

Study on Interferometric Stability Based on Modulating Frequency, Operating Wavelengths and Temperature using an Electro Optic Multi-Wavelength Distance Sensor

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Abstract: The influence of modulating frequency, operating wavelengths and external temperature on the stability in distance measurement by an Electro Optic (EO) multi-wavelength distance sensor has been studied in this work. Previously, we reported the compatibility of EO phase modulation to replace the Piezoelectric Transducer (PZT) based mechanical phase modulation, for performing faster distance measurement in a multi-wavelength interferometer. Here, we have presented an extension of the previous work to investigate the cause of the distance drift observed for a new prototype of the EO sensor (having lower driving voltage requirement ~ 5 V) under 1.25 kHz and 5 kHz modulating frequency when the target was kept fixed. The results reflected that the measurement stability is independent of modulating frequency for the case of EO sensor compared to PZT which suffered from rapid distance change when it was made to operate at higher driving frequency. The drift of the four wavelengths from the diode laser source was between $\sim 0.0001 - 0.0002$ nm in 14 hours signifying their negligible effect on the observed distance change for the EO sensor. Furthermore, the synchronicity in the distance measurement by each of the employed wavelengths has been tested for the EO sensor at both 1.25 kHz and 5 kHz. Finally, the dependence of the change in measured distance on the external temperature has been studied and the result showed substantial correlation between the environmental temperature variation and the observed distance drift.

Keywords: Multi-Wavelength Interferometry, Interferometric stability, Phase modulation, Electro-Optic sensor, Distance measurement and metrology.

1. Introduction

Interferometry is a method by which small deformation in wavefront can be measured with high accuracy [1-2]. An interferometer is capable of determining the aberrations present in an optical component by producing interference between the reference and the aberrated target wave. Thus, it serves as an important device in optical metrology for non-contact surface measurements [3-4]. The process of

distance (d) measurement using interferometry requires careful observation of fringes and simultaneous tracking of interference phase (Φ) while displacing the target/reflector from its reference position [5]. The phase ' Φ ' is an important parameter which needs to be calculated precisely to unwrap the proper information of 'd' [6]. However, a single wavelength (λ) interferometer is not immune to sudden measurement interruptions because of its comparatively shorter unambiguity range ($\sim \lambda/2$) [7-9].

Hence, any occurrence of unexpected disturbance while performing distance measurement with a single wavelength interferometer, brings unclarity in phase calculation which is widely known in the field as the problem of ‘ 2π phase ambiguity’. Fig. 1 shows an example to explain the problem of erroneous phase while performing measurement with modulo λ .

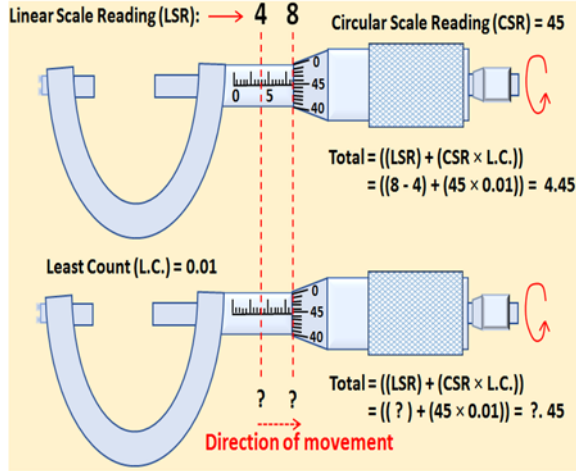


Fig. 1. Analogy to explain ‘ 2π phase ambiguity’. Here, the first micrometer (top) can give the distance information correctly as the calibrated Linear Scale (LS) can count how many times the Circular Scale (CS) has been rotated. However, the unmarked LS (bottom) represents the situation of performing distance measurement with phase ambiguity. The CS reading of second micrometer (bottom) repeats itself after one complete rotation similar to the wavelength of light which repeats its phase with modulo 2π . Hence, if the number of turns of the CS cannot be recorded properly due to the uncalibrated LS then it is impossible to extract the correct distance information. This situation has similarity with such cases of interferometric distance measurements which have been suddenly interrupted and lost the fringe count (like losing the information on how many times the CS of the micrometer has made complete rotations) leading to unclarity in phase measurement.

Multi-Wavelength Interferometry (MWLI) helps to extend the range of unambiguity by employing synthetic wavelength (Λ) which is designed from a suitable combination of two close wavelengths λ_1 and λ_2 [10-16].

$$\Lambda = \frac{\lambda_1 \cdot \lambda_2}{|\lambda_1 - \lambda_2|} \quad (1)$$

The MWLI system presented in this study is operated with four wavelengths ranging from ~ 1530 - 1630 nm. The highest unambiguity range can be produced ~ 1.25 mm which is almost ~ 1000 times larger than the range of unambiguity of a typical single wavelength interferometer (operated with $\lambda \sim 1550$ nm) [17]. However, the speed and precision of absolute distance measurement for the MWLI setup depend on the associated phase modulation technique [18]. For the present system the phase modulation is

achieved by introducing the sinusoidal optical path length modulation with a Piezoelectric Transducer (PZT) on the target path [19]. Eq. (2) represents the intensity (I) distribution of the phase modulated signal,

$$I(d, t) = I_{DC} + I_{AC} \cdot \cos\left(\frac{2\pi}{\lambda} \cdot d + \pi(\sin(\omega_p t))\right) \quad (2)$$

where $I_{DC} = (I_R + I_T)$, is the sum of the reference (I_R) and the target (I_T) beam intensities. $I_{AC} = 2\sqrt{I_R I_T}$ and ‘d’ is the round trip optical path difference. ‘ ω_p ’ is the phase modulating angular frequency and ‘t’ represents time. However, there are some disadvantages in the PZT based mechanical phase modulation process when it comes to operating it at a higher modulating frequency for achieving faster measurements [20]. The limitations of the PZT sensor in our MWLI system are mainly the restricted value for the modulating frequency (~ 1.25 kHz) and the requirement of comparatively higher driving voltage (peak to peak voltage $\sim 64 - 96$ V for the present system). Therefore, in our previous study [21-22], we confirmed the ability of linear EO phase modulation as an alternative method for replacing the mechanical phase modulation to perform faster distance measurement using the MWLI setup. we also showed simultaneous phase modulations of the four source wavelengths using the prototype EO sensor with half wavelength voltage (V_π) ~ 12 - 14 V and checked distance measurement ability under static and moving target conditions. In this work, our goal is to find the reason behind the gradual change in the measured distance for the case of the EO sensor at 1.25 kHz and 5 kHz modulating frequency when the target was kept fixed. Hence, we have studied the dependence of the suffered distance drift on the external and measurement-driving parameters like environmental temperature, operating wavelengths and modulating frequency. Experiments have been performed using a new prototype of LiNbO_3 based EO sensor for which the phase modulation was achieved at a significantly lower value of $V_\pi \sim 5$ V (Section 4.1). The distance measurement using the PZT and the EO sensor under the static target condition for 1.25 kHz and 5 kHz has been given in Section 4.2 to check the influence of modulating frequency on the observed drift. The stability in the values of the four operating wavelengths of the interferometer has been presented in Section - 4.3 where the change in λ (i.e. $\Delta\lambda$) was recorded for 14 hours. The synchronicity in distance measurement by each of the wavelengths has been shown in Section 4.4 to ensure that the drift is not a result of an atypical measurement behaviour of any of these employed wavelengths which can cause the gradual distance change by introducing error in the phase calculation. In Section 4.5, the dependence of the distance drift on the external temperature has been studied where the result showed correlation between the environmental temperature variation and the observed distance drift.

2. Present MWLI Setup with PZT Sensor

Fig. 2 shows the schematic diagram of the present MWLI set up. The working principle is related to Fizeau-homodyne interferometry. The MWLI system is used for industrial applications like quality control of optical components, aspheric lenses or free-forms. The diode laser source sends out four wavelengths ranging from 1530-1630 nm which are coupled by a 4×1 coupler into a single fiber to enter the PZT operated sensor. The PZT makes periodic movement of the reference with modulating frequency ~ 1.25 kHz for performing the phase modulation. The reference beam is separated by a partial back reflection from the end face of the fiber ferrule. The other part of the light gets reflected by the target and coupled back into the sensor to interfere with the reference beam. The four phase modulated interference signals are then separated by the Demultiplexer (DeMux) and get detected by the photo-diodes for further data analysis to unwrap the phase information.

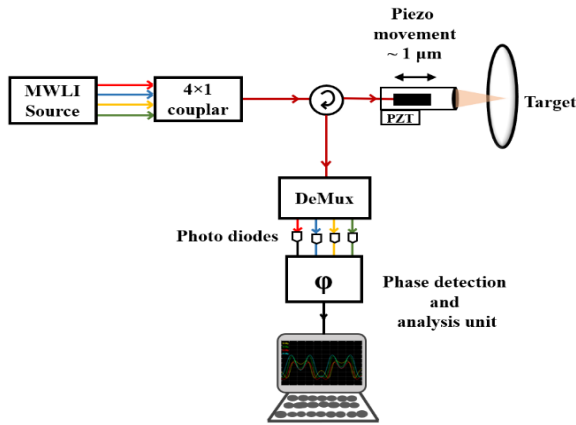


Fig. 2. Schematic diagram of present MWLI setup with mechanical phase modulation.

Experiments have been carried out to check the performance of the PZT sensor at higher modulating frequency to have faster measurements using the MWLI system. Fig. 3 shows the distance drift suffered by the PZT sensor when the modulating frequency was increased. The change in distance is a result of initial heat dissipation within the PZT sensor as the modulating frequency was increased from 1 kHz to 5 kHz. The result justifies the reason for replacing the mechanical phase modulation for obtaining faster measurement. The PZT based system is getting affected by the internally generated heat at higher modulating frequency resulting in system instability for interferometric distance measurement.

3. Experimental Setup with Electro Optic Phase Modulation

The Electro Optic Modulator (EOM) was designed using a Lithium Niobate (LiNbO_3) crystal having

Titanium (Ti) indiffused waveguides [23-24], following the same approach as reported in our previous study. In order to reduce the value of V_π the dimension of the crystal was changed compared to the previously reported prototype [21-22]. Because of the dependence of V_π on the crystal dimensions according to Eq. (3) [25], we have chosen a LiNbO_3 crystal with length ~ 21.57 mm and electrode separation ~ 20 μm .

$$V_\pi = \frac{\lambda}{n_e^3 \cdot r_{33}} \left(\frac{w}{l} \right) \quad (3)$$

The extra ordinary refractive index (n_e) is ~ 2.14 and r_{33} is the EO coefficient ~ 30.8 pm/V for LiNbO_3 . w and l refer to the width and length of waveguide respectively. The calculated value of V_π (considering the optical path length travelled by the target beam which passed through the distance between the fiber ferrule and the target twice before interfering with the reference) is ~ 2.4 V but the experimentally obtained value was ~ 5 V. Fig. 4 shows the experimental setup of the EOM sensor and Fig. 5 depicts the schematic diagram of the MWLI system with the EOM sensor for performing distance measurement.

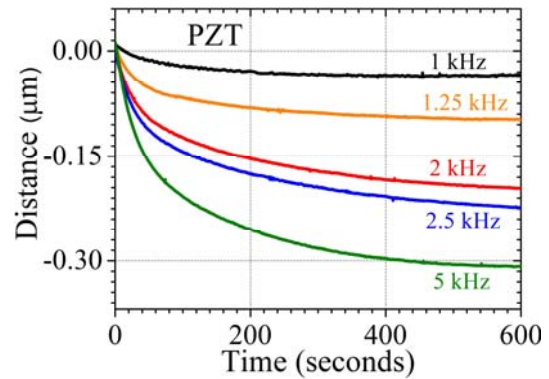


Fig. 3. Distance change due to initial heat dissipation in the PZT sensor when the modulating frequency was increased.



Fig. 4. Experimental setup for the EOM sensor.

4. Results and Discussions

4.1. π - phase Modulation with EOM Sensor

Fig. 6(a) and Fig. 6(b) show the phase modulated signal governed by Eq. (2) from the EOM sensor at 1.25 kHz and 5 kHz respectively.

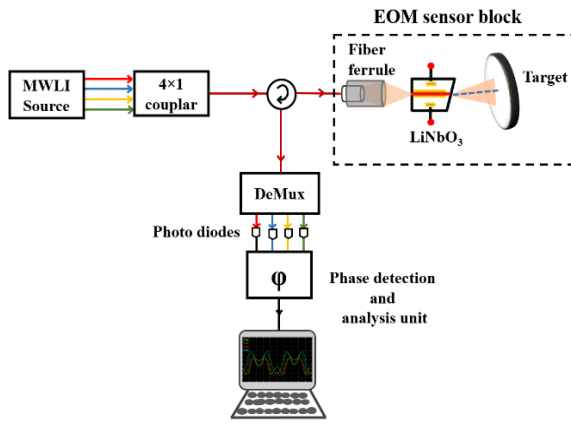


Fig. 5. Schematic diagram of the experimental setup for distance measurement using the EOM sensor.

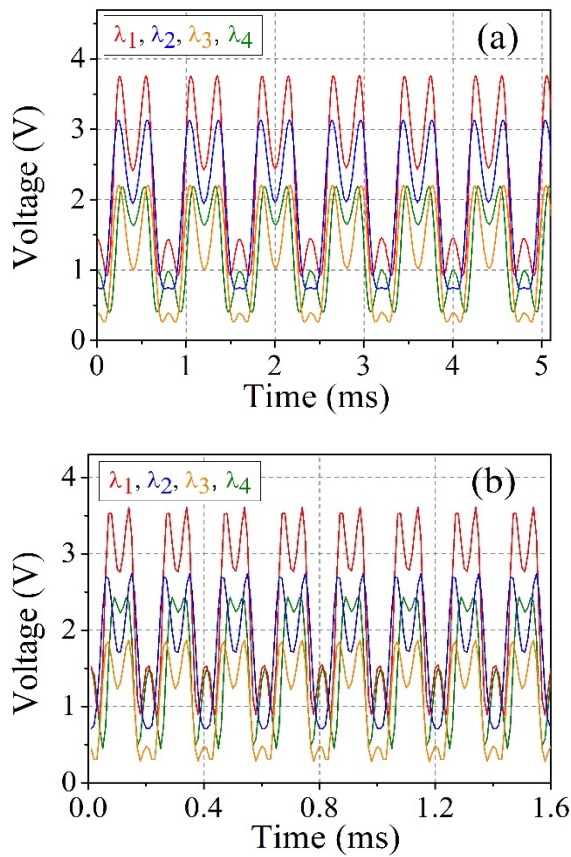


Fig. 6. Phase modulated signal from the EOM at $V_\pi \sim 5$ V for modulating frequency (a) 1.25 kHz and (b) 5 kHz.

Here, the π - phase modulation has been achieved using the same MWLI system but with significantly lower driving voltage $V_\pi \sim 5$ V.

4.2. Comparison on Distance Measurement Using PZT and EOM

Fig. 7(a) and Fig. 7(b) show the performance of the EOM sensor on distance measurement using the MWLI set up when the target/mirror was kept fixed.

The distance drift as monitored by the EOM sensor ~ 70 nm and ~ 100 nm in 600 seconds at modulating frequency 1.25 kHz and 5 kHz respectively. The reason behind this optical path length drift can be an effect of external temperature variation which has been explained in Section 4.5. However, it should be noted that the EOM has not shown any rapid distance drift like in the case of the PZT sensor within the first 180 seconds ($= 3$ minutes) after starting the measurement. The EOM exhibited more stable behavior compared to the fast distance change with higher rate as experienced by the PZT because of the initial heat dissipation. This behavior is noticeable for both 1.25 kHz and 5 kHz modulating frequency (inset of Fig. 7(a) and Fig. 7(b)) where the PZT has suffered ~ 90 nm and ~ 260 nm continuous distance drift but the EOM showed much stable behavior with comparatively less drift ~ 10 -15 nm despite of the higher value of modulating frequency. Hence, the results suggest that unlike the case of PZT, the distance drift observed in EOM is not dependent on the driving frequency which gives it the freedom for performing faster measurement without hampering the interferometric system stability.

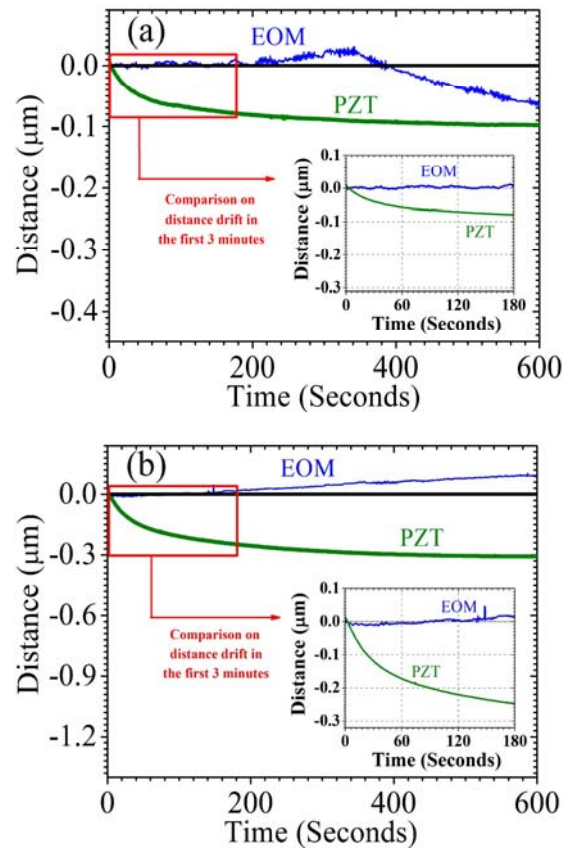


Fig. 7. Comparison on distance drift observed for the PZT and the EOM sensors at (a) 1.25 kHz and (b) 5 kHz, when the target/mirror was kept fixed. The inset graphs show the measurement stability of the EOM compared to the PZT in first 180 seconds after starting the experiment. The drift in the case of the EOM sensor is due to external temperature variation where the PZT has suffered from internal heat generation.

4.3. Experiment on the Stability of the Four Wavelengths from the Diode Laser Source

Experiment has been carried out to check the drift in the source wavelengths in order to find the reason behind the gradual drift observed for the EOM. Fig. 8 shows the amount of change in wavelength (λ) from its initial value (i.e. $\Delta\lambda$) recorded for 14 hours for the four operating wavelengths. The result shows that the amount of $\Delta\lambda$ for λ_1 , λ_2 , λ_3 and λ_4 are ~ 0.00018 nm, ~ 0.0002 nm, ~ 0.0001 nm and ~ 0.00018 nm respectively. The values of $\Delta\lambda$ stayed within 0.0001 - 0.0002 nm which are not much capable of bringing significant amount of additional distance change during the measurement. For example, in our case the maximum distance between the target and the reference for the EOM prototype is ~ 30 mm and the average value of the distance change induced by $\Delta\lambda$ of the four wavelengths will be approximately ~ 3.18 nm after 14 hours. Hence, the stability in the values of the employed four wavelengths suggest negligible contribution for the observed distance drift in the case for EOM as shown in Fig. 7.

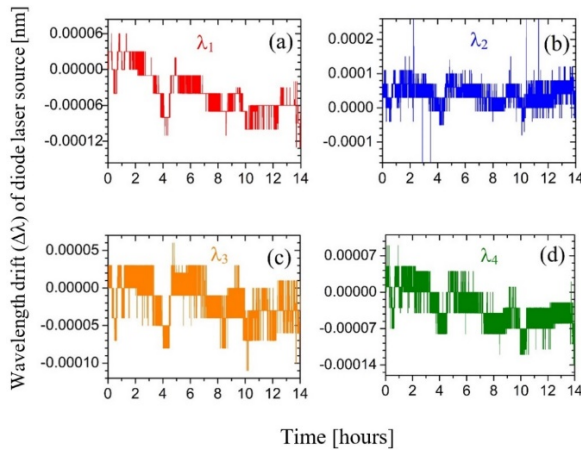


Fig. 8. Wavelength drift ($\Delta\lambda$) of the four source wavelengths observed in 14 hours: (a) $\Delta\lambda_1 \sim 0.00018$ nm, (b) $\Delta\lambda_2 \sim 0.0002$ nm, (c) $\Delta\lambda_3 \sim 0.0001$ nm and (d) $\Delta\lambda_4 \sim 0.00018$ nm.

4.4. Synchronicity in Distance Measurement by the Source Wavelengths

The data obtained from the distance measurement by the EOM has been checked with the measured distances by each of the wavelengths to test the synchronicity. Fig. 9(a) and Fig. 9(b) depict that the amount of distance change (as shown in Fig. 7(a) and Fig. 7(b)) seen by each of the wavelengths are nearly same at both 1.25 kHz and 5 kHz. The projection of the measurements made by the four wavelengths on the two-dimensional plane of 'Distance vs. Time' (the ZX plane of Fig. 9(a) and Fig. 9(b)) shows that the plots have overlapped with each other. The result

ensure that the drift is not due to the unusual behavior of any of the four operating wavelengths which can be a reason behind adding up error in measurement resulting in a gradual distance change. Hence, it can be said that the distance drift suffered by the EOM sensor does not have significant dependency on the measurement related parameters like the operating wavelengths and the modulating frequency.

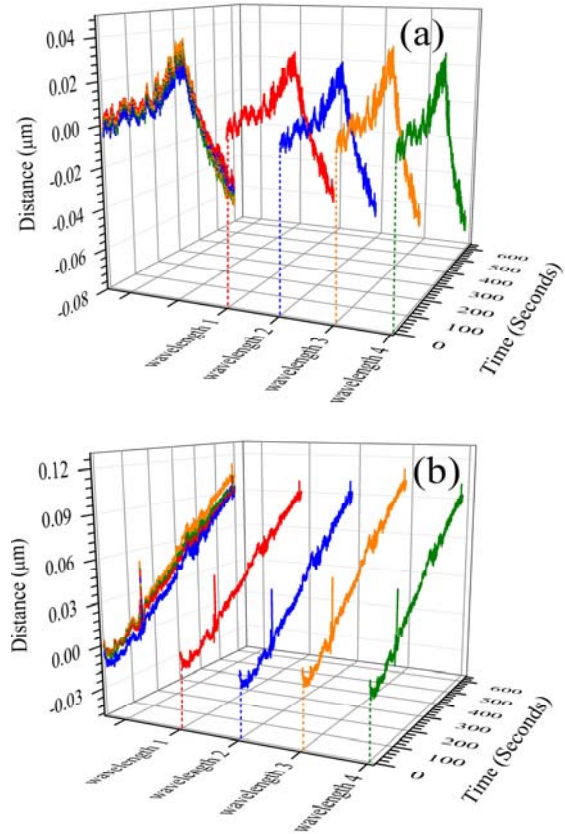


Fig. 9. Synchronicity in distance measurement by the four operating wavelengths at (a) 1.25 kHz and (b) 5 kHz.

4.5. Influence of the Environmental Temperature Variation on the Distance Drift Suffered by the EOM Sensor

To check the influence of the environmental temperature variation on the distance drift experienced by the experimental setup of the EOM sensor, a long-term measurement has been done for 14 hours. Fig. 10 shows the effect of the environmental temperature on distance measurement. The temperature variation has a clear correlation with the drift in the optical path length sensed by the EOM. However, the rate of distance drift with temperature in the first 2 hours does not have similarity with the rate which has been observed later. This might be a result of other external perturbing influences as the experimental set up is open and is susceptible of getting affected by the environmental factors like – slow response of the thermal sensor to record rapid changes in the room

temperature, presence of the experimenter near the set up or, the air turbulence near the EOM crystal resulting in erroneous distance drift due to the slight misalignment in the set up. Hence, the next step is to build an encapsulation for the EOM sensor and enclose the entire set up to minimize the influence of external temperature and other environmental perturbations.

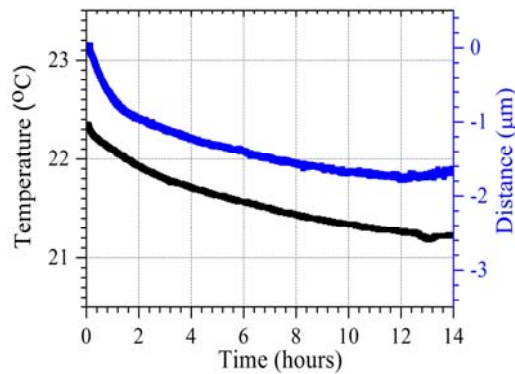


Fig. 10. Distance drift due to external temperature variation in the experimental setup with the EOM sensor.

5. Conclusions

We presented an extension of our previously reported work [21] which showed the efficiency of EO effect for replacing the PZT based mechanical phase modulation in a MWLI system. Here, our goal was to look for the cause behind the gradual distance drift observed in the case of the EO sensor at 1.25 kHz and 5 kHz modulating frequency under static target condition to bring system stability for long-term measurement. Hence, in this work we have presented an analysis on how the interferometric measurement using a new prototype of the EO sensor is affected by the changes in the operating wavelengths, modulating frequency and external temperature variation. Here, the experiments have been done on a LiNbO₃ based EO sensor where the π phase modulation of the four wavelengths has been achieved at a significantly lower value of $V_\pi \sim 5$ V by suitably choosing the crystal dimensions. The V_π of the current PZT sensor for obtaining the π phase modulation is ~ 32 -48 V and compared to it the EOM took much less driving voltage. Results on the comparison of distance drift suffered by the PZT and the EO sensor suggest that the PZT has significant dependency on the driving voltage frequency. As, the modulating frequency was increased the distance change experienced by the PZT also increased because of initial heat dissipation. However, in contrast to the behavior of PZT, the EO sensor showed much better system stability when the modulating frequency was increased. This suggests that the distance drift observed for the EOM is not dependent on modulating frequency. The stability measurements of the source wavelengths showed the drift in the four operating wavelengths over the time of 14 hours, is between ~ 0.0001 - 0.0002 nm which has

negligible effect on bringing additional error in the distance measurement. The synchronicity among the measured distances by each of these wavelengths has also been checked. The result showed that the measured distance data by each of the four wavelengths overlapped with each other suggesting the drift is not due to the unexpected measurement behavior of any of these operating wavelengths which might bring error in distance calculation. Finally, the influence of external temperature variation on the observed distance drift was monitored for 14 hours. The result showed that the present experimental setup with EOM is getting affected by the changes in environmental temperature which can be a dominant reason behind the suffered distance drift. Hence, the future task is to minimize such external influences and encapsulate the system for bringing measurement stability to have the final design of this EO-interferometric distance sensor. The sensor is expected to significantly improve the speed of the absolute distance measurement using the MWLI system.

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