Wavefront versus amplitude division high precision displacement measuring interferometers

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Abstract - Displacement measuring interferometers (DMI's) with sub-Angstrom accuracy are sought in several of NASA's planned missions such as the Space Interferometry Mission (http://huey.jpl.nasa.gov). In this paper, we will review the work we have done at the Jet Propulsion Laboratory on the development of high precision laser heterodyne interferometers for such applications. We will discuss and compare different methods to reduce periodic nonlinear error and improve thermal stability. Experimental results will be presented and discussed.

1 INTRODUCTION

Laser heterodyne interferometers have been widely used in high accuracy displacement measurement ranging from semiconductor wafer manufacturing and inspection to stellar astrometric measurement. Displacement measuring interferometers (DMI) with sub-Angstrom (<100pm) accuracy are sought in several of NASA's planned missions. Currently commercial available DMI's, which are based on traditional polarization-type configurations, are limited to about 1-2 nm in periodic non-linear error.

One common feature of the traditional interferometer is that the reference signal (REF) is obtained with a beam sampler before the measurement beam enters the measurement cavity. Typically, a polarizing beam splitter (PBS) is used to separate and combine the measurement beam. There are several drawbacks of this amplitude-split approach: (1) polarization leakage, leading to high periodic nonlinear error; and (2) un-compensated glass in the measurement path which is subject to temperature sensitivity. Error sources in the traditional interferometers have been a subject of research for the last two decades [1].

Recently, there have been several studies on obtaining the REF signal by using wavefront split in non-polarizing interferometers [2], and encouraging results have been demonstrated. In the mean time, significant progress has been made in improving the performance of traditional polarization-type interferometers. In this paper, we will review some of our work at the Jet Propulsion Laboratory

(JPL) on amplitude-split and wavefront-split interferometers for high precision displacement measurement.

2 AMPLITUDE-SPLIT INTERFEROMETER

Figure 1 shows one implementation of an athermalized interferometer developed at JPL. It is a modified version of standard polarization-type interferometer in which the two heterodyne laser beams (f_o and $f_o+\Delta f$, with Δf being the heterodyne frequency) are orthogonal (p and s) in polarization state. Two polarization maintaining (PM) fibers are used to deliver the p and s polarizations. These two beams are collimated and then combined with a polarizing beam splitter. A 90/10 beam sampler is used to obtain the REF signal by way of amplitudes-split. Any errors on the interfering beams prior to this point will be monitored by the REF signal.

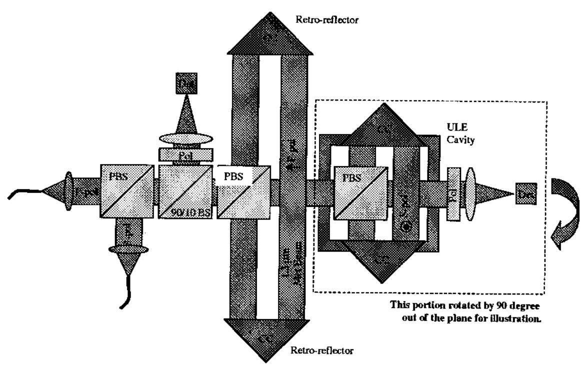

Figure 1. Schematic of an athermalized interferometer with polarization and amplitude-split.

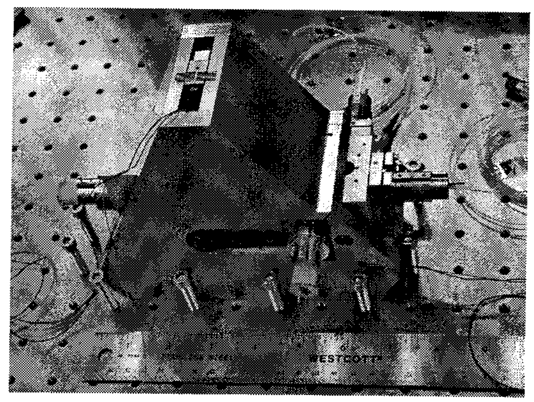
Figure 2. Picture of the prototype interferometer

The measurement beam (s polarization) is then reflected by the second PBS to the measurement cavity. The polarization state of the measurement beam is rotated by 90° by the corner cubes (in other cases with the use of quarter-wave plates). The measurement beam then combines with the straight through p polarization component to form a beat at Δf. Note there are two things which occurred to the measurement beam, s, at this PBS, (1) the s component passes through the PBS twice, while the reference beam p passes only once; and (2) its reflection at the PBS is not 100%, some of it passes directly through the PBS (polarization leakage) without making a round trip to the cavity.

The first problem is solved by adding a second cavity (reference cavity), which contains an identical PBS to compensate for the extra paths of the s beam. The reference cavity is built with thermally stable material such as Zerodur to minimize the temperature sensitivity. Dimensional mismatch of the last two PBS's or temperature gradient across these two optics still causes some temperature sensitivity. In our experiment, without the reference cavity, we found that the interferometer has a temperature sensitivity larger than 20nm/K. With the addition of a Zerodur reference cavity, the sensitivity drops down to about 4nm/K.

The second problem, polarization leakage, causes a well-known periodic nonlinear error [1]. With the state-of-the-art polarizing beam splitters, the leakage is typically –40dB or worse. As a result, the non-linear error is on the order of several nanometers. Several approaches have been proposed and tested to reduce the leakage effect. By modulating either the frequency or phase the measurement beam, *s*, it has been shown that the periodic non-linear error can be "averaged" or "filtered" to some extent [3,4]. Latest results indicate that it is possible to reduce the periodic non-linear error below 100pm.

The advantage of these modulation approaches is that they apply to many existing polarization-type interferometers. The disadvantage is that expensive modulators and complicated electronics are needed in the modulation and demodulation of the measurement signal. The modulation frequency is dependent on the distance of the error source. Therefore, in the presence of multiple error sources (polarization leakage, ghost reflections, etc.) originated at different locations, the modulation approaches can only suppress one of error sources.

3 WAVEFRONT-SPLIT INTERFEROMETER

Recently, wavefront-split approach has been shown to be a simple, yet effective way to reduce the periodic non-linear error. A recent laboratory demonstration indicates that it is feasible to suppress the error to well below 100pm [2]. Several prototype interferometers based on the wavefront-split approach have been built and tested at JPL.

Figures 3 and 4 show one of the interferometers recently developed for use in the Space Interferometry Mission to measure its internal optical path length difference. Instead of having two orthogonal polarizations, the two laser beams with a frequency offset Δf are collimated with stable collimators. One beam is directed to the measurement target with a beam splitter. The first measurement fiducial is a truncated retro-reflector, which reflects a portion of the wavefront back to the interferometer. In the case shown in Figure 3, a mirror with two holes is used. The transmitted wavefront (through the holes) then travels to the second fiducial and is retro-reflected to the interferometer. These two measurement beams are spatially separated with a guard band to reduce the effect of diffraction. The second laser beam with frequency offset Δf then interferes with both measurement beams at the second beam splitter. The Risley prisms are used to align the interfering beams. The two spatially separated fringes are then directed to their own photodiodes with the use of a truncated mirror. The phase difference between the two heterodyne signals give a direct measurement of the optical path length change between the two fiducials.

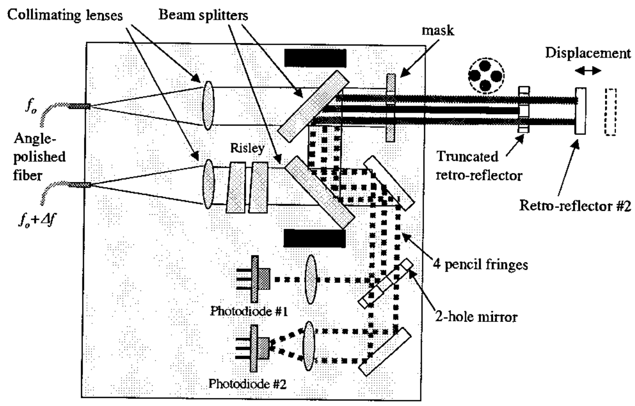

Figure 3. An schematic of a wavefront-split interferometer. A truncated retro-reflector and a second reflector form the measurement cavity. The REF and MEAS signals are derived from the same wavefront and there are no extra optics in the measurement path.

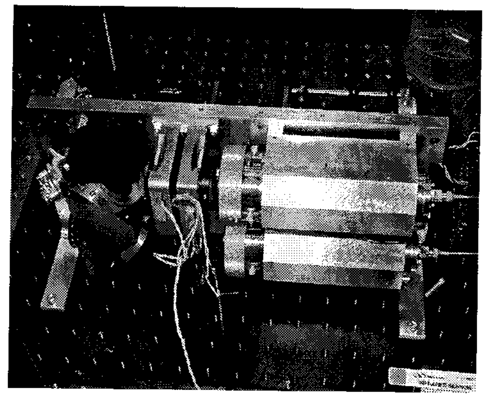

Figure 4. Picture of a prototype interferometer using wavefront-split approach.

In this interferometer, the wavefront of the measurement beam is split into two symmetric portions, with two fiducials reflecting back separately to the interferometer. The REF and MEAS signals are derived from the same wavefront, and referenced with the same reference beam (which serves as a local oscillator). The REF and MEAS signals are common-path except that they pass through different parts of the same optics. Therefore, low non-linear error and good thermal stability can be achieved at the same time quite easily.

This prototype interferometer uses commercial off-the shelf (COTS) optics and its temperature sensitivity is plotted in Figures 5 and 6. The results indicate that it has a good thermal stability, less than 4nm/K at room temperature. It can also be seen from Figure 6 that, the temperature gradient dominates (at the beginning and at the end of the measurement).

Since the wavefronts are spatially separated, diffraction may introduce an error in the measurement. Both analysis and laboratory demonstration have confirmed that the diffraction induced nonlinear error can be controlled to less than 100pm with a proper guard band between the two wavefront portions. Practically, several simple methods such as baffle to isolate the beams, re-imaging of the mask, etc. are quite effective. In addition to these measures, the local oscillator serves as a "spatial filter", which further rejects the stray light when interfering with the measurement beams.

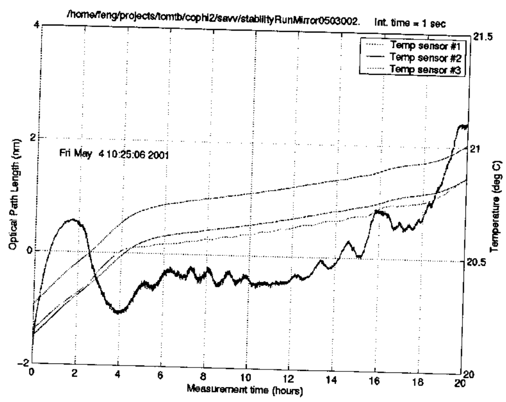

Figure 5. Position read-out noise vs. bulk temperature.

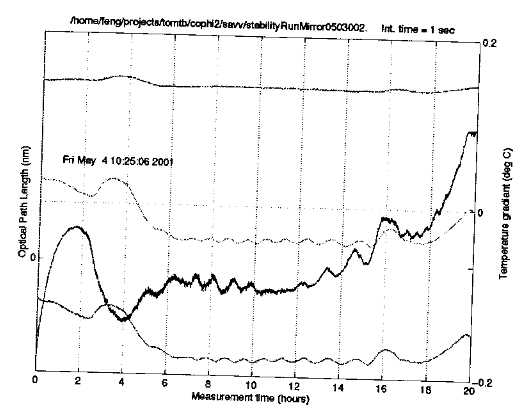

Figure 6. Position read-out noise vs. temperature gradient.

4 SUMMARY

We have developed several prototype interferometers using both amplitude and wavelength division methods to reduce periodic non-linear error and improve thermal stability. Laboratory demonstrations show that it is possible to achieve smaller than 100pm periodic non-linear error with both methods. The amplitude-split approach employs modulating and demodulating the frequency or phase of the measurement beams, while in wavefront-split interferometers, the problem is solved in the optical domain without introducing extra electronics. Good thermal stability has bee demonstrated with both types of interferometers. Overall, it is much easier to implement with a wavefront-split interferometer, since it is intrinsically common-path.

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