Heterodyne interferometer with subnanometer accuracy

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***Abstract* — This paper gives a brief description of the laser interferometer system designed for the next generation watt balance experiment aimed to realize the unit of mass by direct link to the Planck constant at the National Institute of Standards and Technology. The light source is an iodine-stabilized frequency-doubled Nd:YAG laser at λ=532nm. Three heterodyne interferometers with subnanometer non-linearity errors measure the angular and the vertical displacements of the induction coil.**

***Index Terms* — heterodyne interferometry, non-linearity errors, watt balance, Planck constant, unit of mass.**

I. Introduction

An interferometry system is designed for the fourth generation watt balance at the National Institute of Standards and Technology, NIST-4 [1], residing inside a vacuum chamber with the following specifications: sufficient optical power for multiple axes and optical delivery, and reduction to subnanometer level of the periodic non-linearity errors affecting the accuracy of the heterodyne Michelson interferometers. Optical fibers are used to bring the reference and measurement laser beams separately to the three heterodyne interferometers. The interferometry system described herein consists of a light source, a frequency shifting and splitting system, the heterodyne interferometer, and the fringe counting system.

II. Overview of the Laser Interferometer

The light source is a frequency-doubled iodine-stabilized Nd:YAG laser at 532 nm which is one practical realization of the meter [2]. The iodine spectrometer used to stabilize the frequency of the laser is based on the modulation transfer spectroscopy. Fig. 1 shows a simplified schematic of the frequency-doubled iodine-stabilized laser built and delivered in January 2013 by Innolight* [3] (acquired by Coherent). The size of the optical setup is approximately (614 x 512 x 224) mm and it weighs about 60 kg.

For the heterodyne interferometer, two beams of different frequencies are spatially separated with two acousto optic modulators (AOM) as shown in Fig.2 to avoid frequency mixing similar to what Tanaka [4] proposed in 1989. The frequency shift is 1 MHz which is well above all mechanical resonances and sufficient bandwidth to measure the Doppler shift of 7.5 kHz when the coil moves at a typical speed of 2 mm s^{-1}. The reference and the measurement beams are delivered to the interferometer by optical fibers.

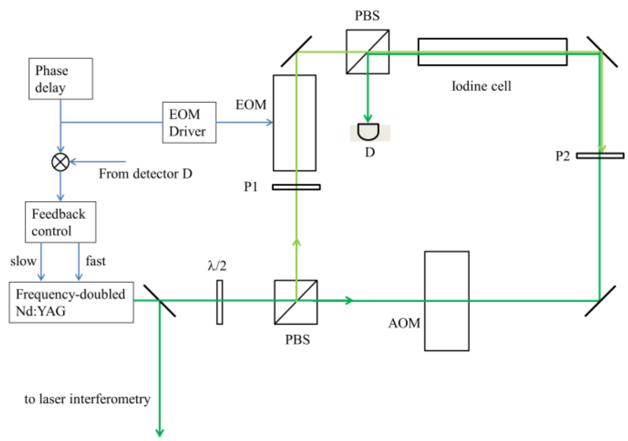

Fig. 1. Simplified scheme of the frequency-doubled iodine-stabilized laser at 532 nm. The light emitted by a diode-pumped monolithic Nd:YAG crystal passes through a periodically poled crystal to generate the second harmonic of the laser. The single frequency laser is split into a pump and a probe beams using a half waveplate λ/2 and a polarizing beam splitter (PBS). The pump beam of 5.5 mW is phase-modulated by an electro-optic modulator (EOM) which produces sidebands that are symmetrically located around the laser optical frequency. The probe beam of 2 mW is frequency-shifted by an acousto-optic modulator (AOM). Due to counter-propagation of the pump and the probe beams in the iodine cell, the probe beam acquires sidebands which are observed on a fast photodiode D and the iodine absorption line broadening by Doppler effect is eliminated. A phase detector mixes the photodiode signal with the voltage of a local oscillator to provide the error signal for the slow temperature and fast piezo actuator feedbacks.

As shown in Fig.3, the reference and the measurement beams travel separately in the arms of the interferometer. Two signals are generated at the interferometer output: a reference signal that is necessary to account for phase changes in the fibers, and a measurement signal. There are three hollow retroreflectors on the coil separated azimuthally by 120° to measure the angular and the vertical displacements. They mathematically combine such that the optical center coincides with the center of mass of the induction coil, compensating for the angular displacements of the coil and therefore reducing the Abbe offset error.

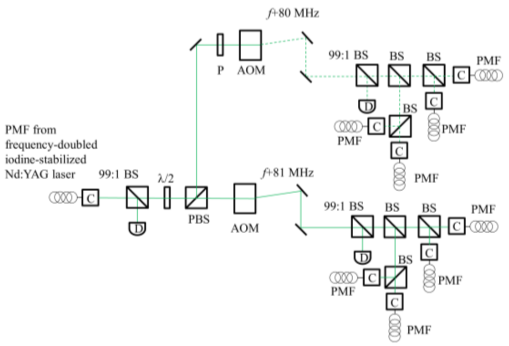

Fig. 2. Frequency shifting and distribution of the optical beam. The optical components shown in this figure are placed in air. The laser beam from the frequency-doubled iodine-stabilized Nd:YAG laser is collimated by a collimator (C) and is split with a half waveplate (λ/2) and a polarizing beam splitter (PBS). The first acousto optic modulator (AOM) shifts the reference beam frequency by 80MHz and the second AOM shifts the measurement beam by 81MHz. A polarizer (P) cleans the state of polarization. Each first-order beams is split into four outputs with 50:50 beam splitters (BS) and then recoupled into polarization maintaining fibers (PMF) to deliver the light to the three main interferometers and a fourth auxiliary interferometer inside the vacuum chamber. A photodiode (D) monitors the alignment of the three input fibers.

Time interval analyzers from Brilliant Instruments [5] measure the zero-crossings of the reference and the measurement signals. Along with the time interval measurements, continuous event counts of the reference and the measurement signals should be maintained on all channels in order to keep track of the coil position during the measurement. Although the standard product does not include an on-board counter for each channel that we require on each of the three boards, the company modified and tested the product to meet our specific need for on-board counters. The modified product can handle an input frequency range between DC and 8 MHz. The displacement of the induction coil can be calculated by:

$$\Delta \boldsymbol{p} = \left(\frac{\boldsymbol{E}_{R_{i+j}} - \boldsymbol{E}_{R_i}}{\boldsymbol{T}_{R_{i+j}} - \boldsymbol{T}_{R_i}} * \left(\boldsymbol{T}_{M_i} - \boldsymbol{T}_{R_i} \right) + \left(\boldsymbol{E}_{M_i} - \boldsymbol{E}_{R_i} \right) \right) \frac{\lambda}{2}, \tag{1}$$

where λ is the vacuum wavelength, E_R and E_M are the event counts of the reference and the measurement signals respectively, and T_R and T_M are the high resolution time stamps of the reference and the measurement signals respectively. The first summand is the fractional fringe count and the second is the integer fringe count. The average velocity is calculated from the difference between successive position and time determinations.

Future work will measure and monitor the absolute frequency of the R(56)32–0 hyperfine transition, component a10 with a femtosecond (fs) optical comb by a direct link between microwave and optical frequencies. At the time of the writing, we are still missing optical components but hope to show results of the velocity measurement, and characterize the periodic non-linearity resulting from some possible frequency leakage in the interferometer.

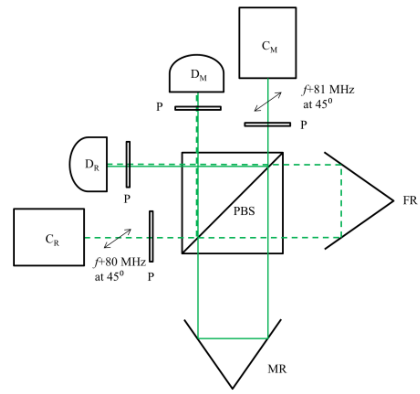

Fig. 3. Fiber-coupled heterodyne interferometer with a reference and measurement signal. The reference beam linearly polarized at 45° and collimated by the adjustable collimator (C_R) is split equally by the polarizing beam splitter (PBS). Part of the beam is reflected directly to the measurement photodetector (D_M). The other part of the beam passes through the PBS and is reflected by a fixed retroreflector (FR) back on the reference photodetector (D_R). The measurement beam collimated by an adjustable collimator (C_M) is also linearly polarized at 45°. The PBS splits it equally and directs part of the beam to D_R and the other part to the moving retroreflector (MR). The two polarizers at 45° (P) in front of C_R and C_M are used to clean the state of polarization whereas the two polarizers at 45° (P) before the photodetectors, D_R and D_M, are used to mix the two beams of different frequency and polarization. Because of the large size of the coupler and the small beam separation on MR dictated by the size of MR inside the 3 cm air gap of the permanent magnet, two mirrors, not shown in the figure, are used to deflect the light onto D_R, D_M. Note that the interferometry measurement is insensitive to optical path change between C_R and the PBS, as well as between C_M and the PBS since it is a common mode on D_R and D_M.

REFERENCES

[1] S. Schlamminger, "Design of the permanent magnet system for NIST-4," *IEEE Trans on Instrum. and Meas.*,vol.62, no.6, pp. 1524-1530, 2013.

[2] R. Felder, "Practical realization of the definition of the metre, including recommended radiations of other optical frequency standards (2003)," *Metrologia*, vol. 42, no. 4, pp. 323–325, 2005.

[3] http://www.coherent.com/products/?2066/Iodine-Frequency-Stabilization

[4] M. Tanaka, T. Yamagami, K. Nahayama, "Linear interpolation of periodic error in a heterodyne laser interferometer at subnanometer levels," *IEEE Trans on Instrum. and Meas.*,vol.38, no.2, pp. 552-554, 1989.

[5] http://www.b-i-inc.com/Products/TIAs/BI220.aspx