Proc. of the 9th Intl. Conf. of Asian Society for Precision Engg. and Nanotechnology (ASPEN 2022)
15–18 November 2022, Singapore. Edited by Nai Mui Ling Sharon and A. Senthil Kumar
doi://10.3850/978-981-18-6021-8_OR-11-0055

A compact differential heterodyne laser interferometer without periodic errors

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KEYWORDS: Heterodyne laser interferometer, Periodic error, Differential interferometer

In this investigation, we propose a thermally stable heterodyne laser interferometer with the spatial beam separation. The optical configuration is designed for the differential type and the reference signal only measures the systematic phase noise in the interferometer while the measurement signal includes both of the displacement of the target and the systematic noise. Then, the phase noise, especially thermal drift caused by the interferometric optics can be canceled out. Furthermore, the spatial separation of two beams can prevent frequency and polarization mixings in the interferometer. In the experiments, long- term stability of the system was estimated, and the measurement results were compared with those of the commercial DMI system. As the result, it was confirmed the periodic nonlinear errors were not detectable in the proposed interferometer while the commercial DMI system has the first order periodic error 0.6 nm.

1. Introduction

Displacement measuring interferometry (DMI) has been a very useful tool to determine the precise position of a moving stage, measure position errors of a target and control the motion of a precise machine because of its non-contact, traceable, accurate and high dynamic range, defined as the ratio of measurement range to resolution, features [1]. Even, DMI is indispensable for dimensional metrology because of the possibility of reaching sub-nm precision opposed to other techniques when it is applied in the vacuum environment such as space missions and EUV lithography. DMI applied in the vacuum environment mostly needs long time usage, which means its long-term stability becomes important. Especially, the interferometer itself should be thermally stable to prevent the long-term drift of the measurement results. For the purpose, differential types of interferometry can make themselves thermally stable because of the common path configuration.

On the other hand, heterodyne laser interferometry is beneficial for providing less sensitivity to source intensity fluctuations, unambiguous direction sense and high dynamic accuracy among several types of DMI. However, its inherent use of two frequency laser source causes the systematic periodic nonlinear errors with the level of 1-10 nm and it prohibits the sub-nm accuracy in the vacuum environment. To overcome this limitation, much effort to analyze and compensate the periodic errors have been put on feedback control schemes and system modifications [2]. Spatial separation of two beams with distinct frequencies has been proposed to fundamentally eliminate the polarization and frequency mixing, which results in sub-nm accuracy without environmental uncertainties [3,4]. However, the differential type of heterodyne laser interferometer without periodic nonlinear errors is difficult to be designed because the spatial separation of two beams restricts the common path schemes. A base plate made of thermally ultra-stable materials such as Zerodur® and ULE can mitigate the long-term drift, but it is not the fundamental approach, and even the optical configuration can be complicated.

In this investigation, we propose a thermally stable heterodyne laser interferometer with the spatial beam separation [5]. The optical configuration is designed for the differential type and the reference signal only measures the systematic phase noise in the interferometer while the measurement signal includes both of the displacement of the target and the systematic noise. Then, the phase noise, especially thermal drift caused by the interferometric optics can be canceled out.

2. Compact differential heterodyne laser interferometer

2.1 Optical configuration

Figure 1 shows the optical configuration of the proposed heterodyne laser interferometer. By using two acousto-optic frequency shifters (AOFSs) although not shown in Fig. 1, the source part can provide spatially-separated two frequency beams (f_0+δf_1, f_0+δf_2) to the interferometer, where f_0 is the optical frequency of an original single frequency laser source, and each of δf_1 and δf_2 indicates the RF frequency applied to the corresponding AOFS. These two beams are fiber-coupled and delivered to the interferometer as aligned vertically. These two vertical beams go through a beam displacer (LBS_1), and divided into horizontally separated beams as shown in Fig. 1. The vertically and horizontally separated four beams then pass through a polarizing beam splitter (PBS) and a 45° rotated quarter-waveplate (QWP) toward a fixed mirror (M_F), a reference mirror (M_R) and a measurement mirror (M_M), respectively. It is noted that the horizontally separated two beams with (f_0+δf_1) are reflected off by M_F and two beams with (f_0+δf_2) are reflected off by M_R and M_M, respectively. The four beams go back to PBS after passing through QWP again and reflected by PBS to go toward the other non-polarizing beam displacer (LBS_2). Then, the vertically aligned beams can be combined with each other and generate the beating signals used for the heterodyne laser interferometer. In this case, two kinds of beating signals can be obtained and they are reference and measurement signals according to the reflections by M_R and M_M, respectively. By measuring phase difference between two signals, the proposed interferometer can measure the relative displacement (ΔL) between M_R and M_M.

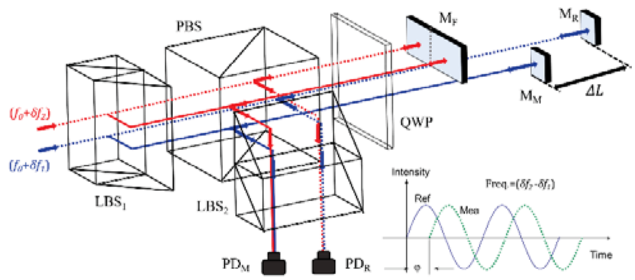

Fig. 1 Optical configuration of the proposed differential heterodyne laser interferometer; LBS, beam displacer; PBS, polarizing beam splitter; QWP, 45° rotated quarter wave plate; M_F, fixed mirror, M_R, reference mirror; M_M, measurement mirror; PD_R, reference photo-detector; PD_M, measurement photo-detector.

In order to build a highly stable interferometer, our interferometer was designed to theoretically eliminate the phase noise caused by the thermal effect even though the optical paths are not exactly overlapped. By the geometrical relationships between the four beams, the phase difference for measuring displacements, obtained by the reference and measurement signals, can be free from the thermal noise of the interferometer.

2.2 Elimination of periodic nonlinear errors

The periodic nonlinear errors in heterodyne interferometry are mainly caused by frequency or polarization mixing of two beams occurred from the optical source to the interferometer itself. In order to prevent the mixing of two beams from the optical source, two AOFSs were used, and the first order diffracted beams with slightly different RF frequencies (δf_1 and δf_2) are only fiber-coupled. Even though the original beams with f_0 are included in the diffracted beams, they can only generate the beating frequencies of δf_1 and δf_2, which are not used for the phase measurement because the reference and measurement signal have the beating frequency of (δf_2-δf_1) and the others can be electronically filtered out. Moreover, these two beams have the same polarization with the aid of the delivery by polarization maintain fibers (PMFs), and there is no opportunity to meet each other in the interferometer thanks to the beam separation. The only concern is the possibility of periodic nonlinear errors by the surface reflection of optical components, but it can be practically eliminated by the slight misalignment of the optical components.

3. Experimental results

Figure 2(a) and 2(b) present the temperature variation and the displacement measurement result, respectively. As shown in Fig. 2, the long-tern drift of the displacements was clearly caused by the temperature variations, and the drift was approximately 2.7 nm as the temperature varied from 22.4 °C to 21.9 °C. With the assumption of the linear relationship between the temperature variation and the drift, the thermal drift ratio was calculated as 5.4 nm/°C. It is noted that a commercial plane mirror interferometer for high stability has approximately 30 nm/°C provided by the manufacturer.

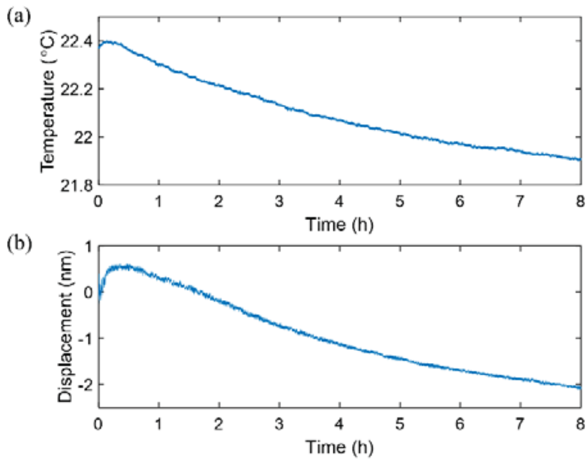

Fig. 2 (a) Temperature variation and (b) displacement measurement results during 8 h.

Nonlinear errors of the interferometers were also evaluated with the residual position errors after applying the polynomial curve fitting to the stage motion. To reduce the transient errors of the motion, displacements were measured at every 50 nm step during 5 s and averaged for 7 µm measurement range. Figure 3 shows the measurement results and nonlinear errors. The displacement measurement results of the proposed interferometer were exactly opposite to those of the commercial DMI for the linear motion of the stage and the measurement results were fitted with the 8^{th} order polynomial curve and the residual errors were calculated by the assumption of continuous stage motion to extract the nonlinear errors as shown in Fig. 3(a).

In order to confirm the elimination of periodic nonlinear errors in the proposed interferometer, the residual errors were Fourier-transformed and presented along the periods of half the wavelength (λ/2). As the result, there were no detectable first, second and even higher order periodic errors in the proposed interferometer while the commercial DMI had 0.6 nm of first periodic nonlinear as shown in Fig. 2(b) even though it is a homodyne laser interferometer. It may be caused by the quadrature detection scheme to use polarizing optics to determine the direction and measure the phase, which leads to polarization mixing.

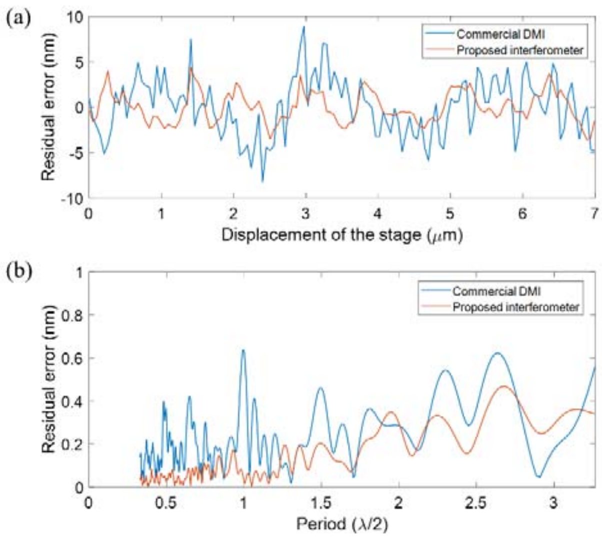

Fig. 3 (a) Displacement measurement results and (b) the periodicity of the residual errors for the commercial DMI and the proposed interferometer.

4. Conclusion

We proposed and experimentally verified a compact differential type of a heterodyne laser interferometer without periodic nonlinear errors. Spatial separation of two beams are adopted to prevent frequency and polarization mixings in the interferometer and the optical configuration was designed for the differential type, where the reference signal only measures the systematic phase noise in the interferometer while the measurement signal includes both of the displacement of the target and the systematic noise. Then, the phase noise, especially thermal drift caused by the interferometric optics can be canceled out. In the experiments, long- term stability of the system was estimated and the measurement results were compared with those of the commercial DMI. As the result, it was confirmed the periodic nonlinear errors were not detectable in the proposed interferometer while the commercial DMI has the first order periodic error 0.6 nm.

ACKNOWLEDGEMENT

It is noted that this conference proceeding is written and modified based on the journal paper [5] reported in JOSA A.

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