Compact diode laser homodyne vibrometers

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\textbf{ABSTRACT}

We discuss the architecture and performance of compact, robust, alignment-free, homodyne vibrometers using telecom diode lasers as the illumination source. The technical challenges and performance of implementations using conventional macroscopic optical components are compared with ultra-miniature micro-bench components and assembly methods. Focused sensitivity exceeding 4.6 pm/SQRT(Hz) at 1m range, 23 pm/SQRT(Hz) at 5m range, and useful operation to >20m have been demonstrated with COTS 1550 nm sources, 1.5 cm transmit/receive beam diameter and 32 mW transmitted power. Vibrometer measurement bandwidth exceeds 100 kHz with current electronics. Demonstrated performance is suitable for a variety of defense, security, and inspection applications.

\textbf{Keywords:} Lidar, ladar, Vibrometer, homodyne

\textbf{INTRODUCTION}

Non-contact optical vibrometers have many useful applications in remote monitoring of machinery health. When environment or logistics do not allow contact sensing, stand-off sensing may be the only means of safe access, for example in or around operating jet engines or rocket motors. Environmental factors precluding direct sensor contact or human access include extreme heat, steam, the presence of explosive or chemical vapors, or high voltage or magnetic fields. Hand-held, non-contact optical vibrometers are also useful for quick health and status checks in HVAC and oil field pump and pipeline maintenance situations and in checking the status of otherwise inaccessible components. Defense and security applications include observing surface vibrations indicative of hidden tunnel or facility operations, and perimeter monitoring. All of these applications require mechanically robust and reliable devices. For portable applications, minimal size, weight, and electrical power consumption are also enabling requirements. Applications requiring stealth can also benefit from operation at wavelengths beyond the sensitivity range of human vision and CCD cameras. Where multiple field deployments are desired, cost is also a consideration. It is the primary objective of the sponsored work reported here to achieve the highest sensitivity possible in the smallest and most robust package suitable for battery operation at ranges >10m.

\textbf{1.1 WHY HOMODYNE}

There are several architectures useful for high-sensitivity, non-contact optical vibrometry operable at useful stand-off range; all depend on optical phase shifts in light backscattered from the surface due to tiny cyclic surface range changes at the frequencies of interest (typically, 10 Hz – 100 kHz). Common optical vibrometry methods include heterodyne and homodyne coherent detection, and Self-mixing Laser Interferometers (SMiLI).

SMiLI’s\textsuperscript{1} are the simplest potential sensors and, when executed properly, the most robust of the common architectures. Figure 1 shows a SMiLI sensor. The SMiLI optical head requires only a single-frequency laser and a lens in a stable housing. In operation, a SMiLI sensor typically focuses the light from the laser on the target. A small amount of light backscattered from the target is collected by the same lens, and focused back into the laser cavity through the output coupler. Interference between the circulating light and the return light in the cavity causes a small periodic modulation of the circulating optical power in the cavity. If a diode laser is used, this modulation can be observed directly as a modulation of the laser current; thus, a separate detector is not even required. Misalignments between the receiver and transmitter are nearly impossible. LightWorks has developed and manufactured SMiLI devices for velocity, length,
displacement, and vibration measurements for industrial, military, and scientific applications since 1996. It was natural that our first attempt to produce small, robust high-sensitivity vibrometers focused on examining how far SMiLI technology could be pushed in range and sensitive performance.

Although simple and robust, SMiLI’s built with COTS laser diodes have several important limitations due to the short cavity lengths and laser physics. These include limited coherence length and laser instabilities (mode hopping, multimoding) for bright or distant targets. An interesting but limiting characteristic of these devices is that the achievable signal to noise ratio (SNR) depends primarily on the ratio of the reflected light intensity circulating in the cavity to the circulating laser power; increasing the transmitted laser power has no impact on the SNR, so the sensitivity cannot be increased by simply transmitting more power. We found that, when focused at 1m range, optimized SMiLI sensors using COTS DFB laser diodes operating at 1.3 \( \mu \text{m} \) wavelength can achieve ~90 pm-Hz \( ^{1/2} \) sensitivity, and have a useful maximum range of ~3m (select devices can reach 5m). While adequate for many industrial monitoring applications, the maximum achievable range and sensitivity with SMiLI devices were insufficient to fulfill security application requirements. Ultimately, the achievable SNR is limited by shot noise competition with the signal photons in the laser cavity.

In contrast, homodyne and heterodyne coherent detection sensors can be constructed to achieve signal shot noise limited performance. While these approaches escape some of the SMiLI sensor performance limitations, they are far more difficult to build and align, require several more components including a separate detector (all occupying physical volumes), and are intrinsically less robust than SMiLI’s. However, the achievable SNR with these architectures scales with the laser power and target return power, and they do not exhibit the SMiLI instabilities with increasing backscatter power and range.

Figure 2 shows the typical layouts of homodyne and heterodyne systems. In both systems, collimated polarized light from the laser is projected through a polarizing beam splitter (PBS) and quarter wave plate (QWP) to the target. Scattered light returning from the target is translated to the orthogonal linear polarization and reflected by the PBS to the
The PBS and QWP act as a transmit/receive switch allowing the return beam to be directed to the detector. In the heterodyne approach, a few percent reflective beam splitter is inserted in the path between the PBS and the detector and a second collimated laser beam, the local oscillator (LO), is aligned with the return signal light so that there is a substantial overlap in position and match in wave front curvature at the common intercept on the beam splitter. Interference between the signal and LO beams causes a modulation of the optical power on the detector at the optical difference frequency (beat note) between the two beams. For the beat note to remain within the electrical bandwidth of the detector and electronic circuits, a precise optical frequency offset must be maintained between the transmitted laser and LO laser. This lock is sometimes simplified by tapping a fraction of the transmit laser light and frequency shifting it using, e.g., an acousto-optic modulator (AOM). In this approach, the transmit and LO optical frequencies track perfectly at the offset determined by the electrical drive signal to the AOM. The advantage of the heterodyne approach is that the sign of the Doppler shift due to gross relative line of sight (LOS) motion between the vibrometer and the target (a.k.a. platform motion) is resolved by the beat note frequency; a lower frequency indicates approach while a higher frequency indicates increasing separation. This distinction is not available from homodyne sensors. If the target is vibrating, the phase of the beat note varies according to the optical phase shift with the minute periodic range changes. The signal processor demodulates the vibration signal from the carrier beat note frequency.

The homodyne architecture departs from the heterodyne in that there is no need for a separate LO source or the attendant frequency locking system between the LO and transmitted optical frequencies. Instead, the LO is derived from the reflected beam from a partial reflecting window placed in the path between the QWP and the target. The window is precisely aligned so that the reflected beam substantially overlaps the return beam and has the same wave front curvature at the PBS. The beat note generated by interference between the LO and return signal is detected in the same way as in heterodyne detection, but, since the LO and transmit optical frequencies are identical, a return from a stationary target produces a DC offset (zero frequency beat) whose magnitude is proportional to phase difference between the signal and LO. LOS platform motion introduces the same Doppler frequency offset regardless of the direction of motion. As with heterodyne detection, vibration of the target produces a periodic modulation of the phase of the beat note, and signal processing comprises detection of this phase variation.

For either system, a telescope can be added between the sensor and the target to increase the effective beam diameter, and increase the operating range. LightWorks sensors are made both with and without telescopes for different applications, and to allow customer adaptations of the sensor for proprietary applications.

Despite the platform velocity sign ambiguity, the simplicity advantage of the homodyne sensor clearly leads to the simplest, smallest, and lowest power coherent detection vibration sensing architecture. For this reason, LightWorks chose to develop the homodyne vibration sensing architecture.

1.2 HOMODYNE LASER CHOICE

Commercial vibrometer use many types of lasers. He-Ne gas discharge lasers are frequently employed because of their intrinsically long coherence lengths and stability. Unfortunately, the size of the lasers, fragility of the gas tube envelope, power inefficiency, visible wavelength, and high voltage requirements preclude this type of laser for handheld, battery-operated, and stealthy applications. Other devices use solid-state lasers, fiber lasers, or diode lasers. However, all commercial devices have quite large optical heads and separate signal processing units, and are not suitable for battery operation.

For some defense and security applications, sensitivity to vibration displacement amplitudes <1 nm are required. This displacement is much less than typical light wavelengths (~1.5 µm). Backscatter target range measurements, including optical phase, gain a factor of two in sensitivity because the displacement is seen on both approaching and reflected paths. Still, optical phase resolution >1000 is required. This requirement demands very low noise optical devices.

Fortunately, select telecom laser diodes operating in the 1.3 µm – 1.6 µm wavelength region offer a useful combination of environmental ruggedness, low relative intensity noise (RIN), long coherence length (narrow bandwidth), and stealthy wavelength. For these reasons, LightWorks chose to use telecom lasers as sources for the homodyne vibrometer.
1.3 THEORETICAL HOMODYNE SENSOR PERFORMANCE

\[ s_v(t) = a \cdot \sin(\omega t) \]  

Equation 1 gives the expression for a time varying sinusoidal vibration signal \( s_v(t) \), where \( \omega \) is angular frequency of the vibration and \( a \) is the vibration amplitude. Defining a parameter \( k = \frac{2\pi}{\lambda} \), where \( \lambda \) is the carrier (optical) wavelength, the measured signal at the detector \( S(t) \) follows the proportionality given equation 2, where \( \Phi_0 \) is the mean phase of the optical carrier returning from the target at angular frequency \( \omega_c \). Equation 2 also shows expansion of \( S(t) \) into sums of odd and even Bessel functions so that different modulation strength, \( ka \), regimes can be more easily examined.

\[ S(t) \propto \cos(\omega t + 2k * s_v(t) + \Phi_0) = \cos(\omega t + \Phi_0) \left[ J_0(2ka) + 2 \sum_{m=1,\text{even}} J_m(2ka)\cos(m\omega_c t) \right] + \sin(\omega t + \Phi_0) \left[ 2 \sum_{m=1,\text{odd}} J_m(2ka)\cos(m\omega_c t) \right] \]  

When \( ka \) is \( \gg 1 \), equation 2 describes the regime where typical FM signal demodulation is useful and the carrier frequency is Doppler shifted in proportion to the instantaneous vibration velocity. Many industrial vibrometry applications fall in this regime. For \( ka \ll 1 \), as is the case for the small vibration amplitudes of most interest to this study, equation 2 can be approximated by equation 3

\[ S(t) \approx 2ka \cos(\omega t + \Phi_0) \cos(\omega_c t) \]  

For small modulation depth, the homodyne vibration signal \( s_v(t) \) from a stationary target appears as an AM modulation of the carrier. The intrinsic low pass filtering imposed by real detectors and electronics time averages over the carrier frequency component resulting in direct demodulation of \( s_v(t) \) into a baseband signal \( S(t) \sim 2kS_v \).

For a focused coherent detection system, the carrier to noise ratio (CNR) provides a measure of the detection performance. The CNR for a focused system with sufficient LO power on the detector to achieve shot noise limited detection is given by equation 4 where \( P \) is the optical power transmitted, \( h \) is Planck’s constant, \( c \) the speed of light, \( B \) is the measurement bandwidth, \( \xi \) is the system optical efficiency, \( \rho \) is the target reflectivity (sr\(^{-1}\)), \( R \) is the target range, \( \lambda \) is the optical wavelength, and \( D \) is the effective transmitted beam diameter (note: not the optic size).

\[ CNR = \frac{P \cdot \xi \cdot \rho \cdot \lambda}{hcB} \left( \frac{\pi D^2}{4 \cdot R^2} \right) \]  

To evaluate the theoretical vibration detection performance of a miniature homodyne sensor, we first calculate the CNR assuming some practical parameters: \( D = 1.3 \) cm, \( \rho = 0.02 \) sr\(^{-1}\), \( \xi = 0.1 \), \( F = R = 10 \) m, \( B = 10 \) Hz and \( P = 32 \) mW. For these parameters, the expected CNR is \( \sim 79 \) dB. For a homodyne system with small target vibration amplitude, the vibration SNR is then given by equation 5.

\[ SNR = CNR \cdot \left( \frac{2\pi a}{\lambda} \right)^2 \]  

Equation 5 suggests that, for a vibration amplitude \( a = 40 \) nm (typical PZT test target amplitude), the theoretical vibration SNR from a practical, compact, shot noise limited homodyne sensor is \( \sim \text{CNR-16 dB = 63 dB at 10m stand-off range.} \)

Miniature Homodyne Vibrometer ImplementationS

1.4 MACRO-BENCH ASSEMBLY

The first proof of concept homodyne vibrometer was built and tested in 2005 on an optical table using standard mounts and large optics. Figure 3 shows the first reduction of the prototype design to a miniaturized form (circa 2006), using
conventional assembly methods in a custom aluminum assembly. The laser is coupled via SM/PM fiber, and the detector through a multimode fiber, to a separate electrical assembly (not shown). During initial testing, it was found that the detector fiber caused unwanted reflections that fed back into the system causing strong oscillations within the baseband spectrum. The unit was subsequently modified to eliminate this fiber, and free-space couple the detector to the PBS optical output.

![Image](image.png)

Figure 3. (left) Homodyne sensor constructed using traditional methods employing ordinary size optical components. Both the laser and detector are fiber coupled (not shown). (center) Homodyne sensor with telescope and visible pointing laser attached. (right) Homodyne sensor with telescope assembled in a housing.

Testing of the macro-bench sensor proved adequate for the customers needs, so we proceeded to miniaturize the design.

### 1.5 MICRO-BENCH ASSEMBLY

In 2008, LightWorks engaged Innovative Photonic Solutions (IPS) to translate the macro-bench prototype design into a micro-bench solution. Figure 4 shows the conceptual construction of the micro-bench head. Beyond size, the micro-bench approach integrates the laser and all optical components including the detector into a single monolithic assembly. This leads to a very robust and stable assembly.

![Diagram](diagram.png)

Figure 4. The conceptual architecture for a micro-bench homodyne optical head is shown. The small size contributes to the mechanical stability and demonstrated performance, but introduced significant difficulties with scattered light control that had to be overcome during development.

In the Fall of 2008, IPS reduced the design to practice. Figure 5 (left) shows a micro-bench unit built into a standard butterfly package that supports the signal and pointing laser drivers and signal amplifier circuit board. The sensor is hard-mounted in an assembly that includes a telescope producing a 13 mm transmitter beam diameter, and an 850nm wavelength pointing laser that is invisible to the eye but can be viewed on a CCD camera. The right panel of figure 5 shows the completed micro-bench vibrometer configured with a control unit that provides convenient operation from a small AC supply and provided laser emission warning lights and switching for both the signal and pointing lasers. LightWorks has begun limited production of this system (VibeReader LRAS-1). This is the configuration evaluated in section 3.
Vibrometer Performance

1.6 TEST SETUP

Because of the high sensitivity of the homodyne sensors, validating the ultimate performance proved difficult. The test range is located in a largely residential area of Boulder Colorado. The sensor was mounted to an optical breadboard supported by a stout wood frame bench resting on a concrete slab floor, that was poured directly on soil that is largely composed of loose sand and gravel (i.e. acoustically absorptive). The test target is a calibrated PZT with a diffuse reflecting surface that was mounted on a sturdy tripod for convenience, and also resting on the concrete slab. When operating over ranges of 5-10m, it was found that environmental disturbances propagating through the ground such as distant light traffic and wind noise coupled into the slab from the lab walls could be observed as intermittent broadening of the spectral peak from the target. To avoid outside disturbances, the reported ultimate sensitivity and bandwidth measurements were typically made during early morning Sunday hours on calm nights. The longest range measurements were always somewhat affected by refractive turbulence along the path, and probably underestimate the ultimate sensor SNR by ~3 dB. Typically, the PZT target is excited with 1 V p-p sine wave at the frequency of interest which produces a surface motion of ~40 nm peak (28 nm RMS).

1.7 RELATIVE MACRO- AND MICRO-BENCH PERFORMANCE

According to equation 5, the theoretical SNR limit for shot noise limited detection at 10m for the as-built homodyne devices and a target displacement amplitude of 40nm in a 10 Hz bandwidth is 63 dB. Figure 6 shows the average SNR (55 measurements) observed for both the macro- and micro-bench vibrometers under these conditions. Allowing for perhaps ~10 dB of environmental degradation during the averaging time suggests the micro-bench unit is operating within 12 dB of the theoretical limit and the macro-bench unit within 18 dB of the theoretical limit. The discrepancies from theoretical performance are most likely due to imperfect (non Gaussian) beam profiles, effects of finite laser bandwidth, and speckle fading.

1.8 ULTIMATE MICRO-BENCH PERFORMANCE

Several micro-bench units have been fabricated to date. One of these was chosen to study in greater detail. A shorter range (5m) was used in these tests to mitigate the effects of environmental vibrations and refractive turbulence. For this range, and a 3 Hz power spectral resolution bandwidth, but otherwise using the same test conditions, the theoretical SNR limit is 72 dB. Figure 7 shows the results of this test (no averaging was done). The measured SNR is 60 dB, within 12 dB of theoretical expectation. Allowing for environmental conditions, it is clear that the signal bandwidth is transform limited below 3 Hz.

The noise equivalent sensitivity implied by this measurement is 23 pm-Hz$^{1/2}$ at 5m range and, scaling with equation 5 to 1 m range, implies a sensitivity of 4.6 pm-Hz$^{1/2}$. To put this sensitivity in perspective, the typical atomic radius is ~100
pm. Fortunately, the spot diameter is ~0.6 mm at 5m, encompassing perhaps $10^{12}$ randomly vibrating atoms or this sensitivity of measurement would not be feasible.

Figure 6. The performance of the macro-bench prototype (red) is compared with the completed micro-bench sensor (VibeReader LRAS-1) (yellow) with a calibrated PZT target at 10m range excited with a 1 V p-p signal (28nm RMS displacement) sine wave at ~1kHz. The green trace occurs where the yellow and red traces overlap. The power spectrum was acquired with 10 Hz bandwidth. Both sensor beams traveled along the same path and had coincident foci on the target. 55 acquisitions were averaged so that the noise floor could be accurately determined and any speckle fading or atmospheric refractive turbulence effects on the SNR were mitigated. The averaging decreases the true sensor SNR, but makes for a more accurate intercomparison. The micro-bench sensor exhibited 41 dB average SNR, while the macro-bench showed 35 dB demonstrating the efficacy of the micro-bench construction.

Figure 7. 3 Hz resolution power spectrum of the signal observed from a 40nm vibration with the micro-bench VibeReader LRAS-1, demonstrating noise equivalent sensitivity of 23 pm/SQRT(Hz) at 5m range, and transform limited performance.
plans

A major impact on practical application of this technology for many applications is the effect of platform motion. For the highest sensitivity measurements, transverse, and to a lesser extent, longitudinal motion of the target relative to the sensor beam causes rapid speckle fading. The resultant discontinuities in the carrier phase increase the signal bandwidth consequently reducing the effective SNR. For large LOS platform motion, a net Doppler shift is also imposed on the vibration signal, translating the carrier and its vibration sidebands away from baseband. While beyond the scope of this paper, LightWorks is actively pursuing several hardware and signal processing mitigations for the deleterious effects of platform motion.

Conclusions

We have demonstrated miniature, robust, and extremely sensitive homodyne vibrometers suitable for industrial, scientific, and security applications. The monolithic micro-bench construction provides significant size, stability and performance advantages over conventional construction techniques. Noise equivalent sensitivities of 4.6 pm/Hz$^{1/2}$ at 1 m range and 23 pm/Hz$^{1/2}$ at 5 m range have been demonstrated. The device designs and fabrication techniques have been developed sufficiently that these devices can be manufactured in limited quantities at reasonable cost.

REFERENCES