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Ultra-Sensitive Focused Laser Differential Interferometer Using Balanced Detection

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Balanced detection is demonstrated to be a simple method for achieving shot-noise limited measurements with a focused laser differential interferometer (FLDI). Both polarization components of the signal beam are separately detected, and differential amplification of the two signals cancels common-mode laser-intensity noise. An ultrasonic source is used to provide a reference signal to compare measurements made by a conventional FLDI with those from the modified instrument. Balanced detection is shown to improve the signal-to-noise ratio by 30 dB and demonstrated to achieve shot-noise limited measurements.

The focused laser differential interferometer (FLDI) invented by Smeets [1, 2] has become a standard tool for interrogating fluid flows in many aerospace research facilities. The instrument enables measurement of density fluctuations with high spatial and temporal sensitivity while remaining remarkably insensitive to ambient vibration and facility boundary layers. See reference [3] for a recent review of prior work on FLDI, and see reference [4] for a detailed description of typical methods and modeling. As an interferometer, FLDI is sensitive to density fluctuations, and consequently signal amplitudes are directly proportional to the fluid density. Hypersonic flow research facilities like expansion tubes often generate low-density flows for which signals can be weak. Signal-to-noise ratio (SNR) is limited in most FLDI implementations by residual intensity noise in the laser. Consequently, eliminating laser noise has been identified as a major avenue for improving FLDI measurements in these research facilities [4, 5]. The present study builds on the past work using a variation of the configuration developed by Smeets to examine the specific issue of reducing laser and instrumentation noise using balanced detection.

Methods to eliminate laser intensity noise include heterodyne interferometry and laser-noise canceling techniques, like the balanced detection method employed by Smeets in his initial demonstrations [1]. Balanced detection uses either subtraction or division of two signals to cancel common-mode noise. Several auto-balancing circuits are presented and described in detail by Hobbs [6], and some balanced detectors are commercially available. Here, a simple construction is employed for balanced detection using two reverse-biased photodiodes and a low-noise differential amplifier. Balanced detection has been implemented in FLDI by recent investigators [7, 8], where improvement to SNR was highlighted, however the performance of balanced detection was not investigated in detail or quantified. The purpose of this Letter is to demonstrate and quantify the greatly improved sensitivity attainable with this simple modification to the FLDI.

Figure 1 shows the optical construction used to implement balanced detection with an FLDI. The key difference between this setup and a conventional FLDI is that the signal beams are interfered in a polarizing beam splitter (PBS) instead of with a linear polarizer. The first quarter-wave plate (QWP) is used to generate circularly polarized light, enabling Wollaston prism 1 (WP1) and therefore the foci pair to be oriented at any angle in the xy-plane. WP2 recombines the beams, and the second QWP allows the analyzer to again be oriented at any angle relative to the foci pair. This is essential for employing a PBS as an analyzer, since the PBS is most conveniently aligned parallel to the optical bench. This construction is similar to both those used in prior work [7, 9]. From the advice given by Hobbs [6], a linear polarizer (LP1) was placed at the laser output. This was found to be important for achieving good noise cancellation. The laser used in this work was a 50 mW, 532 nm Coherent Sapphire SF.

Photocurrents from the two reverse-biased photodiodes (Thorlabs DET10A) were converted to voltage signals through external 500 Ω terminations. From datasheet specifications, the detector bandwidth is estimated to be 35 MHz, far greater than the frequencies relevant to this work. The signal from a single detector is equivalent to that obtained with a conventional FLDI, where typical methods would be to align the interferometer at half-fringe and AC couple the signal to a digitizer [4]. Instead, the signals from the two detectors in this setup were subtracted in a low-noise differential amplifier (Stanford Research SR560), which has a common-mode rejection ratio of 90 dB at 1 kHz that decreases 20 dB/decade. The differential signal was balanced by adjusting WP2 and then amplified using the maximum viable gain setting given the input signal amplitude. The digitizer used

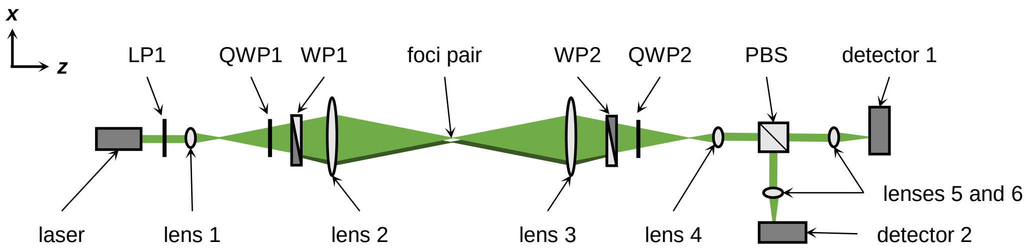

Fig. 1. Schematic for FLDI modified to implement balanced detection. Abbreviated element names refer to linear polizer (LP), quarter-wave plate (QWP), Wollaston prism (WP), and polarizing beam splitter (PBS).

in this work was a Tektronix MSO44B.

The voltage signals outputted by the two terminated photodiodes can be modeled by

$$v_1 = \frac{A}{2}(B - \sin(\phi)) + v_{RIN} + v_S + v_J \, , \qquad (1)$$
$$v_2 = \frac{A}{2}(B + \sin(\phi)) + v_{RIN} + v_S + v_J \, .$$

The Jones calculus necessary to derive the phase response is not included here but is given by Settles and Fulghum [7]. Here, ϕ is the differential phase measured by the FLDI, and A and B are calibration factors, found from the fringe-shift amplitude and mean. v_{RIN}, v_S, and v_J are the contributions from residual laser intensity noise, shot noise, and thermal Johnson noise. The ratio of shot noise power and thermal noise power is given by

$$\frac{v_S^2}{v_J^2} = \frac{Rei}{2k_BT} \, , \qquad (2)$$

where R is the termination resistance, e is the charge of an electron, i is the photocurrent, k_B is the Boltzmann constant, and T is the resistor temperature. In a typical setup used in this work $i = 2.18$ mA, so that from Eq. (2) the shot noise exceeds thermal noise by 13 dB and so can be neglected. SNR is typically limited by the laser intensity noise, however this noise in the optical intensity produces the same noise currents in both photodetectors. Consequently, this common-mode signal can be eliminated in a differential amplifier. The signal obtained from differential amplification of Eq. (1) is

$$v_d = G(A\sin(\phi) + 2v_S) \, , \qquad (3)$$

where G is the gain. Both the digitizer and amplifier can contribute significant noise to the final signal, however these noise sources can be made negligible using sufficient amplifier gain. Eq. (3) shows that SNR is shot-noise limited, and so it can be further increased by increasing the laser power.

To illustrate the performance of this setup, an ultrasonic transducer was used to generate a weak reference signal at 100 kHz. Signal acquisition parameters were varied, and Figure 2 shows a comparison between the resulting FLDI signals. (a) shows a single FLDI channel (i.e., from one detector) with unity gain, equivalent to the signal produced by a conventional FLDI. (b) shows the effect of amplifying the single AC-coupled signal; a significant improvement upon (a), because the signal is amplified out of the digitizer's noise floor. Noise in (b) is residual laser intensity noise. (c) shows the differential signal for unity gain, i.e., without amplification and therefore additional noise from the digitizer. Finally, (d) shows the signal obtained with differential amplification, a remarkable improvement upon the conventional measurement in (a).

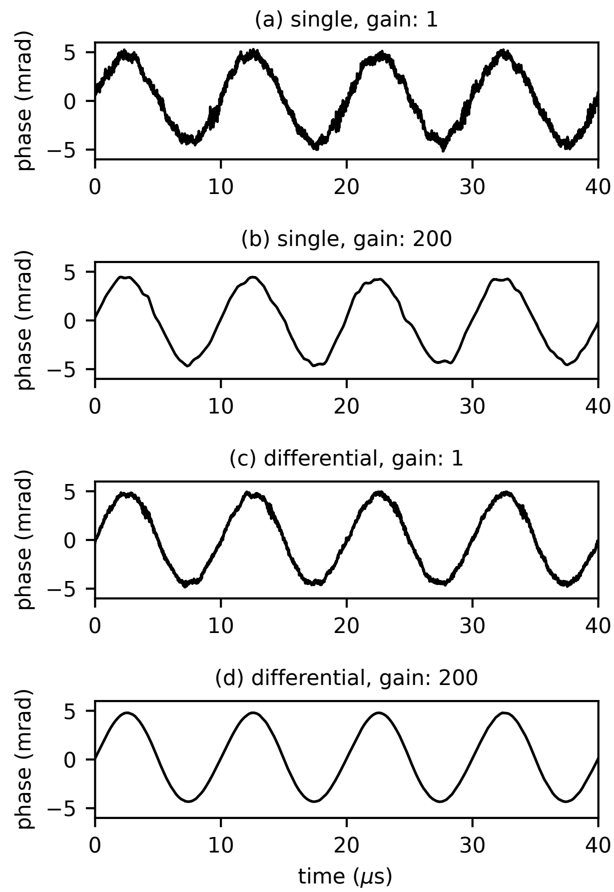

Fig. 2. Comparison of signals obtained using FLDI with balanced detection and differential amplification. (a) shows the signal obtained from a conventional FLDI.

Power-spectral densities (PSD) for the four cases above are estimated using Welch's method [10] and plotted in Figure 3. Amplification of the AC-coupled single-ended signal reduces significant high-frequency noise, but laser noise still dominates at low frequencies. By implementing balanced detection with differential amplification, the noise floor has been dropped by such a degree that ninth-order signal harmonics are clearly observable. In a 1 MHz measurement bandwidth, phase resolution is approximately 7 μrad and SNR is improved by 30 dB over conventional methods.

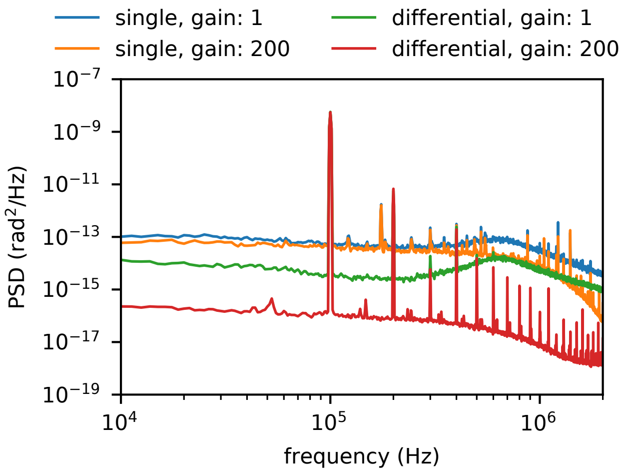

Fig. 3. Comparison of power spectra of signals obtained using FLDI with balanced detection and differential amplification.

In order to quantify the laser-noise cancellation, the instrument noise floor can be compared with the expected shot noise limit from the photocurrent. Hobbs [11] gives a procedure for making these measurements, where an incandescent light bulb is powered with a low-noise DC supply to generate broadband light, free from intensity noise. By matching photocurrents with those obtained using the laser, the resulting noise spectra can be compared. To focus enough light onto the photodetectors, a pair of aspheric condenser lenses was used. Light bulb position was adjusted to match the required signal levels and null the differential signal. Figure 4 compares the spectrum of a reference signal from the balanced FLDI with that obtained using the white-noise light. These two spectra are barely distinguishable, illustrating that the residual intensity noise from the laser has been effectively canceled and the remaining noise can be attributed to photocurrent shot noise.

To confirm shot-noise limited performance, results are compared with theoretical expectations. The power spectral density, S, of shot noise from a photocurrent i is

$$S = 2ie, \quad (4)$$

where e is the charge of an electron, and units of S are A^2Hz^{-1}. Shot noise is an example of white noise, exhibiting a uniform power spectral density across all frequencies. The current noise is converted to voltage noise in the terminating resistor of the photodiode, and the voltage noise is assumed to be linearly amplified by the preamplifier gain. The DC photocurrent was measured to be 2.18 mA, giving an amplified voltage noise density of $7 \cdot 10^{-12}$ V^2Hz^{-1}. The shot noise from both detectors is uncorrelated, so their subtraction in the amplifier gives an output noise spectral density that is the sum of both. Hence the expected power spectral density from photocurrent shot noise in the detected signal is $1.4 \cdot 10^{-11}$ V^2Hz^{-1}.

Two function generators (Stanford Research DS345) were used to generate 10-MHz band-limited white noise. In this bandwidth, the theoretical shot-noise root-mean-square (RMS) voltage is 8.35 mV in each channel. The two function generators were configured to each deliver 8.35 mV rms noise to the differential input of the preamplifier, configured to unity gain. Figure 4 shows the resulting power spectral density. The simulated photocurrent shot noise accurately reproduces the measured shot-noise spectral densities from the incandescent light bulb and the balanced FLDI. The small difference in spectra shown is expected to be from the different gain setting on the preamplifier. The background noise from the oscilloscope is also plotted in Figure 4, which was obtained by externally terminating the oscilloscope at 50 Ω, the output impedance of the pre-amplifier.

Figure 4 shows that white noise measurements are rolled off above 1 MHz. To show that this roll-off is from the preamplifier, the same noise power was directly connected to the digitizer input. As expected, the resulting spectrum is flat, consistent with white noise.

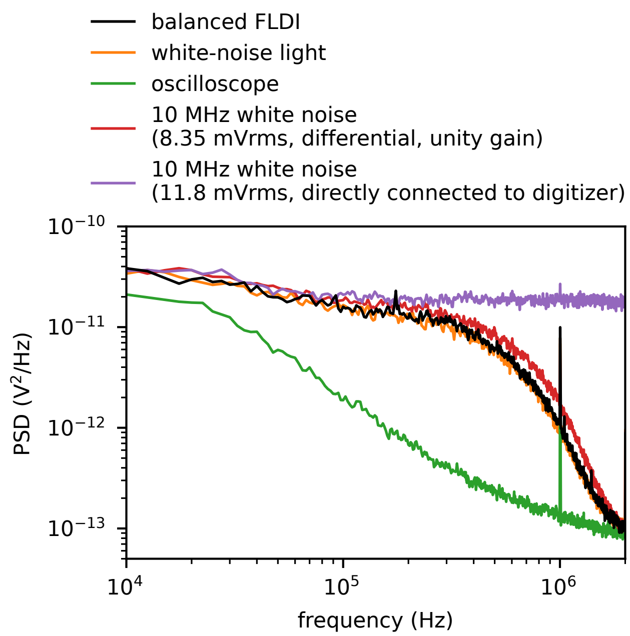

Fig. 4. Comparison of power-spectral densities from balanced FLDI with white-noise sources.

The measurement bandwidth in the present setup is limited by the preamplifier. Some FLDI measurements require higher bandwidths [12], and in these cases a different amplifier could be used.

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Data Availability Statement. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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