. [PubMed: 20523401]
11. Beheim G, Fritsch K. Applied Optics. 1986; 25(9):1439. [PubMed: 18231356]
12. Beheim G. Applied Optics. 1986; 25(19):3469. [PubMed: 18235649]
13. Zhang, J. Optical frequency-modulated continuous-wave (FMCW) interferometry. Springer; 2005. 2005
14. Badami, VG., Deck, LL., Fletcher, CD., Selberg, LA., Winkowski, DO., Egashira, Y., Redlitz, K. Proceedings of the American Society of Precision Engineering. Elsevier; 2009. p. 67
15. Wilkinson PR, Pratt JR. Applied Optics. 2011; 50:4671. [PubMed: 21833146]
16. Nemoto S, Makimoto T. Opts and Quantum Elec. 1979; 11:447.
17. Kirkendall CK, Dandridge A. J Phys D: Appl Phys. 2004; 37:R197.
18. Karrai, K., Braun, P-F. US Patent Pub No. US2011/0211199 A1. Sep 1. 2011 Pub. Date

Figure 1.
Block diagram of the main system components.

Figure 2.

A schematic diagram of the interference response of a symmetric, low-finesse Fabry-Perot (FP) cavity with laser wavelength 1550 nm.

a

b

Figure 3.

a) Experimental data for the FP interference fringe (red, dashed), the intensity of the response at modulation frequency f (gray) and the intensity of the response at twice the modulation frequency (black) for a change in cavity length of approximately 800 nm (slightly over one interference fringe). All amplitudes are arbitrary, but the f and $2f$ data have been normalized to have the same peak-to-peak amplitude. b) The f and $2f$ data from a), displayed as a polar vector plot.

Figure 4.
Dynamic tracking test. Cavity length was changing by approximately 450 $\mu\text{m/s}$.

Figure 5. Angular deviations from an ideal circulating vector. a) Measured angle verses ideal. b) Deviation from ideal. (10 cycles overlapped)

Figure 6. Residual periodic deviations before (dashed black) and after (solid red) correction for non-linearities.

Figure 7.

A plot of the theoretical modulation width, from Eqn. 3, with experimentally determined optimal modulation widths for two cavity lengths, as shown in Table 1.

Figure 8.
Block diagram of control strategy for reducing periodic errors due to changing maximum values of I_f and I_{2f}

Figure 9.
Cavity assembly for interferometer stability testing.

Figure 10.

Laser stability test over 66 hours with data acquired at a rate of 10 samples per minute. Inset shows short-term deviations.

Figure 11.
Displacement noise measurement over a 10 s time period extracted from the data in Figure 9.

Figure 12.

Plot of RTL wavelength variations over a 60 h time period, with active wavelength control enabled for the first 17 h only. Inset shows short term fluctuations in the wavelength while under active wavelength control.

Figure 13.
Fiber target misalignment experimental set-up.

Figure 14.

A variety of materials that all created functional Fabry-Perot cavities, 1) a cured, unpolished epoxy resin, 2) polished poly (methyl methacrylate), 3) polished polycrystalline alumina, 4) a polished silicon wafer, and 5) polished high-density polyethylene.

Table 1

Theoretical and measured values for the absolute cavity separation and wavelength modulation widths at two separations.

Cavity Length, h [mm]	Optimal Dither, Calculated [nm]	Optimal Dither, Measured [nm]
3.72	0.54	0.58
13.65	0.15	0.17

Table 2

Peak to peak fringe measurements and surface roughness values for 7 surfaces tested.

Specimen material	Roughness Ra [μm]	Detector signal pk-pk [mV]	Operational?
1. Cured epoxy resin (unpolished)	2.104	48	Borderline
2. PMMA (polished)	0.021	72	Yes
3. Polycrystalline alumina (polished)	0.101	81	Yes
4. Silicon wafer (polished)	0.021	176	Yes
5. HDPE (polished)	0.563	59	Yes
6. Aluminum, mirror-polished	0.022	434	Yes
7. Aluminum, 600 grit sanding	0.456	100	Yes