Evaluation method of constant air refractive index chamber at 10^{-10} order using a temperature-stabilized Fabry-Perot cavity

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In the field of laser interferometry, air refractive index fluctuation is a big uncertainty factor that causes the difficulty to archive sub-nanometer resolution. We propose a method for the active suppression of air refractive index fluctuation at 10^{-10} order using a temperature-stabilized Fabry-Perot cavity and an Iondine frequency stabilized He-Ne laser and a piezoelectric actuator. We construct a constant air refractive index chamber in which, the air refractive index fluctuation is precisely measured at 10^{-10} order and the chamber volume is precisely adjusted via a piezoelectric actuator to compensate the measured fluctuation. We also presented a method to measure air refractive index fluctuation for the evaluation of the stability of air refractive index. The air refractive index is measured based on the laser frequency technique. The resolution of 10^{-10} order or less can be archived.

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1. Introduction

Nowadays, laser interferometers are widely used in displacement measuring systems because of their high resolution. However, in normal air environment, it is difficult to achieve sub-nanometer level because of air refractive index fluctuation (Δn_{air}). In this article, we introduce a method to suppress Δn_{air} in order to achieve sub-nanometer uncertainty in displacement measurement. A stabilized-n_{air} chamber is proposed. The method is based on a precise measurement of Δn_{air}[1] using a temperature-stabilized Fabry-Perot cavity (FPC) and the Iondine frequency stabilized He-Ne laser (FSL). The volume of the chamber can be changed via a bellows-piezoelectric (PZT) actuator. The inside n_{air} can be adjusted by changing the position of the bellows. From the precise observation of Δn_{air}, the volume of the chamber is adjusted by controlling PZT actuator to compensate the amount of the measured Δn_{air}. In this article, we also present a Δn_{air} measurement method from laser frequency change using an acoustic optical modulator (AOM) and voltage controllable oscillator (VCO). Δn_{air} can be derived from controlled FSL frequency at 10^{-10} order or less.

2. Principles

Schematic of the constant nair chamber is shown in Fig. 1. The sealed chamber is connected to a constant-temperature-water bath through the pipes that are roundly covered the chamber wall. The pure water, flows around the chamber through the pipes circularly, can keep the temperature to be stabilized within 10 mK order[2]. In the chamber, two temperature-stabilized Fabry-Perot cavities are used. Both cavities have same light source from the FSL whose frequency fluctuation is less than 10^{-11} order. The first FPC is used to control the PZT volume actuator for the compensation of Δn_{air}. The second FPC is used to measure Δn_{air} for the evaluation of the stability of air refractive index. Using the ideal gas law, Δn_{air} can be calculated by the following equation

$$\Delta n_{air} = -\frac{\partial n_{air}}{\partial p} p \frac{\Delta V}{V} \qquad (1)$$

where p, V are pressure and the chamber volume. In the region of 633 nm, $\partial n_{air}/\partial p$ and $\partial n_{air}/\partial T$ are 2.7x10^{-9} Pa^{-1}, -9.4x10^{-7} K^{-1}, respectively. If the nominal T, p and ΔT are 296 K, 101.3 kPa and 10 mK, respectively, then Δn_{air} owing to ΔT can be neglected. Therefore, we can compensate Δn_{air} by adjusting the volume ΔV of the chamber. Since the Δn_{air} can be observed by the first FPC using Pound-Drever-Hall technique[3], the chamber volume actuator can be precisely controlled to compensate the amount of Δn_{air}. At the same time, Δn_{air} is measured by the second FPC using a modification of the technique described in[1], in which Δn_{air} is derived from laser frequency change

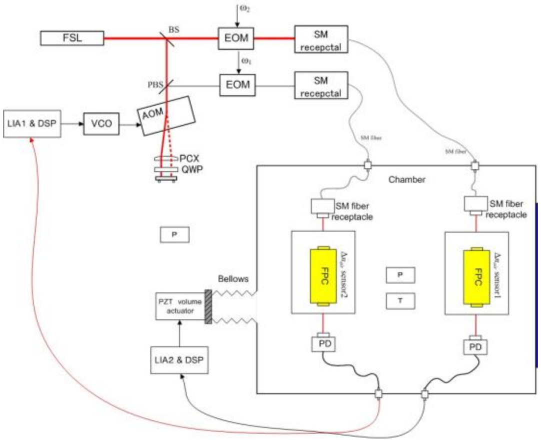

Fig. 1 Schematic of the proposed constant n_{air} chamber

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

The FSL frequency can be changed using the AOM with double pass configuration and the VCO. From the monitoring of Δn_{air}, the VCO is controlled to change laser frequency in order to track the resonance of the FPC. The estimated uncertainty of the measurement is of 10^{-10} order.

3. Preliminary experimental result [4]

For the preliminary experiment, we tested the system with a He-Ne laser (Spectra Physics, 1117A) whose frequency fluctuation of 10^{-9} order and use conventional methods (the Ciddor method [5] and the Wavelength tracker[6]) to measure Δn_{air} instead of the described evaluation method above. Fig. 2 shows the measurement of Δn_{air} in the chamber when the PZT volume actuator is not controlled. It can be seen that, during the measurement time of ~100 s, Δn_{air} changes by ~$3\text{x}10^{-8}$. On the contrary, Fig. 3 shows the measurement of Δn_{air} when the PZT actuator is controlled. It shows that Δn_{air} is kept within $4\text{x}10^{-9}$ during the measurement time of ~ 100 s. Moreover, the LIA signal, shown in Fig. 3 is null during the measurement. This means that, by controlling the PZT volume actuator, air refractive index can be locked to the specific resonance of the FPC. The uncertainty of the air refractive index stabilization depends on the laser frequency fluctuation, the deformation of the FPC`s length and noise level of the control signal, respectively. Finally, the uncertainty is estimated ~$4\text{x}10^{-9}$, at the current time.

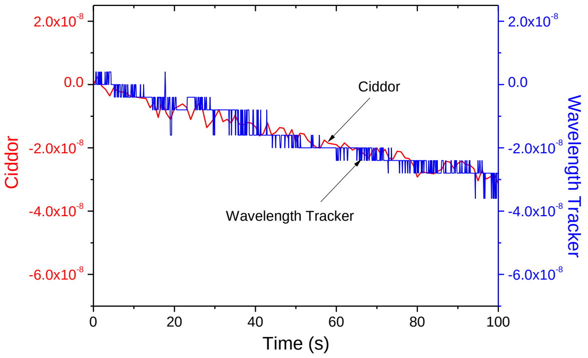

Fig. 2 Δn_{air} measurement by the Ciddor method and the Wavelength Tracker without control system

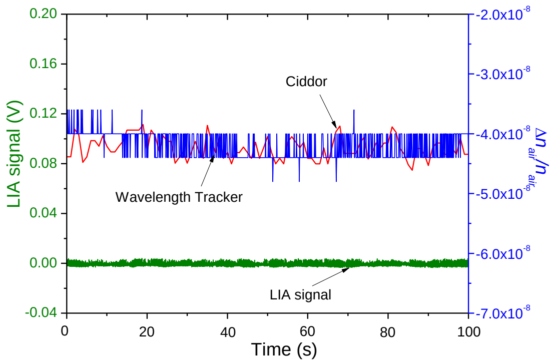

Fig. 3 Δn_{air} measurement by the Ciddor method and the Wavelength Tracker with control system

4. Conclusions

The constant "air-refractive-index" chamber using the combination of the temperature-stabilized FPC, the FSL and the PZT volume actuator was constructed. The air-refractive-index fluctuation inside the chamber was actively suppressed with the uncertainty of 10^{-9}-order. At the current time, our proposed chamber is valid for only short measurement time (~100 s) due to the limitation of the frequency stability of the FSL. In the near future, the improvement of the uncertainty to 10^{-10}-order or less will be performed using the Iodine-frequency stabilized He-Ne laser with frequency stability of ~$2.5\text{x}10^{-11}$ order.

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