A common-path, multi-channel heterodyne laser interferometer for sub-nanometer surface metrology

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ABSTRACT

A multi-channel heterodyne laser interferometer is proposed for measurement of optical surface deformations at the sub-nanometer level. This interferometer employs a common-path configuration and heterodyne detection, by which fringe errors due to laser frequency fluctuations and optical path variations due to vibration can be reduced. By measuring the heterodyne signal phase among sub-apertures (pixels) with a 2-D detector array, the surface height can be reconstructed and surface deformation can be measured by comparing consecutive measurements. Detection of sub-nanometer level surface deformation is achieved using high precision digital phase meters and athermalized opto-mechanical systems. This paper describes the interferometer design criteria and experiment methodologies.

Key words: heterodyne interferometry, metrology, nano-technology.

1. INTRODUCTION

There is an increasing demand for highly stable optical systems for various space-based astronomical observatories [1-2]. Temperature fluctuations are a main cause of time-varying wavefront errors which deteriorate the astronomical measurement accuracy. Stringent thermal control is a key to maintaining its optical stability. To validate the thermal modeling tools and verify the stability of the optics, interferometers that are capable of measuring the change of optical surface deformations at the 10-picometer level are needed.

Conventional interferometers based on phase-shifting interferometry (PSI) are widely used to characterize optical elements [3]. However, the resolution of conventional interferometers is limited to about $10^2 - 10^3$ pm. The performance limit is due to a wide range of error sources, including phase shifter errors, electronics noise, coherent optical noise, vibrations, etc. [3-7]. Reaching 10pm resolution is considered to be extremely difficult [8].

2. COMMON-PATH HETERODYNE INTERFEROMETER

In this paper, we propose a multi-channel, common-path heterodyne interferometer (COPHI) for use in the measurement of thermal stability of optical systems. We take advantage of the high precision laser fringe counter developed at JPL for sub-Angstrom 1-D metrology [9-10]. Referring to Figure 1, two single-mode fibers deliver laser beams that are slightly different in frequency. The two beams are then collimated, and one is used as a "local oscillator", mixed with the other beam reflected from the optics under test. The surface height of the test optics is converted into the phase of the interference fringe. By measuring the

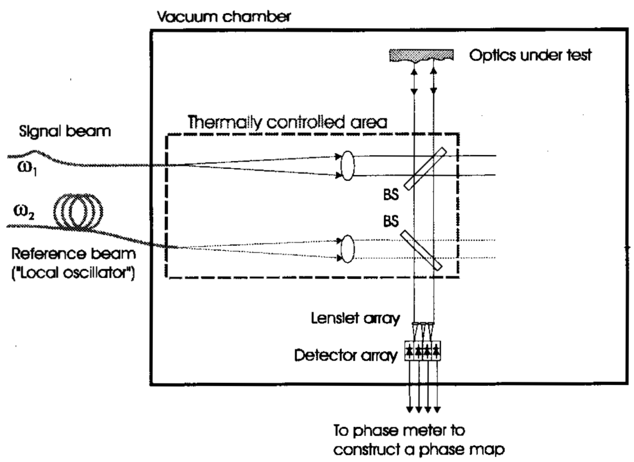

Figure 1. Schematic of the multi-channel, common-path heterodyne interferometer.

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heterodyne signal phase among sub-apertures (pixels) with a 2-D detector array, the surface height can be reconstructed and time-varying surface deformations can be measured by comparing consecutive measurements. Detection of sub-Angstrom level changes of surface deformation can be achieved using the high precision laser fringe counter and an athermalized opto-mechanical system.

One major advantage of the proposed heterodyne interferometer is that the reference heterodyne signal and measurement heterodyne signals are derived from the same wavefront (except from different areas), thus many error sources such as vibrations and metrology source noise are common mode. Other advantages of COPHI include faster response, which can be potentially useful in closed-loop control of optical wavefront stability.

3. INTERFEROMETER DESIGN

To achieve the desired 10pm resolution, a careful design of almost every aspect of the instrument is required. In this section, we focus our attention on (1) athermalization; (2) coherent optical noise; (3) detector array; and (4) data acquisition.

3.1. Athermalization of Key Optical Components

As shown in Figure 1, only four "non-common" optical components, i.e., two collimator lenses, and two beam splitters, are subject to time-varying wavefront errors due to temperature fluctuations. To reduce the total amount of wavefront error, we (1) use off-axis parabolic reflectors made of materials with ultra-low coefficient of thermal expansion (CTE), such as Zerodur, to improve the collimation stability; (2) use a Zerodur base plate to reduce collimation defocusing error; (3) minimize wavefront distortion in reflection (CTE only) and transmission (both CTE and dn/dT) in selecting substrate material for the beam splitters; (4) Super-Invar micrometer screws on beam splitter mount to maintain alignment stability; and (5) de-couple thermal radiation from surrounding heat sources by aluminizing all mirror surfaces and enclosing them in a thermal shield. To ease thermal requirements, we also propose the use of a stable reference mirror made of ultra-low CTE substrate that periodically "calibrates" the wavefront, thus reducing the thermal stability requirement from over 1 hour to only a few minutes. Care has been taken in the positioning repeatability of the chopping mirror to minimize undesired beam walk errors. Figure 2 illustrates the layout of the athermalized part of the interferometer setup.

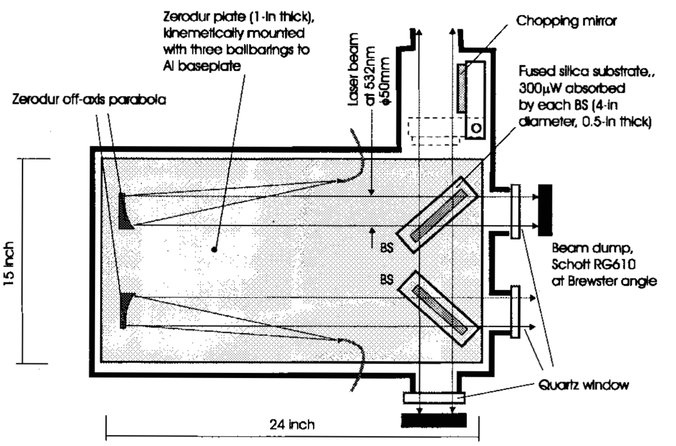

Figure 2. Layout of athermalized optical setup.

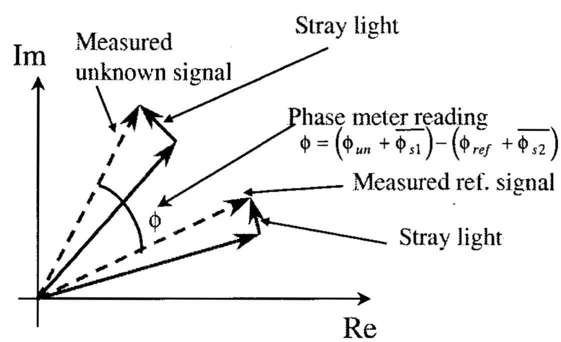

Figure 3. Phaser diagram of fringe phase measurement.

3.2. Coherent Optical Noise Control in COPHI

Coherent stray light will impart a phase error to the heterodyne signal when it interferes with the measurement beam at the detector. Since COPHI will measure changes in wavefront, only the time-varying part of the phase error is important (see Figure 3). In other words, if the stray light stays constant in both phase and intensity relative to the heterodyne interfering beams, then the contribution of the stray light can be negligible. One example is the reflection from the back surface of the beam splitter. It contributes a same constant phase shift to both the reference and measurement signals, because the reference and measurement detectors see this reflection from the same surface that has a constant optical path length from the front surface.

Even if this is not the case for some stray light sources, several other factors can also reduce their net effect, such as large stray light incident angle, large detector area, and poor stray light wavefront quality, due to the stray light being "averaged out"). To control the coherent optical noise to a level that is acceptable to 10pm measurement, we have taken the following steps, (1) apply V-coating on the back surface of the beam splitter to reduce the reflection to a minimum (~ 0.1%), and use 0.5 degree wedge such that the back reflection can be spatially filtered. (2) remove (steer away) the back reflection from the fiber tip by using an APC connector (angle-polished, 8 degrees) to launch the fiber light; (3) randomize the reflection from detectors by using a "diffusor" such that the back reflection from the detectors is spatially incoherent; and (4) conduct the experiment in a clean environment to minimize the scattering from dust particles.

3.3. Detector Array

Since the primary goal of COPHI is to detect changes in optical surface figure due to temperature fluctuations, we use a low-resolution camera, which is composed of a 2-D array of silicon PIN photo-diodes. Because the thermal distortion in an optics is primarily in the low spatial frequency band, a 10×10 sampling grid is sufficient to detect the thermal distortions of interest. Figure 4 shows a schematic of the detector array, in which a precision photo-mask is used to define the sampling grid points on the incoming wavefront. The aperture (grid) positioning accuracy of the photo-mask is better than 1μm to ensure a linear optical path length change across the sampling points as the wavefront tilts. The sampled portion of the beam is then focused on its corresponding detector with a lenslet array.

The phase of all the signals is measured against a common reference signal derived from a detector located close to the center (see Fig. 4). Since both reference and measurement signals are derived from the same wavefront, vibrations (piston mode) in the interferometer setup and laser source noise are common-mode errors to the measurement. Tip/tilt vibration modes are monitored with two "tip" and "tilt" detectors and wavefront tip/tilt are removed from the final phase map calculation. These features of COPHI make it possible to measure wavefront distortions (second order and higher) with precision that other types of interferometers can not reach.

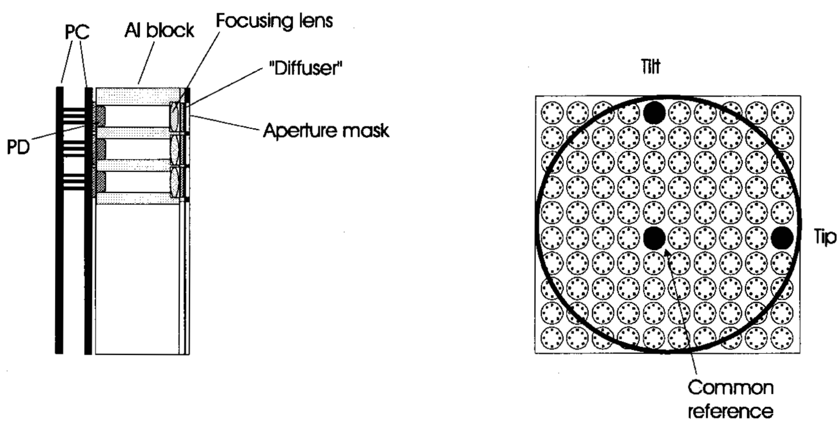

Figure 4. Schematic of the photo-detector array.

3.4. Data Acquisition

The data acquisition system and fringe phase meters are a modified version of our 1-D metrology system [10], except that a 100×10 MUX is used to handle 100 heterodyne signals by 10 parallel phase meters. Figure 5 shows the data acquisition schematic diagram. The 10 kHz sinusoidal heterodyne signals are amplified and converted into square waves, which are then fed into the digital phase meters for phase measurement. These have achieved $2\pi\times10^{-4}$ *rad* instantaneous phase resolution and $2\pi\times10^{-6}$ rads for 1 second averaging [9]. Such high precision phase meters enable the measurement of optical surface deformations at the sub-Angstrom level. In addition, low noise and highly stable electronics are used in all pre-amps, MUX, amplifiers and comparators to ensure phase measurement sensitivity and stabiltity.

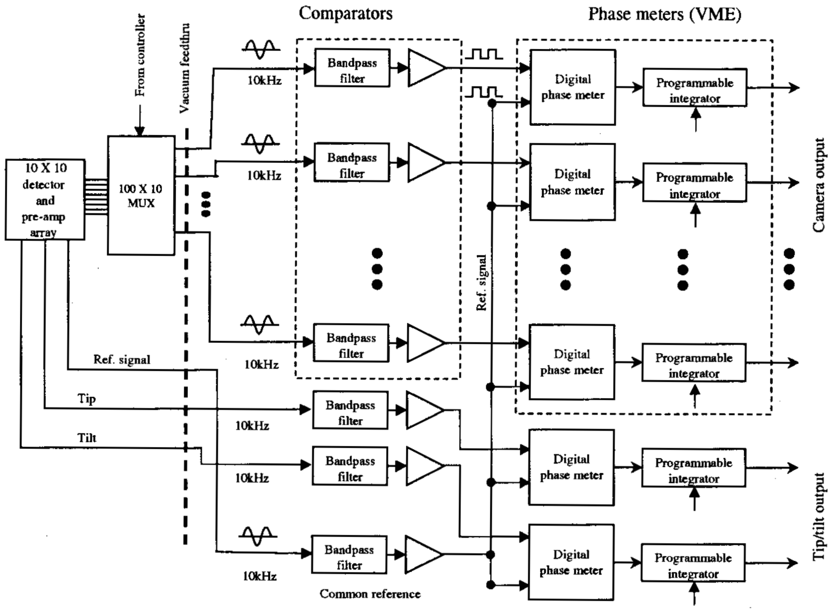

Figure 5. DAQ schematic diagram.

4. SUMMARY

In this paper, we describe the instrument design and methodologies of a surface metrology interferometer based on a unique laser heterodyne interferometry configuration. The common-mode feature of the measurement and reference signals rejects many phase measurement error sources that are inherent to phase-shifting interferometry. The combination of athermalization and high precision phase meters should make it possible to achieve sub-Angstrom measurement of surface deformations.

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