

Widefield ultrastable heterodyne interferometry using a custom CMOS modulated light camera

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Abstract: A method of detecting optical heterodyne interference fringes using a custom CMOS modulated light camera array has been developed. Widefield phase images are generated using quadrature demodulation and are kept stable using a feedback system.

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1. Introduction

Interferometry is used in a wide variety of fields for instrumentation and analysis of subjects and the environment. Interfering two beams of light will produce fringe patterns. Ultimately, the result sought is the difference in optical path length of beams and is determined by measuring the phase difference. Types of interferometry can be split into two categories, homodyne interferometry uses beams with the same frequency. The phase difference between the beams is calculated using the intensity of the light across the fringe pattern with maximum intensity showing beams being in-phase and minimum intensity revealing beams being π out of phase. However, background optical and electrical noise makes detection difficult. Heterodyne interferometry uses light with different frequencies. The intensity of fringe pattern will now be modulated at a beat frequency, the difference between the two light frequencies. The phase difference can be determined using a local reference signal with the same frequency. Background optical noise and shot noise have a lesser effect on the modulated light. Demodulation of the measured light is done using quadrature demodulation [1]. Past methods of measuring heterodyne interference include using a point detector to scan a pattern at high frequencies [2] and using a CCD camera at low frequencies [3].

Whilst optical and electrical noise have been addressed, mechanical vibrations, still interfere with the measuring process by altering the optical path length difference in the interferometer. Methods such as shifting interferometer components to counteract movement have been developed [4]. This paper will describe a method of creating an ultrastable widefield image using a CMOS modulated light camera and a signal feedback system.

2. Instrumentation

Interfering two beams of light, represented by wavefronts, travelling in the same direction with different frequencies generates a detectable fringe pattern with intensity that is modulated at the frequency equal to the difference in frequency of the wavefronts, the beat frequency f_d , and a constant DC intensity. The detected intensity of the sum of the two wavefronts, $I(x, y, t)$, can be expressed by,

$$I(x, y, t) = I_{dc}(x, y) + A(x, y) \cos(\omega_d t + \phi_d(x, y) + \psi(t)) \quad (1)$$

where $\omega_d = 2\pi f_d$, the constant DC intensity is represented by $I_{dc}(x, y)$ and the amplitude of the modulation is equal to $A(x, y)$. The phase difference of the modulation, $\phi_d(x, y)$, is the same as the difference in phase of the two wavefronts. In practical terms, mechanical vibration will shift the modulation phase by $\psi(t)$. When the wavefronts are interfered, sum and difference intensities as well as intensities at double the original wavefront frequencies and DC intensity components are present, however, the detector used will only detect the DC and difference frequency intensities.

The custom CMOS modulated light camera (MLC), LIDAR1, has a 32×32 active pixel array. Each pixel has a fill factor of 16% and contains a trans-impedance amplifier, Gilbert cells and low pass filters. Previous implementations of the camera included a single test pixel [1] and use of the previous generation of the camera used for LIDAR purposes [5]. Once the detected intensity is amplified, two Gilbert cells are used to mix the detected signal with two separate local reference signals with the same frequency as the beat frequency, f_d , but with a phase difference of 90° .

For a non-ultrastable configuration, a signal generator is used to generate the local reference signals with an amplitude B and a phase $\psi_0(t)$. Mixing the measured signal with the in-phase and quadrature signal produces $I_{\text{outp}}(x, y, t)$ and $Q_{\text{outp}}(x, y, t)$,

$$I_{\text{outp}}(x, y, t) = I_{dc}(x, y)B \cos(\omega_d + \psi_0(t)) + \frac{BA(x, y)}{2} [\cos(2\omega_d t + \phi_d(x, y) + \psi(t) + \psi_0(t)) + \cos(\phi_d(x, y) + \psi(t) - \psi_0(t))] \quad (2)$$

with $Q_{\text{outp}}(x, y, t)$ being similar to $I_{\text{outp}}(x, y, t)$ except using sin instead of cos. After passing through a low pass filter, the resultant outcome can be described by,

$$I_p(x, y) = \frac{BA(x, y)}{2} \cos(\phi_d(x, y) + \psi(t) - \psi_0(t)) \quad Q_p(x, y) = \frac{BA(x, y)}{2} \sin(\phi_d(x, y) + \psi(t) - \psi_0(t)) \quad (3)$$

The Gilbert cells produce a differential output, I_n and Q_n being the negative of I_p and Q_p respectively. The phase can now be determined using,

$$\phi_d(x, y) + \psi(t) - \psi_0(t) = \arctan\left(\frac{Q_d(x, y)}{I_d(x, y)}\right) = \arctan\left(\frac{Q_p(x, y) - Q_n(x, y)}{I_p(x, y) - I_n(x, y)}\right) \quad (4)$$

In a non-ultrastable heterodyne interferometer, $\psi_0(t)$ would remain constant whilst mechanical vibration would change the value of $\psi(t)$, which may be an undesirable element in some experiments. One of the features of LIDAR1 is that it includes an RFout pin for certain pixels. The signal output would be the same as in Eqn. 1. If this is used as the local reference signal instead of using the signal generator output, then $\psi_0(t) = \psi(t)$ for all equations above and would eliminate the effects of mechanical vibrations.

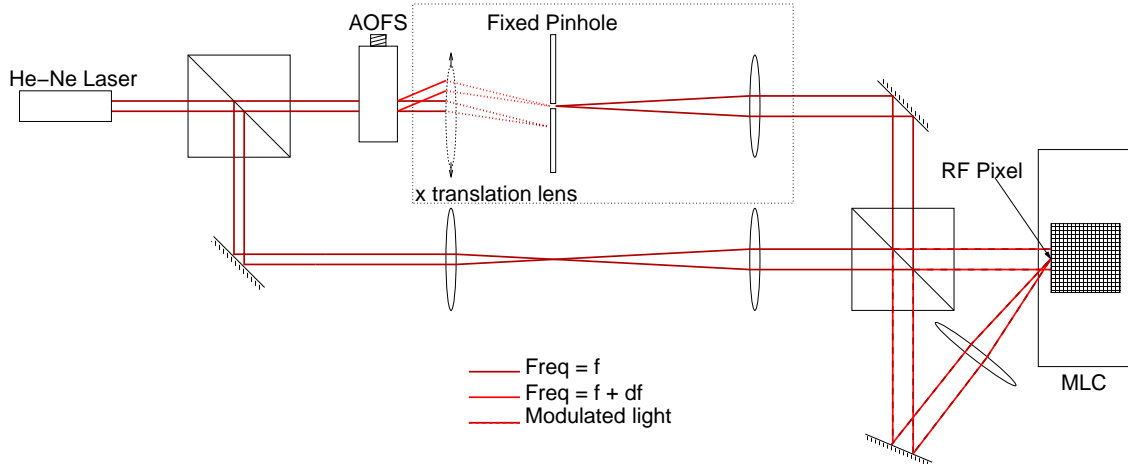


Fig. 1. Modified Mach-Zehnder heterodyne interferometer with homodyne and heterodyne mode switch

The heterodyne interferometer described in this paper is setup in modified Mach-Zehnder configuration, seen in Fig. 1. The light source used is a He-Ne 633nm 10mW laser with a 1mm diameter beam. A relatively large powered laser is used as intensity is lost through the additional modifications to the interferometer. The acousto-optical frequency shifter (AOFS) is used to shift the frequency of light entering it. With an RF signal input, frequency f_d , into the Bragg cell, the device is capable of outputting different orders of light. Each n^{th} order of light has frequency equal to $F_{\text{out}} = F_{\text{in}} + n f_d$, only the 0th and 1st order light are used. The angle of deflection for each order depends on the RF signal input, f_d . The optimum frequency given by the manufacturers of this AOFS is 40MHz however, as mentioned, it is driven at a much lower 15MHz. The modulated light camera, LIDAR1, has a maximum operating frequency of around 70MHz but has an maximum SNR at around 15MHz. A spatial filter is also present in the frequency shifted arm. A pinhole ($\phi = 10\mu\text{m}$) is kept at a fixed position and light from the AOFS is moved by the use of a movable lens so that it passes through this

pinhole. This arrangement allows for preservation of the same spatial phase relationship, $\phi_d(x, y)$, while adjusting the frequency of the Bragg cell and gives the ability of changing from heterodyne to homodyne interferometry mode. The local reference signal, LO, used for demodulation is taken from a RFout pin, the signal detected by the pixel before mixing occurs. The second output from the interferometer is reflected and focused onto this pixel to provide maximum intensity, as seen in Fig. 1. As the phase difference shifts in the light due to mechanical vibrations, so to does this signal.

3. Results

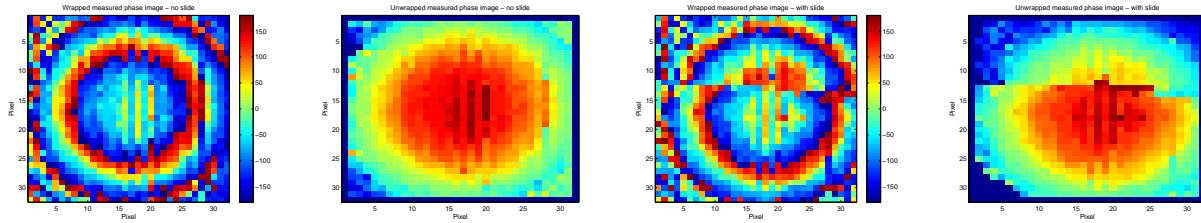


Fig. 2. a) Normal wrapped Fig. 3. b) Normal unwrapped Fig. 4. c) Slide wrapped Fig. 5. d) Slide unwrapped
a) Circular heterodyne fringe pattern captured wrapped, b) unwrapped processed image. c) Heterodyne fringe pattern wrapped image with inserted microscope slide to introduce arbitrary phase shift, d) unwrapped processed image.

Images are taken with the reference beam defocused producing a spherical wave. The exit lens of the reference arm is moved 5mm closer to the entrance lens. An interference pattern of a spherical wave on an uniform plane wave results in a circular fringe pattern being generated. The heterodyne fringe patterns are captured and processed with the centre circle present. With images being captured in real time, vibrations imposed on the apparatus does not change the phase captured by the MLC outside the effects of noise, which can be reduced by averaging pixel data over time. Phase images are displayed wrapped, with the unwrapped image processed after. The fringe pattern (phase range -180° to 180°) can be seen in Fig. 2 with an unwrapped image seen in Fig. 3. An image is also captured with an introduced arbitrary phase shift. A microscope slide is placed halfway across the reference arm beam. The resultant image (phase range -180° to 180°) can be seen in Fig. 4 with an unwrapped image seen in Fig. 5.

4. Conclusion

A method of acquiring ultrastable heterodyne widefield interference pattern images has been discussed along with the experimental setup and details on generating heterodyne interference patterns. The custom CMOS modulated light camera, LIDAR1, is used to detect the intensity on each pixel, amplify then quadrature demodulate using a local reference signal. Certain pixels on the camera can also output the signal pre-demodulation. Using this signal as the reference signal, phase shifts in the detected intensity due to mechanical vibrations are cancelled out.

References

1. P. Dmochowski, B. Hayes-Gill, M. Clark, J. Crowe, M. Somekh, and S. Morgan, "Camera pixel for coherent detection of modulated light," *Electronics Letters* **40**, 1403 – 1404 (2004).
2. N. A. Riza and M. A. Arain, "Angstrom-range optical path-length measurement with a high-speed scanning heterodyne optical interferometer," *Applied Optics* **42**, 2341 – 2345 (2003).
3. F. G. Cervantes, G. Heinzl, A. F. G. Marin, V. Wand, F. Steier, O. Jennrich, and K. Danzmann, "Real-time phase-front detector for heterodyne interferometers," *Applied Optics* **46**, 4541 – 4548 (2007).
4. W. Lehmann, P. Gattinger, M. Keck, F. Kremer, P. Stein, T. Eckert, and H. Finkelmann, "Inverse electromechanical effect in mechanically oriented sc*-elastomers examined by means of an ultra-stable michelson interferometer," *Ferroelectrics* **208**, 373 – 383 (1998).
5. D. Summers, M. Clark, I. Stockford, S. Achamfuo-Yeboah, and J. Pereira Do Carmo, "Modulated light camera for space applications and assessment via a test bench system," *Acta Astronautica* **66**, 1399 – 1403 (2010).