Precise Measurement of Air-refractive-index Using Fabry-Perot Cavity and Tunable Laser Diode

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Abstract

We presents a method for a precise measurement of air-refractive-index fluctuation (Δn_{air}) for precision interferometry system by utilizing a Fabry-Perot cavity (FPC) supported with an ultra low thermal expansion material (ULTEM) and a tunable laser diode (TLD). The air-refractive-index is locked to the resonance of the FPC by controlling the TLD frequency. The Δn_{air} can be derived from the TLD frequency change with the estimation uncertainty of 10^{-9} order. From the experimental results, a constant temperature/air-refractive-index chamber is proposed. The temperature fluctuation inside the chamber is minimized to 1 mK order by a constant temperature water bath and the thermal isolation walls. The air refractive index is stabilized by controlling the volume of the chamber via an actuator. The air-refractive-index inside the chamber is expected to be stabilized with 10^{-10} order.

1 Introductions

The displacement measurement with range of meter order and resolution of sub-nanometer is required due to the rapid progress of nanotechnology. Laser frequency based displacement interferometers are useful for nanometer-order measuring instruments. However, in the normal air environment, the air-refractive-index fluctuation (Δn_{air}) is a dominant uncertainty factor causing the difficulty of achieving sub-nanometer precision. The paper presents a method for a precise measurement of Δn_{air} by utilizing a Fabry-Perot cavity (FPC) supported with an ultralow thermal expansion material (ULTEM) and a tunable laser diode (TLD). The air-refractive-index is locked to the resonance of the FPC. Any change of air-refractive-index will cause the off-resonance of the FPC and, the TLD frequency is changed to track the resonance via the Pound-Drever-Hall method[1]. Δn_{air} can be derived from the TLD frequency change with the estimated uncertainty is of 10^{-9} order.

Based on the experimental result, an active suppression method of Δn_{air} in a chamber is proposed for precise measuring interferometry devices. The Fabry-Perot cavity supported on the ULTEM is installed inside the chamber to monitor the Δn_{air}. The resonance of the FPC is tracked by adjusting the volume of the chamber via an actuator. The Δn_{air} will be precisely monitored and suppressed. The air-refractive-index is expected to be stabilized with 10^{-10} order. The paper presents the principles of the Δn_{air} measurement and the chamber construction, respectively.

2 Measurement princples

Figure 1 shows the schematic diagram of the measurement system. The linear polarization laser beam from a TLD goes through a Faraday isolator (FI) and an anamorphic prism pair (APP). Then it is divided into two beams at a beam splitter (BS). The first beam is phased modulated by an electro optical modulator (EOM) after through a half-wave plate (HWP) and focus lens (L1). After that, the beam incidents to the Fabry-Perot cavity (FPC) after passing a mode matching lens (L_M), a polarization beam splitter (PBS) and a quarterwave plate (QWP), respectively. The reflection from the cavity is back to the QWP, PBS and then, it passes to a pin-hole (PH), which acts as a spatial filter to accept only one laser mode to an avalanche photo-detector (APD). The signal from APD is sent to a lock-in amplifier (LIA) for synchronous phase detection with the modulation signal applied to the EOM. The LIA signal is used by a digital signal processor (DSP) to control the TLD frequency to track the resonance of the FPC. The second beam from the BS, as mentioned above, is combined with the beam from a frequency stabilized laser (FSL) to make a beat frequency light. This light passes to a polarizer (PL) and focus lens (L2) to a high speed photo-detector (PD). Signal from the PD is amplified and go to a frequency counter (FC), which can derive the TLD frequency change.

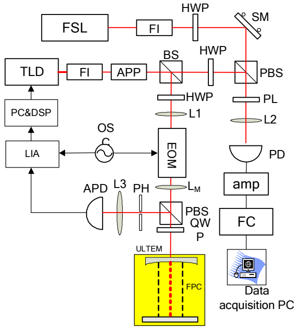

Figure 1: Schematic diagram of the measurement system。 TLD: tunable laser diode, FSL: frequency stabilized laser, EOM: electro optical modulator, LIA: lock-in amplifier, FPC: Fabry-Perot cavity, ULTEM: ultralow thermal expansion material

At the resonance of the FPC, the following equations are satisfied,

$$n_{air}L = \frac{\lambda}{2}N = \frac{c}{2f}N \qquad \text{or} \qquad \frac{\Delta n_{air}}{n_{air}} = -\frac{\Delta f}{f} - \frac{\Delta L}{L} + \frac{\Delta N}{N} \qquad (1),$$

where n_{air}, L, λ, f, N, and c are the air refractive index, the separation between two cavity mirrors, the vacuum wavelength of the TLD, respectively. Δn_{air}, ΔL, Δf and ΔN are the shifts or fluctuations against n_{air}, L, f and N, respectively. In the system, since the N-th order null cross-point must be maintained by tuning the TLD frequency, the change in the ratio of $\Delta N/N$ can be neglected. In addition, two cavity mirrors are fixed on the ULTEM. The ULTEM thermal expansion ratio α is of $2\text{x}10^{-8}\ \text{K}^{-1}$ under the condition of temperature change less than 50 mK, $\Delta n_{air}/n_{air}$ can be written by the next equation with uncertainty of 10^{-9} order.

$$\frac{\Delta n_{air}}{n_{air}} \approx -\frac{\Delta f}{f} \qquad (2).$$

3 Experimental results

In the experiment, environmental sensors such as temperature, pressure and humidity sensors were used to calculate $\Delta n_{air}/n_{air}$ by Ciddor method[2], which is used as a reference to compare with the proposed method. The comparison of the $\Delta n_{air}/n_{air}$ measurement using the FPC and Ciddor methods is shown in figure 2. The experimental result shows a good agreement of Δn_{air} measurement compared with the numerical method given by Ciddor. Figure 3 shows the cross-correlation plot between two methods with the coefficient of 0.90. It means that the Ciddor and our measurement methods are strongly related. The total uncertainty of our proposed method is approximately $2.5\text{x}10^{-9}$ order and it is possible to improve to 10^{-10} order when the signal-to-noise ratio of the control system is improved.

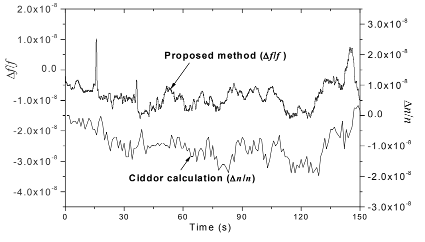

Figure 2: Comparison of $\Delta n_{\text{air}}/n_{\text{air}}$ measurement by the FPC and Ciddor methods

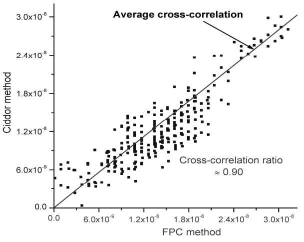

Figure 3: Cross correlation plot of the proposed and the Ciddor methods

4 Propose of an active suppresion of Δn_{air} in a chamber

The planning schematic diagram of the chamber is shown in figure 4. In the chamber, a FPC supported by the ULTEM with the FSL as light source is installed to monitor the Δn_{air} using our method. The LIA signal from the Δn_{air} sensor is used to control a chamber's volume actuator which is driven by the PZT actuator to adjust the volume of the chamber for the compensation of Δn_{air}. The temperature fluctuation inside the chamber is kept minimum within 1 mK using a constant temperature water bath. The iodyne frequency stabilized He-Ne laser ($\Delta f/f \approx 10^{-11}$) is available as the FSL, so that, the uncertainty of Δn_{air} measurement can be improved to 10^{-10} order.

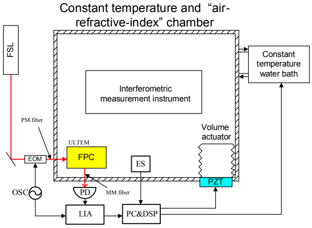

Figure 4: Design of the constant temperature/"air-refractive-index" chamber

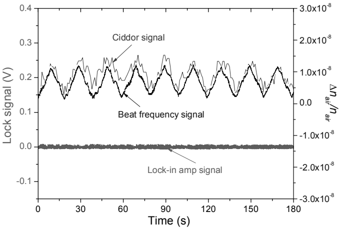

Figure 5: confirmation of the possibility to use PZT actuator for the suppression of Δn_{air}

A preliminary experiment to confirm the possibility to use the PZT actuator for the suppression of Δn_{air} was performed. The Δn_{air} was monitored while the PZT actuator was moving periodly. The inside pressure was changed about 4 Pa according to the motion of the PZT actuator, causing the $\Delta n_{air}/n_{air}$ of approximate $1\text{x}10^{-8}$ order. Figure 5 shows the LIA signal and the measurement result compared with Ciddor method. The LIA signal shows that the resonance of the FPC is locked while the volume actuator is moving. From the result, it is confirmed that PZT actuator can be used for the constant air refractive index chamber.

5 Conclusions

The measurement of the $\Delta n_{air}/n_{air}$ was performed successfully with the uncertainty of 10^{-9} order. In the near future, we will report the constant temperature/"air-refractive-index" chamber for active suppression of Δn_{air} in the precise optical interferometry applications.

References:

[1] Drever, R. W. P., Hall et. al., *Applied Physics B*, Vol. 31, pp. 97, 1983.
[2] Ciddor, P. E., *Applied Optics*, Vol. 35, pp. 1566, 1996.