Developing Atomic-resolution Measurements using a Tunable Diode Laser-based Interferometer

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Abstract

A new implementation of a Michelson interferometer capable of resolution on the order of 20 pm has been developed. This new method uses a tunable diode laser as the light source with the diode laser wavelength continuously tuned to fix the number of fringes in the measured optical path. The diode laser frequency is measured by beating against a reference laser. High speed, accurate frequency measurements of the beat frequency signal enables the diode laser wavelength to be measured with nominally 20 pm resolution. The new interferometer design is light weight and has been mounted directly on an ultra-high vacuum scanning tunneling microscope capable of atomic resolution. Most current commercial interferometry techniques are limited in resolution or accuracy due to polarization mixing errors, fringe interpolation limitations and errors, and environmental instability making them unsuitable or very difficult to use for the current measurement applications[1]. In this paper, the new tunable diode laser Michelson interferometer described here addresses this class of measurements and calibrations.

Tunable diode laser-based Michelson interferometer principles

The basic principle of this measurement system is that the output frequency of a tunable diode laser is adjusted so that as the measurement arm of a Michelson interferometer is scanned, there is no movement of the fringe signal[2]. Figure 1 is a schematic of the optical apparatus and measurement and control strategy. The fringe signal arises in this apparatus from a differential measurement of the reference arm signal against the measurement arm signal. To track the laser diode frequency, a portion of the beam is split off and beat against a reference stabilized HeNe laser. This allows the diode laser wavelength to have a direct, unbroken traceability path. The beat frequency signal is logged synchronously with the acquisition of the STM images. This is a homodyne interferometer system and only a single frequency is used in the interferometer portion of the system. The two-frequency portion of the measurement is completely independent of the interferometer and measurement mirrors. In addition no fringe interpolation is required since the measurement is based on the number of fringes in the optical path difference between the reference arm and the measurement arm being held constant.

The calibration of the system is obtained by counting the number of fringes in the optical path difference between the reference and measurement arms. The number of fringes is determined by the wavelength of the diode laser and the path difference. This distance determines the scan range for the interferometer, when no mode hopping is allowed, based on the tunable diode laser range[3,4]. Although mode hopping can be allowed, it is simplest to explain the principle with a fixed fringe measurement. By scanning the diode laser frequency, with a stationary measurement stage, and monitoring its wavelength based on the HeNe reference, the optical path difference can be obtained. This is accomplished by “mapping” a fringe of the differential intensity signal of the interferometer at the bicell detector while scanning the diode laser wavelength. The diode laser frequency is simultaneously beat against the HeNe laser. The bicell intensity signal of one full or half fringe is then plotted against the beat frequency signal. The map of the diode laser wavelength against the bicell detector intensity pattern results in a unique number of wavelengths making up the optical path difference. We discuss the hardware in more detail next.

Figure 2 shows a schematic of the interferometer and its equivalent Michelson interferometer configuration. The measurement mirror is scanned and the reference mirror is fixed to the isolated microscope stage. The beam is polarized at a 45° angle to the vertical. The beam passes through a non-polarizing beam splitter and travels into a birefringent crystal whose optical axes are at 0° and 90° to vertical. The beam is split as one polarization is bent towards the silvered reference mirror and the other travels straight through the crystal to the measurement mirror. The two beams bounce off of the reference and measurement mirrored surfaces and reverse their direction. They travel back through the birefringent crystal and merge to become an elliptical beam at the birefringent crystal surface on exit of the crystal. They are then reflected at 90° in the non-polarizing beam splitter toward another birefringent crystal, which is at a 45° angle to the first birefringent crystal. This crystal is at 45° to mix the two polarization states, which formed the elliptical beam. This incoming beam is split by the second birefringent crystal into two different combined polarization states, each of which lands on the bicell detector. This differential method of measuring the beam intensity improves the signal to noise ratio and allows removal of any DC offsets. This output signal is logged and monitored for use in the control loop for the diode laser output frequency.

The diode laser frequency is continuously controlled to lock to a null point in the fringe signal measured at the bicell detector. As the measurement mirror is scanned, the diode laser frequency is changed to maintain a constant zero in the difference signal between the two polarization states exiting the 45° rotated birefringent crystal. The diode laser is operated with a control frequency of a few hundred hertz. The fundamental limitation is set by the piezo, which controls the frequency of the diode laser, since it has a maximum operation speed of 2 kHz. However, the limiting component in the current configuration is that the time interval analyzer (TIA) used in the frequency measurement cannot be read faster than 800 Hz. For most measurement applications, and with reasonably linear scanning velocities, these values are adequate and in fact go well beyond what our current applications require.

The optical path for the measurement of the diode laser frequency is also shown in Figure 1. A stabilized HeNe laser is used as the reference signal[5]. The tunable diode laser beam is split with a polarizing beam splitter. Half the signal goes to the reference measurement system and the other half goes to the interferometer. The HeNe reference beam and the diode laser beam come together in the reference measurement paths with orthogonal polarization states. The two beams are then mixed so that they interfere and the beat frequency can be monitored. The combined beam goes through lenses and a collimator and is fed to a microwave amplifier and into the TIA. This nominally 2 GHz signal then gives a direct measure of the output diode laser frequency relative to a stabilized HeNe reference signal, which has been appropriately calibrated. The output signal from the TIA is logged by computer in a burst mode with an appropriate trigger to synchronize the TIA data with the STM z height data.

We will now develop the equations to quantitatively evaluate the system performance and optical path difference mapping capability. The tunable diode laser, with a wavelength of nominally 632 nm, is introduced through a polarization-maintaining optical fiber. A portion of the original diode laser power of 3 mW is split off and used for monitoring the beat frequency of the diode laser against reference HeNe laser. As described above, when the optical path difference changes during a measurement, the frequency of the tunable diode laser is continuously controlled so that the number of wavelengths in the varying optical path difference is kept constant. Under this condition with the tuned laser wavelength λ, there is an integer number N of half wavelengths along the optical path difference (or the arm-length difference) ℓ, such that

$$N\frac{\lambda}{2} = n\ell \qquad (1)$$

where n is the refractive index of the air along the optical path difference. For our system when operating in UHV, n is equal to 1.

Under servo control, the fringe signal is locked to a null point (zero crossing). The expansion $\Delta\ell$ of the optical path difference caused by a sample-scan along the x-axis results in a change in wavelength as follows:

$$N = 2\ell/\lambda = 2(\ell+\Delta\ell)/(\lambda+\Delta\lambda) \qquad (2)$$

Equivalently,

$$\Delta\ell = \left(\Delta f/f\right)\ell \qquad ` \qquad (3)$$

and ℓ can be obtained from an independent measurement of the frequency difference between different interference orders under a fixed optical path difference. The laser wavelength is swept while the optical path difference increases by an integer number m of half wavelengths as follows:

$$\ell = N\frac{\lambda_N}{2} = \frac{Nc}{2f_N} = \frac{(N+m)c}{2(f_N + \Delta f_m)} \tag{4}$$

Equivalently,

$$\ell = \frac{mc}{2\Delta f_m} \tag{5}$$

Equation 5 enables the direct mapping or determination of the optical dead path, ℓ, based on measuring the change in frequency required to yield one half cycle of the wavelength. Then, a displacement $\Delta\ell$ is obtained by monitoring the beat frequency between the diode laser and a reference laser. With this arrangement, an increase of 1 GHz in frequency is equivalent to a measurement mirror motion of 32 nm relative to the interferometer birefringent crystal (reference mirror) with a nominal value for ℓ of 14.5 mm. Atomic resolution on the order of 10 pm can be achieved because of the ability to perform highly accurate frequency measurements. The measurable range, 165 nm in this configuration, is roughly estimated by Eq. (3) with the optical path difference (14.5 mm) and frequency range of the counter (5.4 GHz, twofold range for a beat-frequency).

Polarization Mixing

In general, polarization mixing is a source of uncertainty in a fringe interpolation scheme of heterodyne interferometry[6]. The major causes of polarization mixing are the finite extinction ratio of a polarizing beamsplitter and an adjustment imperfection of the polarization axis to the beamsplitter. For the current homodyne Michelson scheme, we are not using heterodyne interferometry and hence there is no polarization mixing error. It is possible, however, that stray light from multiple reflections may disturb the fringe at the detector. The influence of stray light on the current frequency-tracking scheme is under investigation as well as polarization effects due to temperature changes in the birefringent crystals.

Conclusion

A new lightweight interferometer design and tunable diode laser measurement scheme was successfully implemented. The gains over conventional interferometry were outlined and the overall key components in the uncertainty were calculated to be 20 nm. We have preliminarily examined most of the uncertainty components in this system. A more detailed discussion is available[7].

Although the interferometry methodology and system presented here was designed to measure distances such as atomic spacings or linewidths in the 100 nm range, the method can be expanded to measure larger distances. The key in this type of application is to allow mode hopping in the differential measurement of the interferometer bicell detector output. In this case, as the sample is scanned and the diode laser reaches its maximum or a pre-set value, the diode laser frequency is quickly swept back by a defined number of wavelengths. The scanning does not need to stop during this mode hop if the scanning is well behaved and linear. We have examined this method preliminarily and are able to move the diode laser piezo stack at near to 1 kHz, which is the expected limiting element. Consequently, if one allows mode hoping, and keeps track of the number of modes hopped and the change in the optical path difference, significantly larger scanning distances are possible.

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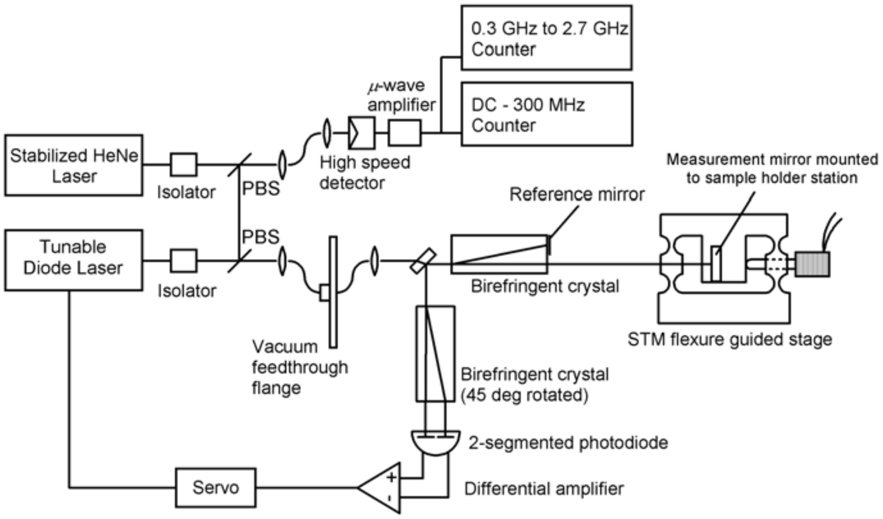
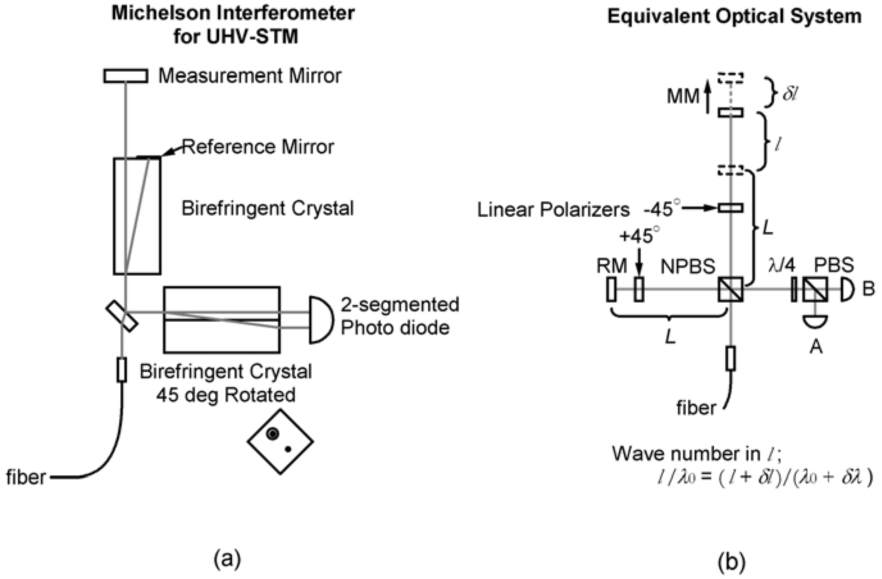


Figure 2. This shows the general methodology for tracking the measurement mirror motion and the general hardware functions. The reference measurement process is also shown between the HeNe and diode laser.



(a)

(b)

Figure 4. This is the interferometer configuration and the equivalent functional Michelson interferometer.