Absolute positioning by multi-wavelength interferometry referenced to the frequency comb of a femtosecond laser

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Abstract: A multi-wavelength interferometer utilizing the frequency comb of a femtosecond laser as the wavelength ruler is tested for its capability of ultra-precision positioning for machine axis control. The interferometer uses four different wavelengths phase-locked to the frequency comb and then determines the absolute position through a multi-channel scheme of detecting interference phases in parallel so as to enable fast, precise and stable measurements continuously over a few meters of axis-travel. Test results show that the proposed interferometer proves itself as a potential candidate of absolute-type position transducer needed for next-generation ultra-precision machine axis control, demonstrating linear errors of less than 61.9 nm in peak-to-valley over a 1-meter travel with an update rate of 100 Hz when compared to an incremental-type He-Ne laser interferometer.

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References and links

1. Introduction

Ultra-precision machines with the control capability of nanometer-resolution positioning over extensive axis-travel ranges up to several meters are essential for efficient production of high-density microelectronic products such as semiconductor integrated circuits, flat panel displays and solar cell devices. Such high precision machines are currently built with incremental-type laser interferometers as position-feedback transducers which provide nanometer resolutions in environment-controlled workshop conditions [1–4]. Most laser interferometers commercially available at present for the purpose operate on homodyne or heterodyne principles of phase measurement using single-wavelength light sources such as He-Ne tube lasers. The use of a single wavelength basically constrains the non-ambiguity range (NAR) of an instantaneous phase measurement to half a wavelength [5]. Thus, the phase measurement has to be repeated at fast update rates of usually a few kHz to determine the machine axis position accurately by integration without loss of movement. Further, the incremental-type distance measurement (IDM) interferometers permit no interruption of the beam path between the laser source and the target mirror during measurement.

As the counterpart of IDM interferometers, absolute-type distance measurement (ADM) interferometers are intended to measure the total distance directly to the end position without incremental addition of movements of the target mirror all the way from the zero datum. In the past, relying mainly on modulation techniques of the intensity or frequency of continuous wave laser light [6–8], ADM interferometers provided relatively less accuracy suitable just for coarse measurements of long distances for geodetic surveying and large-scale engineering. However, during the past decade, a remarkable advance has been made with femtosecond...
lasers being proved as a high-potential workhorse to advance optical interferometry [9,10]. The frequency comb of a femtosecond laser provides few hundreds of thousands of narrowlinewidth wavelengths over a broad optical spectral range, enabling various advanced ADM techniques. The examples include synthetic wavelength interferometry [11–13], dispersive interferometry [14–16], multi-wavelength interferometry [17–21], dual-comb interferometry [22,23], and time-of-flight measurement using nonlinear optical cross-correlation [24–26]. These frequency-comb-based ADM methods have their own merits and disadvantages, which can conveniently be evaluated in comparison to the well-established performance of IDM interferometers.

Our work described here is concerned with the ADM method of multi-wavelength interferometry which exploits the frequency comb of a femtosecond laser as the wavelength ruler. Based on the proposed principle and system configuration published in Ref 20, a prototype ADM interferometer is built and tested for its competence as an absolute-type positioning transducer for ultra-precision machine axis control. This ADM interferometer implements multi-wavelength interferometry by generating four different wavelengths accurately by phase-locking to the frequency comb. The absolute position is determined through a synchronized phase-detection scheme along with parallel data-processing of the multiple interference phases so as to enable fast, precise and stable measurements continuously over a few meters of axis-travel. Finally, the measurement performance and stability of the ADM interferometer is evaluated under varying environmental conditions as a potential candidate of absolute-type position transducer needed for next-generation ultra-precision machine axis control.

2. Interferometer design

Figure 1 shows the overall system of the ADM interferometer configured in this investigation. As the wavelength ruler to generate four wavelengths, an Er-doped fiber femtosecond laser is adopted with its frequency comb being stabilized to the Rb clock [27]. The light source is comprised of four distributed-feedback (DFB) lasers which are simultaneously phase-locked to the frequency comb by PLL (phase-locked-loop) control [28,29], each being tuned to its individually designated wavelength. The continuous wave output beams of the DFB lasers are then combined into a single-mode fiber connected to two acousto-optic modulators (AOMs) employed to generate a heterodyne frequency shift of 40 kHz equally for all the four wavelengths. The optical setup of the interferometer is an extended form of Michelson type in which the interference phase of each DFB laser is measured individually in parallel by means of heterodyne phase detection. The beam splitting unit placed in the middle of the ADM interferometer is comprised of four non-polarization beam splitters separating the combined beam of four wavelengths into the reference and measurement paths with subsequent recombination. The beam splitting unit uses no polarization optics so that the intended heterodyne phase measurement can be implemented without non-linear errors caused by unwanted polarization mixing and leaking [5]. The resulting four interference signals between the reference and measurement paths are detected using high sensitive photodiodes simultaneously. Then a custom-built multi-channel phase meter is used to measure the interference phases of four wavelengths individually but simultaneously without significant timing lag between channels. For performance evaluation of the multi-wavelength ADM interferometer, a commercial IDM-type He-Ne laser interferometer (5530, Agilent) is installed along the same measurement optical path of the target mirror travelling on a 3-m long granite air-bearing stage.

The granite air-bearing stage is constructed with its horizontal and vertical straightness being corrected to be less than ~5 µm over the entire range of axis-travel. The target mirror is made of a corner-cube retro-reflector, of which the movement along the stage is automatically activated using the position feedback from an optical linear encoder (OLE, RGH24Y, Renishaw). The whole interferometer system including the granite stage is enclosed by a 10-mm thick insulation container to minimize air turbulence, temperature change, and acoustic noise inclusion. No active temperature control is made while the air distribution inside the
container is maintained as uniformly homogeneous as possible over the whole measurement path. The refractive index of air is then estimated with an uncertainty of $1.6 \times 10^{-8}$ using the Ciddor’s equation with sensing of temperature, pressure, humidity, and CO$_2$ concentration [30]. The optical linear encoder (OLE) attached on the stage offers a 0.1 μm resolution which is not significantly affected by the refractive index of air. The beam path length ($L_{IDM}$) of the IDM interferometer is set to almost equal to $L_{ADM}$ which is the beam path length of the ADM interferometer, so that they are subject to the same influence of the refractive index of air and also the thermal expansion of the stage length.

![Diagram](image)

**Fig. 1.** Multi-wavelength ADM interferometer configured in this investigation. ADM: absolute distance measurement, IDM: incremental distance measurement, $L_{ADM}$: target distance measured by ADM, $L_{IDM}$: target distance measured by IDM, M: mirror, PBS: polarization beam splitter, $M_R$: reference mirror, BS: beam splitter, C: collimator, Ref. beam: reference beam, Mea. beam: measurement beam, DM: dichroic mirror, R: retro-reflector, Rb clock: rubidium atomic clock, OLE: optical linear encoder.

Figure 2(a) shows the opto-electronic layout of the multi-channel phase meter designed and built in this investigation, which performs two functions of wavelength de-multiplexing and interference phase detection in sequence. First, the reference and measurement beams transferred from the interferometer are separated into four channels by means of wavelength de-multiplexing using a fiber Bragg grating array (FBGA). Each Bragg grating offers a 90 GHz transmission bandwidth to isolate only a single wavelength with a 25 dB extinction ratio for subsequent phase detection. Second, the de-multiplexed optical signals are converted into electric signals using eight photo-detectors (PDs), one for each optical signal, with subsequent band-pass filtering about a heterodyne frequency of 40 kHz. For detection of the interference phases, the filtered electric signals are transformed into square waves and then digitized using a high-speed data acquisition board (PCIe-6361, National Instruments). Figure 2(b) illustrates how the interference phases are detected; in each individual channel, the time elapse between the rising edges of the reference and measurement square waves is counted using a 100 MHz clock synchronized to the Rb atomic clock. The counted time elapse $\tau_i$ ($i = 1,2,3,4$) for each channel is finally converted to the interference phase $\phi_i$ ($i = 1,2,3,4$) by multiplying the time count for each channel. The fractional resolution of the phase measurement of a single time count is equal to the ratio of the heterodyne frequency (40 kHz) to the digitization frequency (100 MHz) which is worked out to be 0.0004, being equivalent to $\sim 0.14^\circ$ in the phase term. The update rate of the phase detection ($T_{update}$) depends on the total data-processing time including the phase sampling, time elapse counting and phase calculation, which is 100 Hz for the current version of multi-channel phase detection.
The performance of the multi-channel phase detection of Fig. 2 is evaluated by inputting to each channel a pair of 40 kHz heterodyne signals of which the phase difference is precisely scanned from 0° to 360° with high precision. Using a two-channel RF signal generator (AFG3252, Tektronix) operating in synchronization to the Rb clock, the linearity error is measured $8.79 \times 10^{-4}$ being just twice the fractional resolution of phase detection. Figure 3(a) shows that the measured phase value well agrees with the calibration reference value of the used RF signal generator. The residual phase error is 0.58° (10 mrad) in peak-to-valley and 0.097° (1.7 mrad) in standard deviation over the whole phase range from 0° to 360°. An exemplary time trace of the measured phases from the multi-wavelength ADM interferometer over 5 s is present in Fig. 3(b), demonstrating that the measured phase maintains a same variation pattern with a nearly constant offset between channels. The residual phase deviation between channels is attributable to random phase noise which is about 1.1° (19 mrad) in the phase term after 10-Hz low-pass filtering. This fractional noise level is low enough not to affect the accuracy of the absolute distance up to several meters to be determined by combining the four measured interference phases [20].

In generating four different wavelengths, a single wavelength-tunable laser may be used as the working laser, being sequentially tuned and phase-locked to a set of pre-selected optical modes of the frequency comb [20,21]. Here in this ADM interferometer, in order to realize real-time measurement, four DFB lasers are phase-locked in parallel the same way as successfully demonstrated in high-density optical telecommunications [28,29]. The individual positions of the four wavelengths are selected so as to maximize the non-ambiguity range of...
multi-wavelength interferometry [31], which are 1530.27813 nm, 1531.04871 nm, 1554.17669 nm, and 1554.94118 nm, respectively. The detailed procedure of determining the absolute distance by combining the four interference phases is omitted here as it is well documented already in the authors’ publication of Ref. 20.

Figure 4(a) shows the phase-locked four wavelengths monitored using an optical spectrum analyzer (MS9710C, Anritsu) with a 0.05 nm resolution over a 40 nm wavelength bandwidth. The signal-to-noise ratio of all the wavelengths is ~50 dB, which is large enough to produce strong monochromatic light sources for the ADM interferometer. The exact position of each wavelength is found stable over 24 hours when monitored using a high-precision wavelength meter of 0.2 pm accuracy; this implies that no phase-slip or frequency hopping is created by our phase-locking control. The uncertainty of each wavelength is precisely quantified by measuring the frequency stability of the frequency comb mode \( f_c \) together with the beat frequency \( f_b \) between the DFB lasers and the frequency comb using a frequency counter (53131A, Agilent). The relative uncertainty of \( f_b \) with respect to the comb is in the range of \( 10^{-14} \) at 10-s averaging, indicating that the phase-locked DFB lasers are accurately phase-locked to the frequency comb with negligible errors as presented in Fig. 4(b).

3. Test results

First of all, Fig. 5 shows a linearity test result obtained while translating the target mirror over a 1.0 m axis-travel repeatedly with a 100 mm step. The air-bearing is turned on during movement and subsequently turned off during measurement to avoid air-induced stage vibration. The ADM measurement result is compared with that of the IDM HeNe interferometer of which the zero datum is set to an offset distance of 1.8 m to that of the ADM interferometer. Two measurement results, presented as ADM and IDM for convenience, show a good linearity slope of 1.0000039 with a 61.9 nm residual error in peak-to-valley (20.1 nm in standard deviation). The maximum residual error is in the range of \( 10^{-8} \) in the fractional term, which is in fact almost in the same level of the stability of the refractive index of air maintained during the testing interval of 300 s. This implies that the current linearity test confirms that the ADM result is comparable to the IDM result in short-term measurements, not being able to conclude which is better than which. Next, with the aim of demonstrating the real-time measurement capability of the ADM interferometer, a mechanical chopper is installed, as shown in Fig. 1, to block the ADM beam path periodically at an on-off switching rate of 2 Hz when the target mirror is located near the far end of the granite stage at a ~3.8 m distance from the zero-datum of the ADM interferometer. In the meanwhile, with its beam path uninterrupted at all, the IDM interferometer is operated to continue its measurements. The ADM and IDM results are plotted together with the constant offset of the two readings being removed in Fig. 6(a). The comparison clearly shows that since the ADM interferometer is capable of updating the target distance without accumulation of prior information, the ADM distance reading readily catches up with that of the IDM interferometer every time when the measurement beam is recovered. Figure 6(b) shows a magnified view of Fig. 6(a), which indicates more precisely that instantaneous ADM and
IDM readings are well matched but fluctuate with an amplitude of ~50 nm which is estimated attributable to the air turbulence and vibration additionally induced by the chopper during its rotation.

![Graph showing residual vs. IDM by conventional laser interferometer](image)

**Fig. 5.** Linearity comparison of the ADM interferometer with the IDM HeNe interferometer over a 1 m axis travel during a 1 min. The residual is the confidence level of ± 2σ.

![Graph showing distance measurement over time](image)

**Fig. 6.** Comparative distance measurement between ADM and IDM under optical chopping in beam path of ADM. (a) Distance measurements under chopper operation. (b) A magnified view over 5 seconds.

Another comparative ADM and IDM measurement over 400 seconds for a fixed ADM target distance of ~3.8 m is shown in Fig. 7(a), in which ADM and IDM readings are in good
agreement with each other at 100 Hz and 1 Hz update rates. For more detailed stability analysis, the Allan deviation for ADM and IDM readings with different averaging intervals is presented in Fig. 7(b). In addition, the Fourier-transform frequency spectra up to 50 Hz for ADM and IDM readings are also given in Fig. 7(c). It is clearly observed that there is no notable difference between the ADM and IDM readings while the Allan deviation of both the two readings decreases until the averaging interval reaches 0.5 s but begins to increase for longer averaging intervals being affected by slowly-varying environmental drift. The two frequency spectra also show no significant difference with their spectral power being concentrated on two regions; one in a lower frequency region from 0 to 2 Hz and a relatively higher frequency region from 20 to 45 Hz. This comparative test confirms that the ADM interferometer provides almost the same level of performance as that of the IDM interferometer in terms of the measurement resolution, speed and stability.

Finally, a 24 hour comparison test is summarized in Fig. 8 for demonstrating the long-term measurement capability. During this long-term test, the target mirror is positioned at the farthest end of the granite guide way of a ~3.8 m ADM distance and remains stationary at the position with the air-bearing turned off. Air disturbance is stabilized along the beam path with a temperature variation of both the air and stage to be less than 0.5° C throughout the test. Figure 8(a) shows the time-dependent variation of ADM and IDM readings in which the refractive index of air is compensated using the Ciddor’s equation. The maximum deviation between the ADM and IDM readings turns out to be ~1.34 μm as seen in Fig. 8(b), corresponding to a fractional distance change of ~3.5 × 10⁻⁷ with respect to the total ADM distance. This overall time-dependent deviation may be interpreted in terms of two constituents; linear and residual. The linear-fitted deviation is found responsible for a dominant part of about 90% of the overall deviation, being interpreted attributable mainly to the cosine geometrical error between the ADM and IDM beam path alignment as it follows the same linearly-varying pattern of the temperature change of the stage as monitored in Fig. 8(c). Besides, the residual term obtained by subtracting the linear-fitted contribution from the total deviation is assumed attributable to several random errors, among which the effect of imperfect compensation of the refractive index of air is most significant. The reasoning is based on that the environmental parameters of air temperature, pressure, CO₂ concentration, and humidity used for the estimation of the refractive index of air of Fig. 8(d) are analyzed to
have sensor-originated uncertainties of $\Delta 5$ mK, $\Delta 2.5$ Pa, $\Delta 41$ ppm, and $\Delta 1\%$, respectively. The combination of all the possible sensing errors suffices to produce the partial uncertainty contribution of $3.1 \times 10^{-8}$ which the residual constituents exhibit currently in this long-term test. The uncertainty contribution by the frequency-comb-referenced light source is estimated to less than 4.2 pm for a 3.8 m distance while the contribution by the phase-detection unit is about 0.2 nm regardless of the target distance.

Fig. 8. 24 hour Long-term comparative test results. (a) Time-traces of ADM with IDM readings. (b) Difference of ADM and IDM readings. The maximum difference is $\sim 1.34 \mu m$ or $3.5 \times 10^{-7}$ in fractional term. The peak-to-valley value of the linear-fitted residual is 118 nm or $3.1 \times 10^{-8}$ in fractional term. (c) Variations of air temperature and stage surface temperature. (d) Air refractive indices for ADM and IDM reading determined by the Ciddor’s equation.

4. Conclusions

The prototype ADM interferometer built in this study to evaluate the measurement capacity of multi-wavelength interferometry adopting the frequency comb of a femtosecond laser shows an overall performance comparable to that of the IDM HeNe laser in the measurement resolution, speed and stability during a series of tests from 300 s to 24 hours. As for the uncertainty when measuring a $\sim 3.8$ m distance, both the ADM and IDM interferometers exhibit a difference of $3.1 \times 10^{-8}$ which is within the partial uncertainty contribution due to the sensing random errors of the environmental parameters in estimating the refractive index of air. Unlike the IDM interferometer, the ADM interferometer offers an advantage of requires no continuous movement of the target mirror all the way from the zero-datum and moreover remains operational even in the occurrence of measurement beam interruption. This test outcome indicates that the ADM interferometer can be applied as an absolute-type position-feedback transducer for next-generation machine axis control needed in unmanned operations of remote factories or even in space.

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