Picometer Laser Metrology for the Space Interferometry Mission (SIM)

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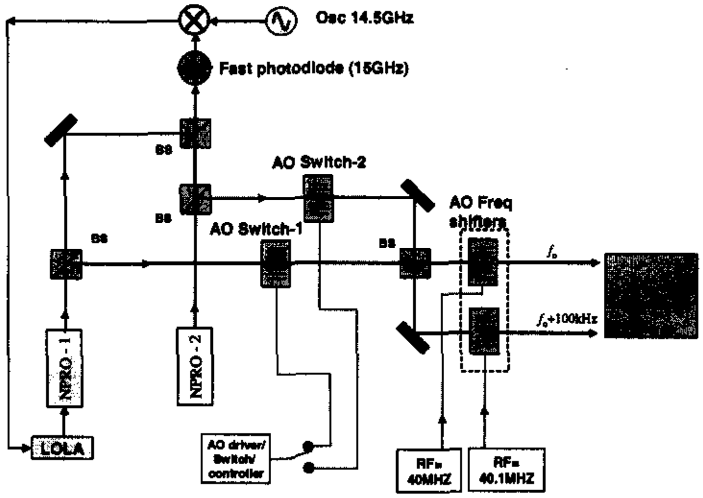
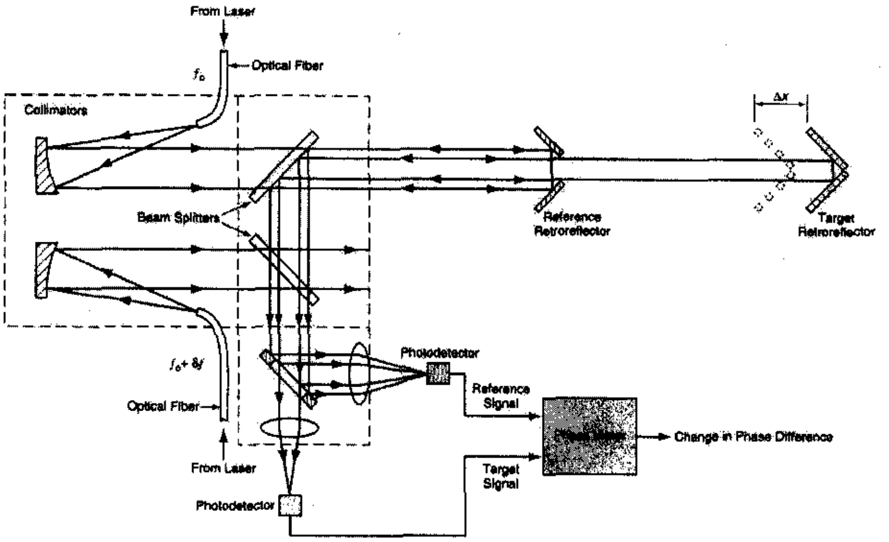
Abstract: This paper reports the progress on displacement measuring laser heterodyne interferometers for the SIM program. We will also describe the technical approaches and results from ground testbeds.

Displacement measuring interferometers (DMI) with ~10 picometer (pm) accuracy are sought in several of NASA's planned missions, such as the Space Interferometry Mission (SIM). 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. In addition to picometer displacement measurement, absolute distance measurement with an accuracy of about 1-3 microns are also need by SIM. These challenging requirements are beyond the capability of commercial available interferometers.

Over the past several years, we have made significant progress at JPL toward a laser heterodyne interferometer system that can provide both picometer displacement measurement and micron level absolute distance measurement. Figure 1 is the schematic diagram of our laser heterodyne interferometer, which employs a "switched heterodyne laser source" and a "common-path heterodyne interferometer (COPHI)". The switched heterodyne laser source consists of two single frequency lasers (Lightwave 125 NPRO) that are frequency-offset-locked to each other (Δf_o=15GHz) using Lightwave 2000 LOLA. Two acousto-optic modulators (AOM) are used as high contrast optical switches to switch between the two lasers. The 15GHz resulted from this "two color laser" produces a synthetic wavelength of about 2cm, which will be used to do absolute distance measurement. The alternating input (1 kHz switching) from the NPRO lasers is then sent to the third and fourth AOM's which are used as frequency shifters. The third and fourth AOM's are driven at different frequencies (for example δf=100kHz), resulting in a pair of heterodyne laser beams with heterodyne frequency being δf=100kHz.



The heterodyne laser beams are then sent to a common-path interferometer (Figure 2 for details). These two beams are collimated with stable optical collimators. The f_o wavefront is split into two or more sections by a retro-reflective reference device that could be, for example, a truncated corner-cube reflector or a mirror with holes. The portion of the f_o wavefront reflected by the reference device serves as reference wavefront. The portion of the f_o wavefront not reflected by the reference device is directed to the target in the form of a retro-reflector.



The light reflected by the target travels back through the optical systems alongside the retro-reflected reference light. Along the way, both the target and reference light beams pass through a beam splitter where the $f_o + \delta f$ beam is superimposed upon them. Then by use of truncated mirrors and lenses, the target signal and part of the $f_o + \delta f$ signal are sent to one photodetector while the reference signal and part of the $f_o + \delta f$ signal are sent to another photodetector. The lowest-frequency components of the heterodyne outputs of the two photodetectors are signals of frequency δf. The phase difference between the two heterodyne signals is in the form

$$\phi = \phi_1 - \phi_2 \approx \frac{4\pi}{c} f_o d\,,$$

where c is the speed of light, f_o is the laser frequency and d is the distance between the reference and target reflectors. Change of the phase difference between the two signals can be caused by changes in both the laser frequency (Δf_o) and the distance (displacement Δd),

$$\Delta\phi = \frac{4\pi}{c} d\Delta f_o + \frac{4\pi}{c} f_o \Delta d\,.$$

The first term represents absolute distance measurement by introducing a laser frequency change with switching between the two lasers. By measuring the phase change, and the laser frequency offset, the absolute distance d can be measured. The 15GHz change in frequency results in 2π ambiguity corresponding to 2cm (its synthetic wavelength), which can be easily determined by mechanical means. The second term is the change is distance (displacement), which is measured in the same way as conventional DMI's. With proper laser switching speed, the two phase terms can be extracted from each other, therefore both absolute distance and displacement measurements can be made with this interferometer.

One feature worth mentioning is that the common-path heterodyne interferometer has much smaller optical cross-talk, thus cyclic error as compared with conventional heterodyne interferometers. Cyclic errors present the most serious systematic error in DMI's. It is also a major error in limiting the accuracy of absolute distance measurement. We have demonstrated with our prototype interferometers that cyclic error <20pm RMS and absolute distance measurement to about 3microns over several meters.