Widefield two laser interferometry

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Abstract: A novel system has been developed that can capture the widefield interference pattern generated by interfering two independent and incoherent laser sources. The interferograms are captured using a custom CMOS modulated light camera (MLC) which is capable of demodulating light in the megahertz region. Two stabilised HeNe lasers were constructed in order to keep the optical frequency difference (beat frequency) between the beams within the operational range of the camera.

This system is based on previously reported work of an ultrastable heterodyne interferometer [Opt. Express **20**, 17722 (2012)]. The system used an electronic feedback system to mix down the heterodyne signal captured at each pixel on the camera to cancel out the effects of time varying piston phase changes observed across the array. In this paper, a similar technique is used to track and negate the effects of beat frequency variations across the two laser pattern. This technique makes it possible to capture the full field interferogram caused by interfering two independent lasers even though the beat frequency is effectively random.

As a demonstration of the system's widefield interferogram capture capability, an image of a phase shifting object is taken using a very simple two laser interferometer.

OCIS codes: (100.3175) Interferometric imaging; (110.3175) Interferometric imaging.

References and links

1. J. H. Bruning, D. R. Herriott, J. E. Gallagher, D. P. Rosenfeld, A. D. White, and D. J. Brangaccio, "Digital wavefront measuring interferometer for testing optical surfaces and lenses," Appl. Opt. **13**, 2693–2703 (1974).
2. M. Takeda, H. Ina, and S. Kobayashi, "Fourier-transform method of fringe-pattern analysis for computer-based topography and interferometry," J. Opt. Soc. Am. **72**, 156–160 (1982).
3. N. A. Massie, R. D. Nelson, and S. Holly, "High-performance real-time heterodyne interferometry," Appl. Opt. **18**, 1797–1803 (1979).
4. R. Dandliker, R. Thalmann, and D. Prongue, "Two-wavelength laser interferometry using superheterodyne detection," Opt. Lett. **13**, 339–341 (1988).
5. M. Akiba, K. P. Chan, and N. Tanno, "Real-Time, micrometer depth-resolved imaging by low-coherence reflectometry and a two-dimensional heterodyne detection technique," Jpn. J. App. Phys. **39**, 1194–1196 (2000).
6. S. Bourquin and V. Monterosso and P. Seitz and R. P. Salathe, "Video-rate optical low-coherence reflectometry based on a linear smart detector array," Opt. Lett. **25**, 102–104 (2000).
7. M. C. Pitter, C. W. See, and M. G. Somekh, "Full-field heterodyne interference microscope with spatially incoherent illumination," Opt. Lett. **29**, 1200–1202 (2004).
8. A. Kimachi, "Real-time heterodyne speckle pattern interferometry using the correlation image sensor," Appl. Opt. **49**, 6808–6815 (2010).
9. R. Patel, S. Achamfuo-Yeboah, R. Light, and M. Clark, "Widefield heterodyne interferometry using a custom CMOS modulated light camera," Opt. Express **19**, 24546–24556 (2011).

10. G. Scarcelli, A. Valencia, and Y. Shih, "Two-photon interference with thermal light," in Quantum Electronics Laser Science Conference (QELS) **1**, 292–294 (2005).
11. D. T. Pegg, "Interference of light from independent sources," Phys. Rev. A **74**, 063812 (2006).
12. Z. Y. Ou, "Multi-photon interference and temporal distinguishability of photons," Int. J. Mod. Phys. B **21**, 5033–5058 (2007).
13. H. Paul, "Interference between independent photons," Rev. Mod. Phys. **58**, 209–231 (1986).
14. G. Magyar and L. Mandel, "Interference fringes produced by superposition of two independent maser light beams," Nature (London) **198**, 255–256 (1963).
15. F. Louradour, F. Reynaud, B. Colombeau, and C. Froehly, "Interference fringes between two separate lasers," Am. J. Phys **61**, 242–245 (1993).
16. L. Basano and P. Ottonello "Interference fringes from stabilized diode lasers," Am. J. Phys **68**, 245–247 (2000).
17. T. Kawalec and D. Bartoszek-Bober, "Two-laser interference visible to the naked eye," Eur. J. Phys. **33**, 85–90 (2012).
18. R. Patel, S. Achamfuo-Yeboah, R. Light, and M. Clark, "Ultrastable heterodyne interferometer system using a CMOS modulated light camera," Opt. Express **20**, 17722–17733 (2012).
19. S. J. Bennett, R. E. Ward, and D. C. Wilson, "Comments on: frequency stabilization of internal mirror he-ne lasers," Appl. Opt. **12**, 1406–1406 (1973).
20. C. L. Tang and H. Statz, "Nonlinear effects in the resonant absorption of several oscillating fields by a gas," Phys. Rev. **128**, 1013–1021 (1962).

1. Introduction

In a conventional interferometer, light from one source is split and recombined to produce an interferogram. The interferogram can then be processed in order to derive the optical phase difference between the interfering light, and this can be used to determine the relative optical path length (OPL) at each point in the interferogram.

If the recombined light has the same optical frequency (homodyne interferometry), a static, time invariant intensity pattern is produced. In order to determine the optical phase, a method such as phase-stepping [1] or fringe analysis [2] is required.

In heterodyne interferometers, a frequency shift is introduced into at least one of the beams, producing a time varying intensity pattern that is temporally modulated at the difference frequency between the two beams [3, 4]. The optical phase can be extracted by electronically mixing down the detected signal using an external electronic reference signal (frequency equal to the optical difference frequency), allowing for direct determination of phase without further steps. This arrangement is usually only used in single point interferometers due to the practical challenges associated with capturing widefield time varying fringe patterns. However some systems have been developed to capture real time heterodyne interference patterns in the widefield region at modest modulation frequencies [5–9]. In a previous paper [9], we demonstrated that this could be accomplished for the widefield in the megahertz frequency range using a prototype modulated light camera (MLC).

In conventional homodyne or heterodyne interferometers, the visibility of the fringe pattern is assured as long the OPL difference between the arms is less than the coherence length of the source. The frequency stability of the single light source is not much of issue; if the optical frequency changes at the source, the frequency difference at the point of interference does not.

When light from two different sources are interfered, a heterodyne interference pattern is produced. However, this pattern has a modulation frequency that is unknown and randomly varying; due to this changing frequency, it is challenge to capture a stable interferogram. As the time average fringe visibility will equal zero, the light from the two sources can be considered mutually incoherent. There has been much discussion in the production and capture of the interference pattern generated from using two separate light sources [10–12], with a comprehensive analysis of the phenomenon explored by Paul [13].

Experiments conducted by Magyar and Mandel [14] proved that interference fringe patterns could be generated using two separate optical sources. Over a short enough observation time

(noted as less than the coherence time of the source), fringe patterns could be viewed as being static and therefore imagable. Later experiments conducted improved upon the fringe pattern visibility [15]. By stabilising the centre frequency of the light sources, the duration of a visible pattern could be extended [16]. A method incorporating the measurement of the instantaneous beat frequency and a phase lock-loop (PLL) to control the optical frequency through feedback, can also be implemented for long term visible (e.g. at DC) fringe pattern generation [17]. However, these techniques require feedback from the point of interference to the lasers, potentially limiting the range of applications.

In this paper, we extend the work previously presented on a widefield ultrastable heterodyne interferometer system [18], which used a prototype MLC to capture stable interferograms using signal feedback. In this system, the arrangement is modified to continuously capture a stable interference pattern generated by two independent sources. The system uses two independently frequency stabilised HeNe lasers. Ordinarily, the frequency of each emitted mode varies over time (i.e. due to heat fluctuations). To limit this frequency change, a simple frequency stabilisation mechanism, designed to hold the optical frequency stable [19] (typical frequency variation of $\sim 2\,\mathrm{MHz}$ over 10 minutes), is implemented in each laser. The optical signal measured at one pixel of the MLC, made available at the chip output, is used to demodulate the signals at all the other pixels. Consequently, the system is able to capture an interferogram so long as the sources are spatially coherent and the typical variation of the frequency difference between the lasers does not exceed the detection bandwidth of the MLC.

2. Instrumentation

The interferometer system uses a custom 32×32 CMOS camera (MLC) that employs quadrature demodulation to extract phase information from a captured heterodyne interferogram. Each pixel contains a photodiode, transimpedance and operational amplifiers, two Gilbert cell mixers, low pass filters and column/row read electronics. A simple pixel schematic is shown in Fig. 1. The size of the array was limited by the modest fabrication budget and but could be much larger for a commercial device.
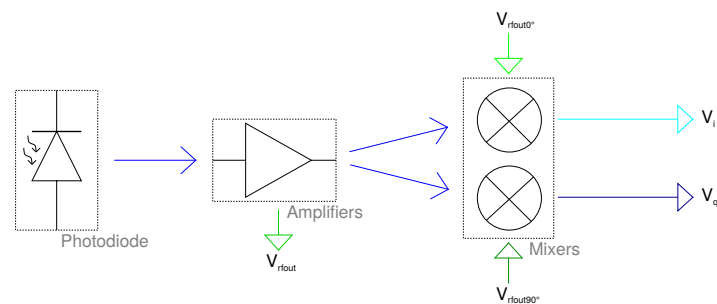

Fig. 1: A simple flow schematic of a MLC pixel. The modulated optical signal is amplified, mixed (with reference signals) and output (when the pixel is selected) continuously. Two laser interferograms appear stable as long as the beat frequency is within the system operational bandwidth, which is dependent on the amplitude/phase/frequency response of the individual components in each pixel. Further details on the MLC is available in a previous publication [9].

Special pixels in the MLC (RFout pixel) are capable of outputting the raw detected (modulated) signal of the incident light. By using the measured signal at one of these pixels as

the reference signal for demodulation, a relative fringe pattern image can be generated across the camera, even in the presence of large piston phase change [18]. Consequently, the camera tracks changes in temporally varying phase seen across the entire camera array and cancels out this effect in the output interferogram image. By adapting this system, we have been able to demonstrate a continuous widefield two laser interferometer.

The optical arrangement, shown in Fig. 2, simply combines the light from the two independent sources. In the arrangement, a beamsplitter and collimating lenses are used to produce a compact system, and polarisers are used to adjust for any differences in polarisation between the two lasers.
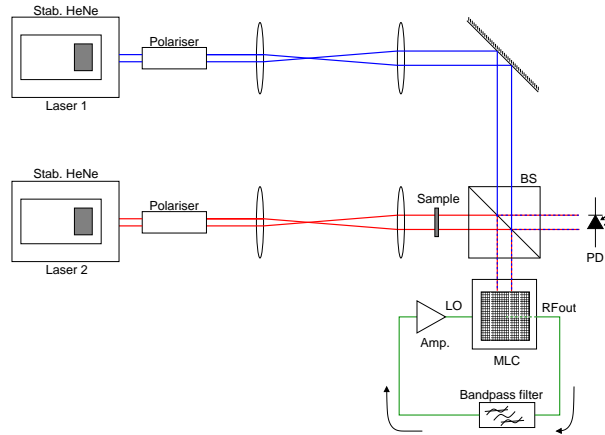

Fig. 2: The two laser interferometer system. Each laser is completely independent with separate power supply units and heated using individual tube coiling, and are aligned separately. Polarisers are used to adjust the polarisation plane, improving fringe visibility. The monitoring photodiode is used to keep track of the beat frequency. The MLC uses the signal generated by one pixel to mix with the detected signal at all other pixels, tracking any changes in frequency and phase relative to that single pixel. Filters and amplifiers are used to clean up the signal before it is used as the reference signal.

3. Operational principle

With a fringe pattern incident on the MLC array, the electronic signal takes two paths in this setup;

Phase information output: The light detected by the photodiode generates a photocurrent, which is converted to a voltage and amplified by the transimpedance amplifier, V_{pixel}; this signal follows the instantaneous intensity at the pixel. V_{pixel} is then mixed with reference signals in the two mixers and filtered, before being read-out. All the pixels operate in parallel, with the nominal bandwidth of the camera equal to $\sim$15 MHz, but this can be extended.

Reference signal: Special pixels in the camera have additional electronics to allow V_{pixel} to be directly output. This signal is filtered and amplified (V_{rfout}), and phase split to give the reference signals.

Each of the signals across the array and the single point feedback signal have a DC voltage offset, $V_{\mathrm{dc\,x,y}}$, $V_{\mathrm{dc\,0}}$, and a time varying component with a peak amplitude, $V_{\mathrm{mod\,x,y}}$, $V_{\mathrm{mod\,0}}$;

$$
\begin{aligned}
V_{\mathrm{pixel}} &= V_{\mathrm{dc\,x,y}} + V_{\mathrm{mod\,x,y}}.\sin(\omega_{\mathrm{x,y,t}}t + \phi_{\mathrm{x,y}}) \\
V_{\mathrm{rfout}} &= V_{\mathrm{dc\,0}} + V_{\mathrm{mod\,0}}.\sin(\omega_{0,\mathrm{t}-\tau}t + \phi_0)
\end{aligned}
\tag{1}
$$

The beat frequency of the detected pattern, $\omega_{\mathrm{x,y,t}}$, is unknown and varying. Given that interfering beams are sufficiently spatially coherent, the same beat frequency is detected on all pixels; this includes the signal detected at the feedback pixel. As the feedback signal propagates through the amplifiers/filters/connection leads, a delay is introduced into the signal. However, in this setup the delay is negligible, such that $\omega_{0,\mathrm{t}-\tau} = \omega_{\mathrm{x,y,t}}$.

The feedback signal is phase split, which produces an in-phase signal, $V_{\mathrm{rfout\,0°}}$, and a 90° out-of-phase signal, $V_{\mathrm{rfout\,90°}}$. Each reference signal is fed to one of the two in-pixel mixers (i.e. as local oscillators). Phase information of the incident modulated light is output continuously through mixing them with the measured signal (V_{pixel}), which produces an in-phase, V_{i}, and quadrature phase, V_{q}, outputs. Each input has its DC component stripped before mixing, and the output is low pass filtered ($<2\,\mathrm{kHz}$) in-pixel.

$$
\begin{aligned}
V_{\mathrm{i}} &= V_{\mathrm{pixel}}.V_{\mathrm{rfout\,0°}} = V_{\mathrm{mod\,x,y}}.V_{\mathrm{mod\,0}}.\sin(\phi_{\mathrm{x,y}} - \phi_0) \\
V_{\mathrm{q}} &= V_{\mathrm{pixel}}.V_{\mathrm{rfout\,90°}} = V_{\mathrm{mod\,x,y}}.V_{\mathrm{mod\,0}}.\cos(\phi_{\mathrm{x,y}} - \phi_0)
\end{aligned}
\tag{2}
$$

The product of the mixers using the reference signal is independent of the randomly varying modulation frequency as the frequency components are cancelled out. The phase component is mixed down to DC which contains the interferogram information. A phase image can be constructed using Eqn. 3;

$$
\phi_{\mathrm{x,y}} = \mathrm{atan}\left(\frac{V_{\mathrm{i}}}{V_{\mathrm{q}}}\right) - \phi_0
\tag{3}
$$

The output contains the phase offset measured at the RFout pixel (ϕ_0), however this can be removed as needed. As long as the optical frequency difference between the lasers are within the operational frequency range of the MLC, two laser interferograms can be captured continuously.

4. Independently stabilised lasers

The large amount of bandwidth flexibility that the MLC provides allows for the two lasers used for interfering to be stabilised independently.

The HeNe lasers used were constructed in-lab using cheap readily available parts. They are based on an updated design of one presented by Bennett et al. [19]. Figure 3 shows a diagram of the feedback stabilisation system used in each laser.

The system involves using a HeNe laser tube with a cavity length chosen so that only two longitudinal modes are emitted (i.e. two modes within the gain bandwidth curve). A property of these HeNe lasers is that each set of two emitted longitudinal modes are linearly polarised and perpendicular to each other [20]. Both modes are emitted through the main exit (front of the tube), but also through the waste exit (rear of the tube) where they are separated using a polarising beamsplitter. As the optical frequency of each mode fluctuates (e.g. due to temperature), their intensities change according to the gain bandwidth curve; the power outputs of each mode are measured and compared using photodiodes and a comparator circuit. The output of
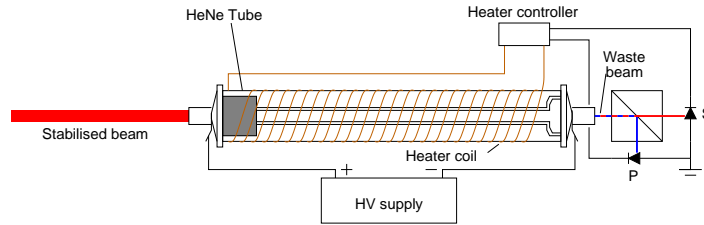
Fig. 3: Stabilised laser system. Each HeNe laser outputs two longitudinal modes which are orthogonally polarised. As the tubes expand and contract (e.g. due to temperature), the optical frequency and intensity of these modes shift. The intensities are detected at the waste exit and compared; the current into the tube coiling is adjusted, which generates heat and changes the tube length. This feedback system is used to maintain a constant frequency for each mode.

the circuit is fed back into a current controlled heater coil around the laser tube; the length of the tube is maintained to produce a stabilised optical frequency.

The lasers constructed have a laser gain bandwidth of $\sim$650 MHz and the power varies between 0.4 mW and 1.2 mW (especially during initial warm up). Measuring the beat frequency gives a good indication of the stability of the lasers with respect to each other. After the initial warm up, the maximum beat frequency stability was measured to be $\sim$2 MHz over 10 minutes and $\sim$5 MHz over 30 minutes. In this experiment the lasers were situated on the same optical bench, but as they are independent (with no feedback between them), they can be separated by a significant distance.

5. Results

The two laser interferometer (schematic shown in Fig. 2) was constructed to capture test fringe patterns and to perform a simple phase characterisation experiment. A photograph of the interferometer setup is shown in Fig. 4.
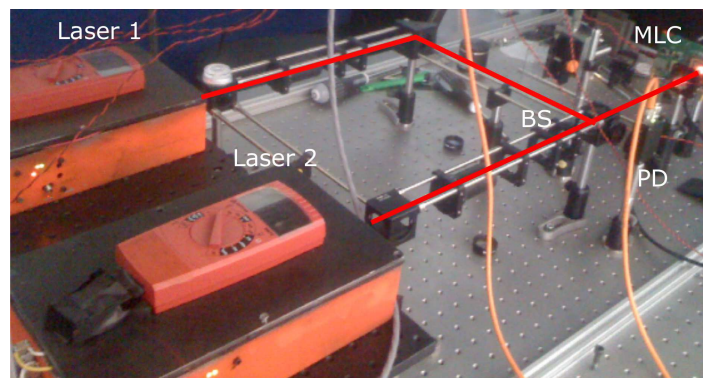

Fig. 4: A photograph of the two laser interferometer system showing that each laser source is independent and the simplicity of the system.

Similar to the previous implementations of this system, the MLC is controlled using a 16-bit ADC card under PC control. With this arrangement, the maximum frame read rate is $\sim$40 fps.

The MLC has been shown to have a phase measurement accuracy of $\pm 6.6°$ [9, 18].

Before conducting the experiments, the lasers were allowed to stabilise. The stabilisation system allows for manual frequency tuning, and an offset voltage is applied to the comparator circuit to ensure that the beat frequency is set to a point within the MLC operation bandwidth. However, as the lasers are not locked together, the beat frequency drifts over time. The interferometer was adjusted to produce a horizontal fringe pattern on the MLC.

A set of phase images, shown in Figs. 5(a)–5(c), were captured with an interval of 60 seconds. The corresponding FFT plot of the beat signal measured on the monitoring photodiode (Fig. 2) at each interval is shown in Figs. 5(d)–5(f). Over the three minutes, the beat frequency fluctuates with a overall decrease in frequency, however, the same relative fringe pattern was captured over this time. To show the system's ability to measure phase change due to a change in OPL, a microscope slide was placed part way through one beam path (shown as the sample in Fig. 2). In figure 6(a), the captured image is shown, with an unwrapped version of the image shown in Fig. 6(b) and a difference image (with a slide-less control image) shown in Fig. 6(c). The normalised image in Fig. 6(c) shows the phase shift induced by the microscope slide across a widefield area in real time on the right section of the image, while the left section remains constant (where no slide is present).
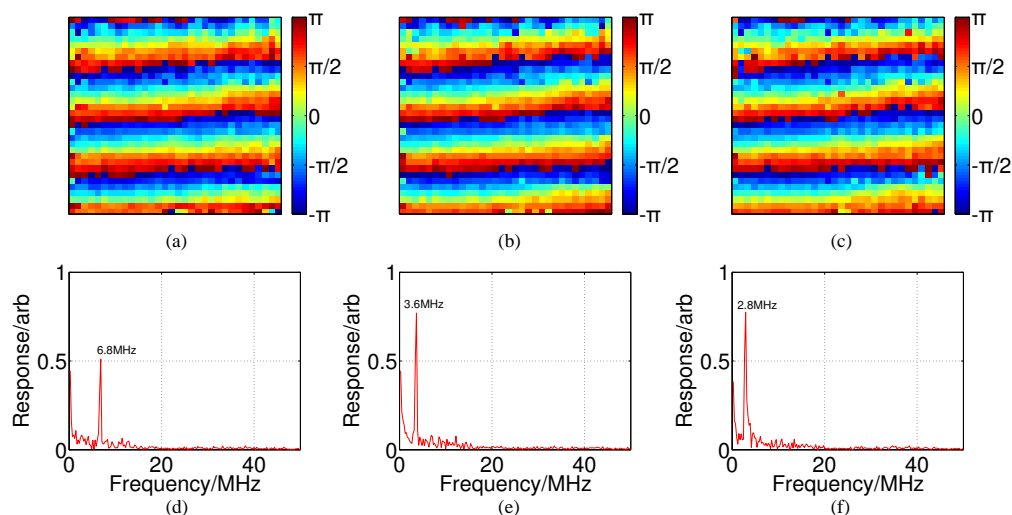

Fig. 5: The images of interference fringe patterns generated using two lasers. Image (a), (b) and (c) show the captured fringe pattern. Colour represents radians. The beat signal is also recorded at the point of each image capture and an FFT is conducted on the snapshot beat signal waveform, shown in plots (d), (e) and (f). Even though this beat frequency varies, the interferometer system compensates and outputs the same relative fringe pattern.

The interferogram is completely stable even as the instantaneous beat frequency varies, so long as the beat frequency stays within the bandwidth of the MLC. The 'fringe visibility' decreases outside of this bandwidth due to the MLC's reduced gain. The position of the fringes also changes as the (normally flat) phase response of the electronics changes.

An interesting point to note is that the relative pattern is only maintained so long as the absolute frequencies of the lasers do not cross over. If they do, the sign of beat frequency becomes inverted, which results in the sign of the phase being inverted (but otherwise the interferogram
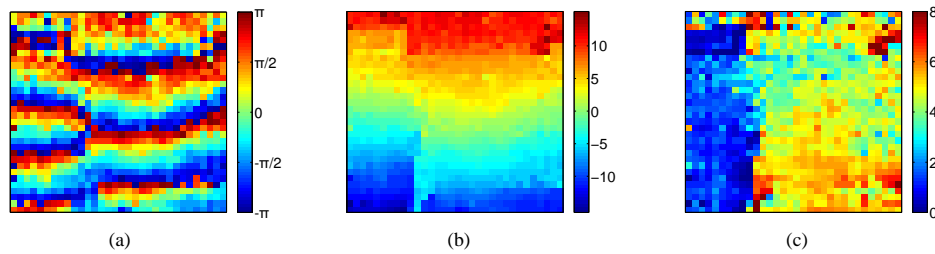
Fig. 6: Figure (a) shows the captured fringe pattern generated by interfering two lasers with a microscope slide introduced part way (right of image). Figure (b) shows the image after an unwrapping process. Figure (c) shows the difference between the exposed and unexposed images (after normalisation and unwrapping). Colour represents radians.

is unchanged). Practically, this is avoided by setting the lasers up with a difference frequency in the middle of the MLC's bandwidth.

6. Discussion and conclusion

A heterodyne widefield interferometer has been presented that captures interferograms produced by two independent and incoherent light sources. The system produce images in real-time. The light sources used are frequency stabilised HeNe lasers using a simple intensity-to-heater feedback circuit; the stabilisation technique has no dependence on the other laser. The widefield detector used to capture the heterodyne fringe patterns is a prototype custom CMOS modulated light camera, which was used and analysed in previous work [9, 18]. The MLC uses quadrature demodulation, mixing the detected signal (on every pixel) with a reference signal. In this implementation, the reference was derived from the detected signal on one of the pixels at the centre of the array, effectively cancelling out the effect of the varying unknown beat frequency from the output image. Another way to look at this is that this arrangement produces a reference signal that tracks the instantaneous difference frequency so that the mixers always mix down the instant interferogram to DC which is then output by the MLC.

From a practical point of view, this two laser interferometer system has some advantages over the conventional split source interferometer. As a minimum, a two laser interferometer requires only the light sources and a detector in order to make OPL measurements. This could lead to cheaper systems (assuming mass production of the prototype MLC) as well as, simpler arrangements (reducing alignment issues).

It can be assumed that the instantaneous beat frequency will be shifting between individual pixel reads, or even as a single pixel is being read. This system is able to output stable widefield images under these conditions. This leads to a relaxation of the temporal coherence limitation present in conventional interferometers and instead have the condition that the instantaneous beat frequency between the lasers remain within the operation bandwidth of the MLC (and feedback filters).

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