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# Self calibrating wavelength multiplexed heterodyne interferometer for angstrom precision measurements

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# SELF CALIBRATING WAVELENGTH MULTIPLEXED HETERODYNE INTERFEROMETER FOR ANGSTROM PRECISION MEASUREMENTS

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## ABSTRACT

Measurement of refractive index, surface quality and temperature of the process materials in defense, petrochemical, power systems, glass, and metal industries is a fundamental need for precision systems performance. However, making these measurements in a super noisy defense or industrial environment is a big challenge faced by sensor technologies. Reported in this paper is the first ever demonstration of a wavelength multiplexed heterodyne interferometer using a single acousto-optic device (AOD). Heterodyne interferometry is pivotal in realizing a highly stable low noise interferometer. Inspite of the physical separation of the two arms of the interferometer, the sensor demonstrates Angstrom level optical path length sensitivity. The proposed sensor can be used in optical path length measurement-based sensing of parameters such as surface profile, refractive index, temperature, and pressure. Proof-of-concept experiment features a high resolution, low-loss, ultra compact, free space scanning interferometer implementation. Results include measurement of surface quality of a test mirror.

**Keywords:** Acousto-optic Devices, Heterodyne optical interferometers, Optical Sensors, Scanning Interferometers

## 1. INTRODUCTION

Optical Interferometry is a useful tool for a host of applications. These include optical surface characterization, optical sensors, optical path length measurements, and displacement measurements. A number of interferometer configurations are available for different applications [1]. Out of these interferometers, heterodyne interferometers are particularly suitable for high precision displacement or surface roughness measurements in high noise environments. In heterodyne interferometers, common path interferometers are especially tolerant to mechanical vibrations and environmental fluctuations making them suitable for high precision measurements. Another desirable feature for an interferometer is scanning capability. A number of scanning heterodyne interferometers have been proposed including in-line acousto-optic interferometers with high speed scanning features [2]. Application of heterodyne Interferometry for instance in optical path length measurements requires a stable RF reference signal for RF phase comparison via an RF phase meter. Comparing the output RF signal of the heterodyne interferometer with a stable external RF source that optically modulates the interferometer is one solution, although using this external RF signal makes the measurements sensitive to the changing environmental conditions that only effect the RF signal produced by the interferometer.

A preferred solution is to use an internally generated reference RF signal produced via the interferometer optics and RF electronics, thus generating an RF signal whose noise is correlated to the environmental



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conditions. Because the signal RF is also produced by the same interferometer optics and electronics, the signal and reference RFs have correlated noise, a condition to maximize phase detection signal-to-noise ratio in the RF phase meter. Recently, a polarization multiplexed interferometer design was demonstrated to enable internal generation of the reference RF [3]. In this paper, an alternate technique based on wavelength multiplexing in the earlier proposed acousto-optic heterodyne interferometer is used to enable internal RF generation. Specifically, this interferometer uses two different wavelengths to provide the stable self calibrating reference signal and the signal RF. The proposed interferometer uses an acousto-optic Bragg cell in double diffraction reflection geometry to realize a compact instrument. The rest of the paper describes the details of the proposed interferometer.

## 2. THEORY AND DESIGN OF ACOUSTO-OPTIC HETERODYNE INTERFEROMETER

The electric field of an optical wave with a wavelength of λ can be expressed as:

$$E(t,r) = E_{\max} e^{j(2\pi\nu t - k\cdot r)}. \qquad (1)$$

Here $E_{max}$ is the maximum amplitude, ν is the optical frequency, $k = 2\pi n/\lambda$ is the wave vector where n is the refractive index of the medium in which wave is traveling and $r$ is the coordinate axis dependent unit vector of the point in space where the electric field is to be expressed. When comparing two electric fields, it is customary to suppress the space dependency, i.e., $k\sum$ term in one of the electric fields as the coordinate axis can be fixed arbitrarily. Hence an electric field can be expressed as $E_1(t) = E_1 e^{j(2\pi\nu t+\alpha)}$ where α is the optical phase with respect to the reference phase. In general, the light output from an AOD such as in Fig.1 consists of an undiffracted DC beam of magnitude $E_{dc}$ and a +1 order positive Doppler shifted diffracted beam of magnitude $E_d$. Note that the relative amplitude of the two beams can also be controlled by selecting the input beam incident angle on the AOD. The diffraction efficiency of an AOD is given by:

$$\eta = |E_d|^2 / |E_{dc}|^2 = \sin^2(\sigma/2), \qquad (2)$$

where $\sigma \equiv 2\pi\Delta nL/\lambda\cos(\theta_o)$ and L is the length of the acousto-optic interaction and $\theta_o$ is the input beam incident angle. The Doppler shifted +1 order beam can be expressed as $E_d(t) = E_d e^{j(2\pi\nu t + 2\pi f t + \beta)}$ where $f$ is the Radio Frequency (RF) drive frequency of the AOD while β is the relative phase shift with respect to the reference phase. Note that the diffraction efficiency can be made flat over a range of wavelengths by appropriately selecting the parameters of the AOD. For the proposed Fig.1 interferometer design at a given wavelength, the +1 order beam and the DC beam are retro-reflected and pass through the AOD again while preserving the Bragg angle condition. Hence a second deflection takes place and the +1 order beam undergoes double diffraction and becomes in-line with the undiffracted DC beam. This +1,+1 double diffracted beam is given by:

$$E_2(t) = E_2 e^{j(2\pi\nu t + 4\pi f t + \beta)}. \qquad (3)$$

Next, the DC and the double diffracted beams undergo heterodyne detection via a high speed photo-detector. The resultant RF signal is detected by a high speed photodetector and is given by:

$$\begin{aligned} i(t) &\propto |E_1(t) + E_2(t)|^2 = \{E_1(t) + E_2(t)\}\{E_1(t) + E_2(t)\}^* \\ i(t) &= C\left[E_1^2 + E_2^2 + E_1E_2 e^{j(\alpha - 4\pi f t - \beta)} + E_1E_2 e^{-j(\alpha - 4\pi f t - \beta)}\right] \end{aligned} \qquad (4)$$

The first two terms are DC terms and hence can be filtered out as DC bias. Using Eulerís identity, Eq. 4 reduces to:

$$i_f(t) = 2CE_1E_2\cos(4\pi f t + \beta - \alpha). \qquad (5)$$

For the surface characterization application, $\beta - \alpha = 4\pi\Delta d/\lambda$ where Δd is the relative thickness of the test material. This information is encoded in the phase of the detected signal and hence if a lock-in amplifier is used, the phase of the signal can be measured and the optical path length can be determined if a desired RF phase reference is present.

## 3. EXPERIMENTAL DEMONSTRATION OF HETERODYNE INTERFEROMETER

The proposed architecture of the wavelength multiplexed heterodyne interferometer is shown in Fig. 1. Here two laser sources of wavelengths $\lambda_1$ (reference beam) and $\lambda_2$ (signal beam) with orthogonal polarizations are used. A PBS combines these two beams and makes them in-line. Next, these beams pass through a beam splitter (BS) and an AOD that is fed with an RF of *f*. Note that here a broadband operation AOD ensures proper diffraction efficiency across the two wavelengths. The +1 order beams are spatially separated on account of different Bragg angles corresponding to the two different wavelengths. These beams pass through a cylindrical lens and become parallel to each other. The two DC beams and the +1 order reference beam are reflected from a highly flat reference mirror while the +1 order signal beam at $\lambda_2$ is reflected from the test surface. These retroreflected beams traverse back and are double diffracted by the AOD. The undiffracted DC beams and the two double diffracted (+1,+1) order beams are stationary while the two (+1, -1) and undiffracted +1 order beams are spatially blocked. The two in-line { DC, (+1,+1)}beam pairs are deflected first through the BS and then are separated from each other by using a PBS. The reference beam at wavelength $\lambda_1$ is heterodyne detected through high speed photodetector $PD_1$ while the signal beam is detected by $PD_2$. Therefore two signals at a RF frequency of $2f$ are obtained. These two signals are then fed into a lock-in amplifier and the relative RF phase between the two beams is measured. This relative phase shift changes as optical beam scanning in one dimension over the test sample is done by changing the RF drive frequency of the AOD. As the two DC beams and the +1 order reference beam are reflected from a flat surface, these beams do not introduce any additional RF phase shift. However, the +1 order signal beam is reflected from a different point on the surface of the test sample leading to a possible change in relative RF phase shift in the lock-in amplifier. Hence, this measured RF phase information provides metrology data for the surface of the test sample. In addition, the RF amplitude data provides a measurement of the light spatial attenuation characteristics in the sample. Using the full RF frequency range of AOD, a one dimensional surface profile map of the test sample can be generated. For a complete two dimensional map, either the sample or the sample engaging signal beam can be translated in the orthogonal linear dimension.

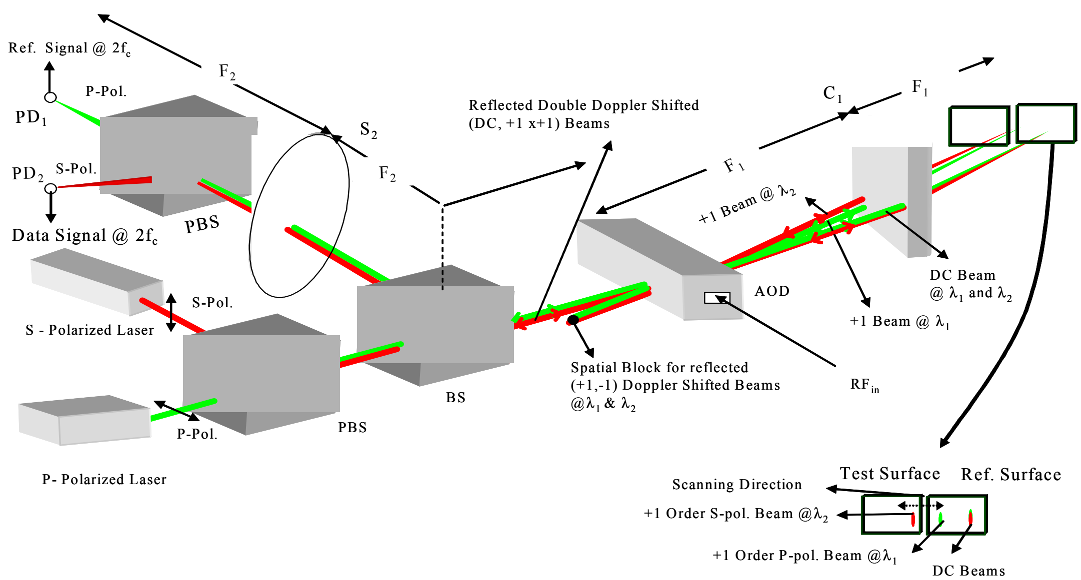


Fig. 1: Proposed wavelength multiplexed acousto-optic scanning heterodyne interferometer with RF self-referencing capability. BS: Beam splitter; PBS: Polarization Beam Splitter; AOD: Acousto-optic Deflector; PD: Photodetector.

As a first demonstration of the proposed internally referenced interferometer concept using wavelength multiplexing, a high flatness mirror is used as a reference surface while a poor flatness quality mirror is used as a test plate. An argon ion laser with a wavelength of 514.5 nm is used as a signal wavelength while a 632 nm HeNe laser is used as the reference wavelength for internal RF reference signal generation. An AOD with a center frequency of 70 MHz and bandwidth of 40 MHz is used for the experiment. Fig. 2 shows the oscilloscope traces of the two detected RF signals. The phase difference is measured using a RF lock-in amplifier SR 844 from Stanford Research Systems with an instrument resolution of $0.02^{o}$. However, in the experiment the fluctuations of the phase readings obtained from the lock-in amplifier amounts to $\pm 0.05^{o}$ which corresponds to an instrument working resolution of $0.1^{o}$ that in turn sets the thickness measurement resolution to 1.4 ≈ for the demonstrated interferometer. The test plate is scanned to get the relative thickness as compared to the 70 MHz reference position on the plate (see Fig. 3). As a laser of 514.5 nm wavelength is used in this experiment, thickness values up-to 514.5/2 = 257.5 nm can be measured using this interferometer.

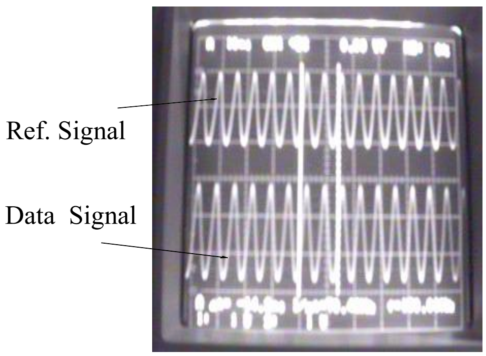


Fig. 2: Oscilloscope traces of the two RF signals @ 70 MHz

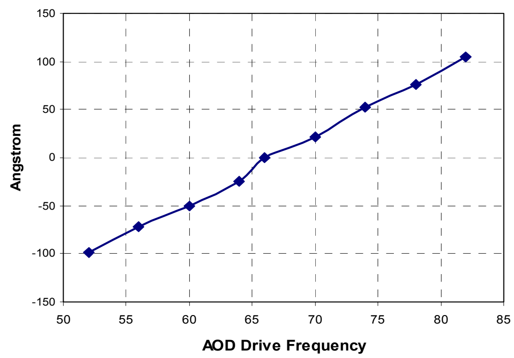


Fig. 3: Relative thickness data of the test plate

## 4. CONCLUSION

In conclusion, a novel wavelength multiplexed heterodyne interferometer has been demonstrated with an Angstrom level sensitivity. The demonstrated interferometer uses a self referencing scheme for highly accurate and reliable surface measurements. Future works relates to the study of noise characteristics and accuracy demonstrations of the instrument.

## REFERENCES

1. P. Hariharan, "Interferometers" in *Handbook of Optics* 2, M. Bass, ed., McGraw-Hill, New York, 1995.
2. N. A. Riza and M. A. Arain, "Angstrom-range optical path-length measurement with a high-speed scanning heterodyne optical interferometer," Appl. Opt., **42**, 2341-2345, (2003).
3. N. A. Riza and M. A. Arain, "Angstrom Sensitivity Polarization Multiplexed Heterodyne Acousto-optic Interferometric Sensor," in proceedings of IEEE Sensors 2004 October 24-27, Vienna, Austria, (Institute of Electrical and Electronic Engineers, New York, 2004).