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Diode Laser-Based Sensors for Extreme Harsh Environment Data Acquisition

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Additional information is available at the end of the chapter

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Abstract

The world has witnessed several step changes in living standards, productivity, growth, and innovation. We are currently witnessing a convergence of intelligent devices, intelligent networks, and intelligent decision making. Obtaining long-term accurate, in situ, and real time data from the machines is necessary for enabling the industrial Internet. This relies heavily on sensor systems. Development of robust sensors that can operate reliably in extreme environments will make it possible to gather data from previously inaccessible locations in the equipment. This will enable machine operators to monitor and optimize the performance of their machines. Diode laser-based diagnostics technology has found applications in a variety of areas and a versatile range of operating conditions. It has proven to be a strong and reliable technique for remote measurements of concentrations and temperatures in harsh environments. Some of the major challenges for implementation of these sensors in real world are machine vibrations, window clogging, cooling, etc. In this chapter, the authors discuss about the application details and specific technologies suitable for the applications. Few case studies are considered, and the theoretical approach, algorithm development, and experimental validation are also discussed.

Keywords: lasers, sensor, harsh environment, tunable diode laser, industrial Internet, optical sensor

1. Introduction

Prior to late eighteenth and early nineteenth century, the human society was primarily agrarian and rural. Then, a step change of innovation occurred: the Industrial Revolution, which gave us a shift from hand tools to steam engine, the internal combustion engine,

telegraph, telephone, and electricity. Productivity and economic growth accelerated sharply [1]. A key upside of the feature characterizing this period was that it harnessed the efficiencies of hierarchical structures, with centralization of controls. It led to reduction in cost as the machines and fleets got larger and production volumes increased. A major downside was that it was more resource intensive. Much of the incremental innovation at later stages was focused on improving efficiency, reducing waste, and enhancing the working environment. The second wave of Industrial Revolution started with the advent of the electronics, computers, and Internet. Here, the key feature was the design of standards and protocols to permit incompatible machines in diverse locations to connect and exchange information. The explosive growth was a result of the combination of speed and volume. Deeper integration, flexible operation, and distributed intelligence led to the creation of new platforms for commerce and social exchange by driving down the cost. Ability for rapid exchange of information and decentralized decision-making process led to open innovation and knowledge-intensive growth. Today, we are witnessing another transformation by melding of the global industrial system with open computing and communication system. The industrial Internet is enabled by the coming together of intelligent devices, intelligent systems, and intelligent decision-making systems [1]. The architecture consists of three technology elements: brilliant machines, advanced analytics, and people at work. A brilliant machine is self-aware of its performance, health condition, and capability. This enables the machine to operate close to its performance boundary. The machine communicates with other machines and operators or service personnel through the Internet.

The first step in this revolution is the generation of data from the machines assuring the real-time health condition information of the machine. Widespread instrumentation of the machines is a necessary factor in this case. A suite of sensors on each machine will enable performance monitoring on a real-time basis and help the operators make the most of their assets [2]. The challenge comes from the increasing technical complexity of the assets in service. Performance data from a sensor located in an unmonitored location in a machine along with powerful software analytics and visualization tools will enable the operator to diagnose the problem with greater confidence. **Table 1** provides a breakup of the value opportunity of industrial Internet for various industry segments [3].

Industry segment	Global base	Capacity	Labor-hours/Year	Value
Power	56,620 (Gas + Steam Turbines)	4156 GW	52M	\$ 7B
Aviation	21,500 Commercial Jet Aircraft	43,000 Jet engines	205M	\$ 10B
Rail	120,000 Freight	7M People + 9.6T Freight tonne-km	52M	\$ 3B
Healthcare	105,000 (CT + MRI Machines)		4M	\$ 250M

Table 1. Value opportunity of industrial Internet for various industry segments [3].

Similarly, in the oil and gas sector, reduction in asset downtime (asset performance management) and operations optimization through predictive analytics and condition-based maintenance can result in substantial cost savings for the oil well owners. For example, the cost for

surfacing a blowout preventer (BOP) from the seabed is around \$10–\$16 million and unplanned downtime costs a mid-size LNG facility \$150 million per year [4]. Most of the downtime in deep sea drilling rig is caused by BOP-related problems, and it costs an oil company more than \$ 1 million per day in lost productivity [5].

Therefore, nowadays when major industrial products, such as gas and steam turbines, aircraft engines, turbomachinery equipment, power transformers, and locomotives, are involved, the primary challenge is to keep the systems operating at peak performance to avoid unwarranted shutdowns. Continuous operation at peak performance not only demands high-fidelity system architecture and design, but also requires optimized operation and maintenance practices. This in-turn necessitates the usage of online sensor systems that can perform desired measurements for continuous monitoring of operational performance and overall system health. The idea is that measurements using multiple sensors in combination with environmental, operational, and performance-related parameters can provide a more accurate system health status. The sensor data can also be used along with statistical pattern recognition and machine-learning techniques to detect changes in machine parameter data, isolate faults, and estimate the remaining useful life (RUL) of the machines [6–9]. This approach assumes a product's loading and operating conditions, geometry, material properties, and failure mechanisms as the parameters to estimate RUL. The sensor systems are used to monitor these parameters for anomalies, faults, and failure predictions [10].

In an example provided in GE Report [11], the operators of Whitegate Power Station near Cork in Ireland placed more than 140 sensors throughout the plant. This allowed the operators to run the plant reliably and efficiently through round-the-clock monitoring and diagnostics of the plant. The sensors digitized the critical plant operating parameters (vibration, temperature, pressure, fuel mix, ambient temperature, and load) and helped to create a virtual dynamic model of the asset in the cloud, which is a mirror of the real asset. The model in conjunction with the sensor data gives us the ability to predict the plant's performance, understand trade-offs (adjust hedging strategies to manage fuel cost volatility), and enhance efficiency. The modeling approach discussed above requires directly sensed parameters, design parameters, and operating condition uncertainties, as well as inspection and historical reliability data. Several techniques, such as stochastic models (which take into account randomness of the operating profiles, extreme operating events), physics-based models, neural networks, or real-time probabilistic models, are used for this purpose. To a large extent, the integrity of the measured parameters determines the fidelity of the models used [9].

It is obvious from the above discussion that robust and reliable online sensors that can accurately measure the desired system parameters are crucial toward optimizing asset performance and maximizing its lifetime. Most of the above-mentioned industrial assets, such as gas turbines or aircraft engines, involve extreme harsh environments such as high temperatures, high pressures, vibrations, shocks, dust and soot load, reacting flow, and thermal transients. Several industrial challenges and applications can be addressed through sensing of parameters under these harsh conditions. Conventional sensors do not work reliably here (or even fail to perform) because these harsh conditions often lie outside the operational envelope of traditional techniques. Therefore, development of new and advanced harsh

environment sensors is becoming increasingly important because such sensors can enable the industrial community to get enhanced value out of their assets. When classified broadly, harsh environment sensors serve the following key application areas: process optimization (or controls), prognostics/health management, better machine design, and monitoring/diagnostics. For all these applications, it is beneficial to have on-line/real-time, accurate, selective, and direct measurement of the harsh environment parameters. In addition, high measurement repeatability and ease of installation and maintenance are extremely desirable. As described in this chapter, optical harsh environment sensors can provide these major advantages over conventional techniques for a host of industrial applications.

Technology	Laser type	Detectors	Measured sample	Information
Laser-induced fluorescence	CW/pulsed, low power	Camera	Fluorescent molecules	Species concentration
Laser-induced incandescence	Pulsed, high power	Camera	Soot particles	Soot distribution
Laser Doppler anemometry	CW, low power	Photodiodes	Particles and droplets	Local flow velocity
Particle imaging velocimetry	Pulsed/modulated, high power	Camera	Seeding particles, fuel droplets	Flow field
Phase Doppler anemometry	CW, low power	Photodiodes	Droplets/Particles	Droplet/particle size
Laser-induced breakdown spectroscopy	Pulsed, high power	Spectrometer	Molecules	Elemental composition
Raman scattering	CW/pulsed, high power	Photodiodes/spectrometer	Molecules	Concentration, temperature
Laser absorption spectroscopy	CW/pulsed, low power	Photodiode	Molecules	Concentration, temperature

Table 2. Overview of common optical techniques for industrial-sensing applications [12].

Laser-based optical sensors provide a unique method for measurement of fluid properties in industrial environments. Typical applications include flow or velocity measurement through techniques such as particle imaging velocimetry (PIV) or laser Doppler anemometry (LDA) and particle size measurement using phase Doppler anemometry (PDA). Laser-induced breakdown spectroscopy (LIBS) is commonly used where elemental composition measurement is required. Furthermore, for applications requiring concentration measurements, laser-induced fluorescence (LIF), Raman scattering, or laser absorption spectroscopy (LAS) is used depending on the type of sample. For fluorescing samples, LIF is preferred. On the other hand, Raman scattering is beneficial for measurements on di-atomics (H_2 , N_2) or for analyzing gases at high pressures. Finally, LAS is used for applications where high sensitivity and selectivity

are crucial. A brief snapshot of the various laser-based industrial-sensing techniques is provided in **Table 2**, and the reader is encouraged to refer the literature [12] for more details on these techniques. To remain within scope, this chapter will remain focused on absorption-based techniques, especially diode laser sensing, which is most promising for harsh environment applications.

Common industrial applications of conventional absorption-based optical sensors include gas monitoring, sensing, and analysis through techniques, such as Fourier transform infrared (FTIR), ultraviolet spectroscopy (UV), nondispersive infrared (NDIR), and photo-acoustic spectroscopy (PAS) [13, 14]. For harsh environment applications, such as power generation and energy systems, these techniques typically require gas extraction to condition the sampled gas. This often leads to unwanted lag in the measurement and requires frequent maintenance of the sampling system [15]. For applications requiring fast response time, high resolution, and good selectivity, such as industrial controls and process optimization, LAS has immense potential that is why it is an active area of research across the industrial and academic community. Tunable diode laser absorption spectroscopy (TDLAS) [16] and quantum cascade laser absorption spectroscopy (QCLAS) [17] are the two most common modalities in which LAS-based optical solutions can be implemented in harsh environments. This is mainly because these techniques, as discussed later in the chapter, can be implemented using economical, robust, and compact diode lasers/quantum cascade lasers that are specifically designed for the required application. In addition, diode lasers/quantum cascade lasers can be mass produced, require minimal maintenance, and have long operation lifetimes (>20,000 h) [18]. In the past decade, the industrial community has been increasingly adopting novel technology solutions based on these lasers. This is acting as the driving force behind the rapid advancement of the diode laser manufacturing industry toward lower cost, higher performance, and increased reliability. As this trend continues, these lasers will become even better and cheaper in the future, which will open new avenues toward novel and affordable optical solutions to today's unsolved challenges. Therefore, diode laser-based sensing techniques, such as TDLAS and QCLAS, are of utmost importance to the industrial community.

TDLAS/QCLAS-based sensors have immense potential and advantages for in situ measurements of concentration of constituents, temperature, and other wide varieties of gas parameters in challenging real-world environments [19–21]. In most of these applications, light emitted from a tunable diode laser system is passed through a gaseous medium to a detector. The transmitted radiation is then used to measure the gas temperature, species concentration, or pressure using spectral absorption models for the target absorbing species [22]. When implemented in line-of-sight [23, 24] or standoff configuration [25], these techniques can offer true in situ measurement capability in harsh environments with high temperatures or pressures. This is because the sensor can make reliable measurements through one or more transmitting windows while being completely decoupled from the harsh environment.

This chapter discusses the technology background of TDLAS from an applied experimental perspective. The two most common methodologies, that is, direct absorption spectroscopy (DAS) and wavelength modulation spectroscopy (WMS), will be covered. Subsequently, the key design philosophy, optomechanical architecture, and instrumentation of a TDLAS sensor

will be presented. Finally, two harsh environment application examples will be provided to demonstrate the power of diode laser sensing toward solving complex real-world challenges. Please note that the implementation of QCLAS is essentially very similar to TDLAS, the only significant difference being that QCLAS uses mid-infrared quantum cascade lasers while TDLAS uses near-infrared tunable diode lasers. For the sake of simplicity, the term TDLAS is used in most places in this chapter but the concepts presented translate directly to QCLAS as well.

2. Technology background: tunable diode laser absorption spectroscopy

The fundamentals of molecular spectroscopy, including concepts such as vibration modes, absorption coefficient, line-shape, spectral width, and spectral broadening have been extensively studied and discussed in several books and articles [26, 27]. This section is presented from an applied experimental perspective and will use the aforementioned concepts assuming that the reader is equipped with basic understanding of molecular spectroscopy.

The absorption of optical radiation by gaseous medium is governed by the Beer–Lambert law. The law describes the optical transmission losses associated with a uniformly absorbing medium. When a narrow spectral radiation of frequency ν passes through a gaseous medium of length L [cm], the incident intensity I_0 , and the transmitted intensity I_1 are related as,

$$I_1 = I_0 e^{(-k_\nu L)} \quad (1)$$

where k_ν [cm^{-1}] is the spectral absorption coefficient. It should be noted that for a mixture in pure gaseous phase (devoid of particulates, water droplets or condensed phases), the Beer–Lambert law assumes the optical scattering of the medium to be negligible. The spectral absorption coefficient k_ν is defined as below for an isolated (interference-free) vibrational transition,

$$k_\nu = P c S_i(T) \varphi_\nu \quad (2)$$

where P [atm] is the total gas pressure, c is the mole fraction of the species of interest, $S_i(T)$ [$\text{cm}^2 \text{atm}^{-1}$] is the temperature dependent line strength of the transition at temperature T [K], and φ_ν is the normalized line-shape function, such that

$$\int_{-\infty}^{\infty} \varphi_\nu d\nu = 1 \quad (3)$$

Using the above equations, the concentration c of the species of interest can be calculated.

The quantity $k_{\nu} L$, called absorbance, is of critical importance in deciding the capability and performance of a tunable diode laser-based gas sensor. For typical laser-based gas-sensing applications, trace concentrations need to be detected, and therefore, the absorbance to be detected is $\ll 1$. In such cases, the Eq. (1) reduces to

$$\frac{I_0 - I_1}{I_0} = \frac{\Delta I}{I_0} \sim k_{\nu} L \quad (4)$$

The quantity $\Delta I/I_0$ is known as the fractional absorbance. The minimum fractional absorbance detectable by a TDLAS system is known as the minimum detectable absorbance (MDA). For a given TDLAS system, MDA is characteristically a function of the different system-level noises (such as laser excess noise, detector thermal noise, optical interference noise, or etalon noise) and does not depend on the species to be measured with that system. For a given path length, the MDA of the system can be used to calculate the minimum detectable concentration (or detection limit) for a measurable species using Eqs. (2) and (4). For most practical TDLAS applications, the MDA is around 10^{-5} to 10^{-6} and is often limited by the optical interference noise or etalon noise of the system [13, 28]. The two most common methodologies in which TDLAS is implemented are direct absorption spectroscopy (DAS) and wavelength modulation spectroscopy (WMS), which are discussed in the following subsections.

2.1. Direct laser absorption spectroscopy (DLAS/DAS)

A key requirement for both DAS and WMS is that the laser source must have a spectral width much narrower (at least 1–2 orders of magnitude) than the gas absorption feature to be measured. Distributed feedback diode lasers (DFB) in the near-infrared (NIR) and quantum cascade lasers (QCL) in the mid-infrared (MIR) can meet this requirement and serve as excellent sources for a majority of applications [18]. These lasers are generally available in both pulsed and continuous wave (cw) modes. The emitted wavelength of a diode laser is a function of the diode temperature and the injection current. Typically, a thermoelectric controller (TEC) is used to set (and control) the diode-operating temperature to a value where the desired wavelength can be reached at the desired injection current. For implementation of DAS [29], the injection current of the diode laser is scanned periodically in a sinusoidal, ramp, or sawtooth fashion. This leads to a related wavelength scanning of the laser. The scan current range has to be selected such that the resulting wavelength scan covers the absorption transition of interest. Typical scan frequencies are in the range of 5–200 Hz. It is highly advisable to use a wavelength-appropriate etalon to characterize the current–wavelength transfer function of the laser at the scan frequency [30].

The scanned laser is made to pass through an absorption cell where it interacts with the species of interest. The transmitted signal is measured using a photodiode (usually DC coupled). Most common detector types are indium gallium arsenide (InGaAs) for near-infrared and mercury cadmium telluride (MCT) for mid-infrared regions, respectively. The basic components and schematic of a direct absorption spectroscopy system are shown in **Figure 1**. In the absence of

absorption, the detector signal will essentially represent the power vs current behavior of the laser. This behavior is typically linear when in small current ranges but could also be of higher order depending on the laser nonlinearity. In the presence of absorption, a typical DAS spectrum looks similar to the embedded graph in **Figure 1**, where a dip in transmission is observed as the laser wavelength scans through the absorption feature. The magnitudes of the photodiode signal at the absorption line center, with absorption and without absorption, are proportional to I_1 and I_0 in the Beer–Lambert law, respectively, and can be used to estimate the species concentration. A common way to calibrate a DAS system involves analyzing and plotting the photodiode signal as a function of the laser wavelength using the aforementioned current–wavelength transfer function. Subsequently, the integrated area under the absorption curve (which is directly proportional to the species number density) is used to correlate the DAS signal to species concentration [13].

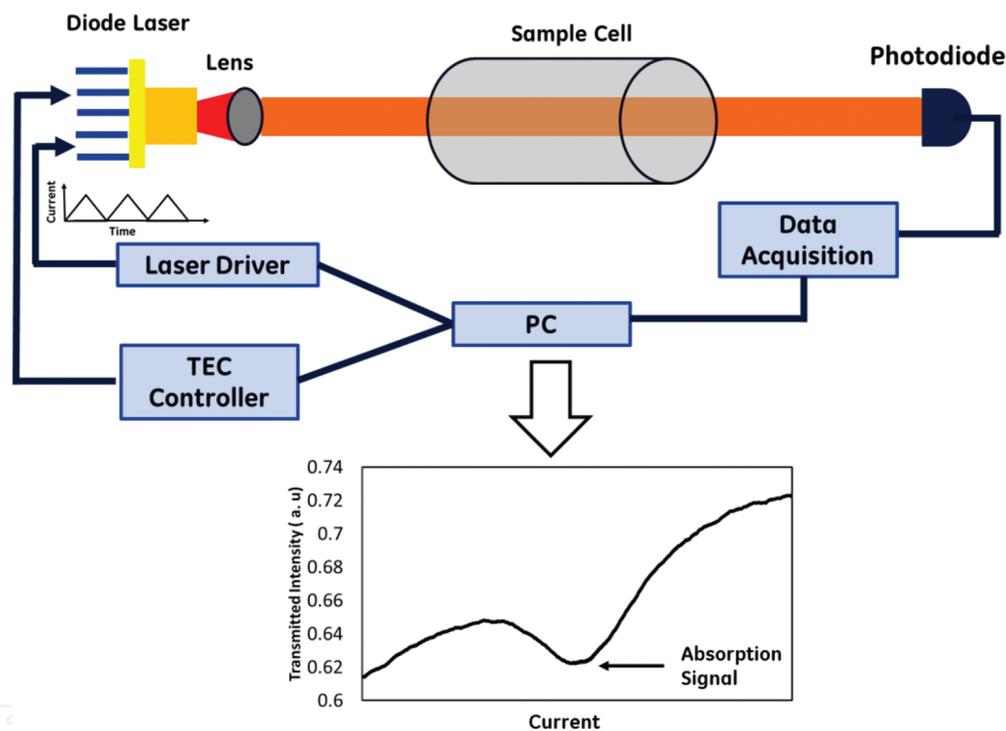


Figure 1. Schematic of a typical direct absorption spectroscopy system.

2.2. Wavelength modulation spectroscopy (WMS)

For TDLAS applications requiring high sensitivity, wavelength modulation spectroscopy (WMS) is a very effective technique [29, 31–33]. A typical WMS setup is shown in **Figure 2**. In addition to the laser scan (as in DAS), a fast current modulation (at a frequency f and amplitude a) is added to the injection current of the laser. The frequency f of the modulation signal is typically in the range 1–20 kHz. As in the case of direct absorption, the wavelength tuning properties of the laser, for both the scan and modulation frequencies, have to be well characterized with an appropriate etalon [30]. The transmitted signal measured by the photodiode

is fed into a lock-in amplifier. As shown in **Figure 2**, it is critical that the reference signal of the lock-in amplifier is the same as the laser's modulation signal. It should be noted that this is a general requirement and applies differently depending on the type of lock-in amplifier. For example, in case the reference is internally generated in the lock-in, the reference signal from the lock-in can be scaled appropriately to modulate the laser. Or, if a software lock-in is used, then the PC generated reference can be used for this purpose. The lock-in analysis frequency is set to twice the modulation frequency of the laser ($2f$) and the spectrum is analyzed in a narrowband around the $2f$ frequency. This is known as second harmonic spectroscopy, and a typical second harmonic ($2f$) signal is shown in the inset of the **Figure 2**. As the modulated laser (at f) is scanned across a typical absorption line profile (Lorentzian, Gaussian, or Voigt), the transmitted on-absorption signal (at absorption line center) changes at a frequency of $2f$, and the transmitted off-absorption signal changes at a frequency of $1f$. Therefore, setting the lock-in band around $2f$ ensures that the system becomes more sensitive and selectively extracts the on-absorption signal. Also, choosing a higher f ensures a lower $1/f$ noise. Hence, the WMS technique is generally more suitable for high sensitivity applications compared to DAS. The typical absorbance limits achievable through WMS in the field are around 10^{-4} for standard WMS and 10^{-5} – 10^{-6} for balanced detection-based WMS (compared to 10^{-2} – 10^{-3} in typical DAS) [28].

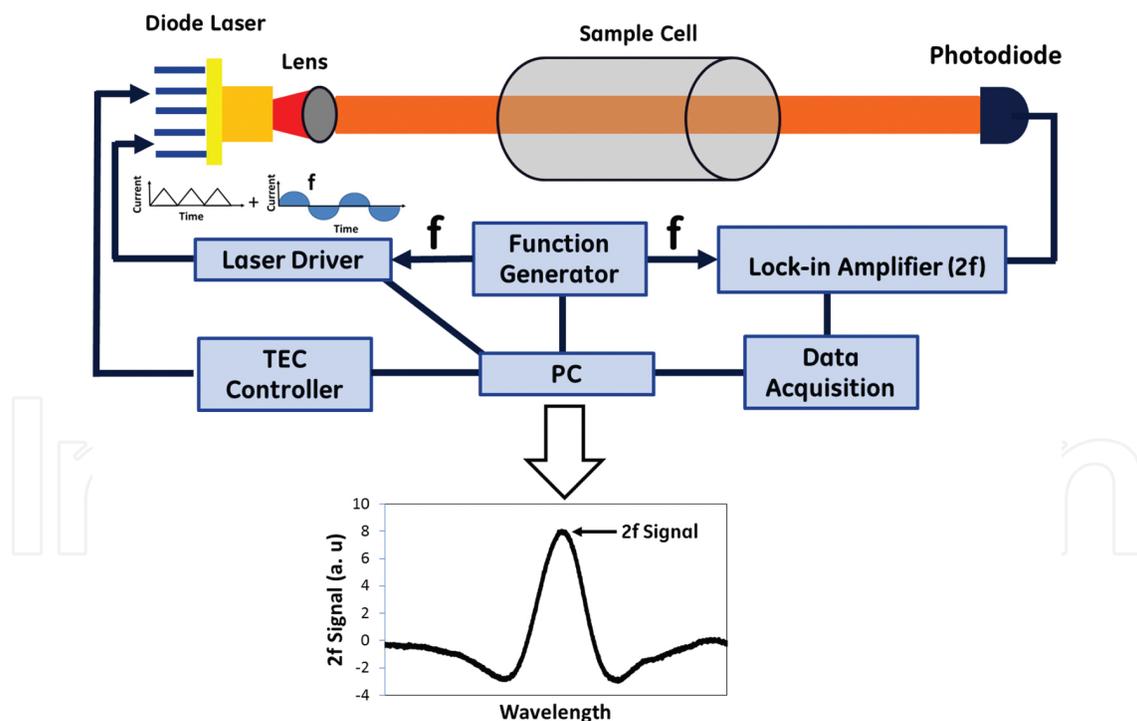


Figure 2. Schematic of a typical wavelength modulation spectroscopy system.

For WMS applications where the transmitted laser intensity fluctuates due to factors other than species concentration, an additional lock-in system is used to extract the $1f$ signal. The $2f$ and $1f$ signals are directly proportional to the transmitted laser intensity. Therefore, the $1f$ normal-

ized $2f$ signal, also known as $2f/1f$, is a good way to desensitize the WMS system to transmission intensity fluctuations caused by external influences [14]. This is a major advantage of WMS that makes it robust and field deployable in environments with high vibrations, dust load, fogged windows, and beam steering.

Another key advantage of WMS is that it is more sensitive to spectrally sharp absorption features. This is because the on-absorption $2f$ signal is stronger for larger absorption gradients around the absorption line center. The concept of modulation index (m), which is the ratio of the modulation amplitude (a) to the half-width half-maximum of the spectral line ($\Delta\nu$), is important to understand this. For a given absorption line, the optimized $2f$ and $1f$ signals are obtained at $m = 2.2$ [34]. For a single absorption line of interest, the appropriate m is chosen to meet this criterion. This makes the WMS system selectively more sensitive to spectral features of that particular width and the $2f$ contribution from broad spectral features and from molecules like water or heavy hydrocarbons that are significantly diminished. Hence, WMS is a powerful tool to overcome spectral interferences and to measure trace concentrations in complex gas mixtures.

The WMS signals are a strong function of the temperature and pressure of the sample gas, and therefore the calibration of such systems is a critical step toward ensuring accuracy and reliability. For sampling-based TDLAS measurements, sample is often filled in an absorption cell. These cells can be single pass, dual pass, or long path multipass cells [13]. The temperature and pressure of the absorption cell are controlled at fixed values, and calibration is performed at these conditions. For applications where temperature and pressure may vary, calibration is done for multiple operating conditions. Dynamic measurements of temperature and pressure combined with spectral models are then used to estimate the gas concentration as the conditions vary. For in situ applications with wide temperature and pressure fluctuations, the calibration-free WMS technique [35], pioneered by the Hanson group at Stanford University, has become widely acceptable. This technique involves thorough characterization of the instrumentation (lasers, detectors, amplifiers, etc.) and combining these details with the quantitative spectroscopy model. This semi-empirical model, where most of the real-world noise sources are accounted or corrected for, is then used to calculate the expected $2f/1f$ signal for an operating condition (known or measured temperature and pressure). The calculated signal is compared with the experimentally measured $2f/1f$ signal. The optimized concentration value in the model, which gives the best match between the two signals, is stated as the in situ concentration of the species.

3. Designing the TDLAS sensor

The design of a TDLAS system, especially for harsh environments, involves several critical steps. Details of the required detection limit, sample gas conditions, sample accessibility, installation methodology, and data reporting frequency are crucial toward designing a reliable, accurate, and robust sensor. The following subsections discuss these in more detail.

3.1. Wavelength selection

Selection of a suitable absorption line for a particular application is the first and the most important step in the sensor design process. The choice of the line is strongly dependent on the species of interest, the sample temperature and pressure, available path length, and background gas composition (background gas constitutes all the other species in the gas mixture apart from the species of interest). The HITRAN molecular spectroscopic database [36] is a fairly comprehensive database and is commonly used for simulations to assist in the spectral line selection process.

To begin, the selected spectral line should have sufficient absorbance to reach the required Lower detection limit (LDL) for the application path length, without considering interference. Absorbance values of 10^{-4} – 10^{-5} are typically achievable in industrial TDLAS systems. Coarse spectral simulations, at the appropriate sample temperature and pressure, can be used to identify the potential candidate lines in the NIR and MIR regions that can meet the detection limit requirements. It should be noted that for very low detection limits (<1 ppm), the MIR region is more promising as it covers the intense fundamental absorption bands of most molecules. Subsequently, for each of the candidate lines, a rigorous background gas interference analysis needs to be done to investigate cross-sensitivity issues and potential LDL degradation. It is critical to perform the interference analysis for the full range of background gas composition variations. A specific case is discussed below to throw more light on the spectral line selection process.

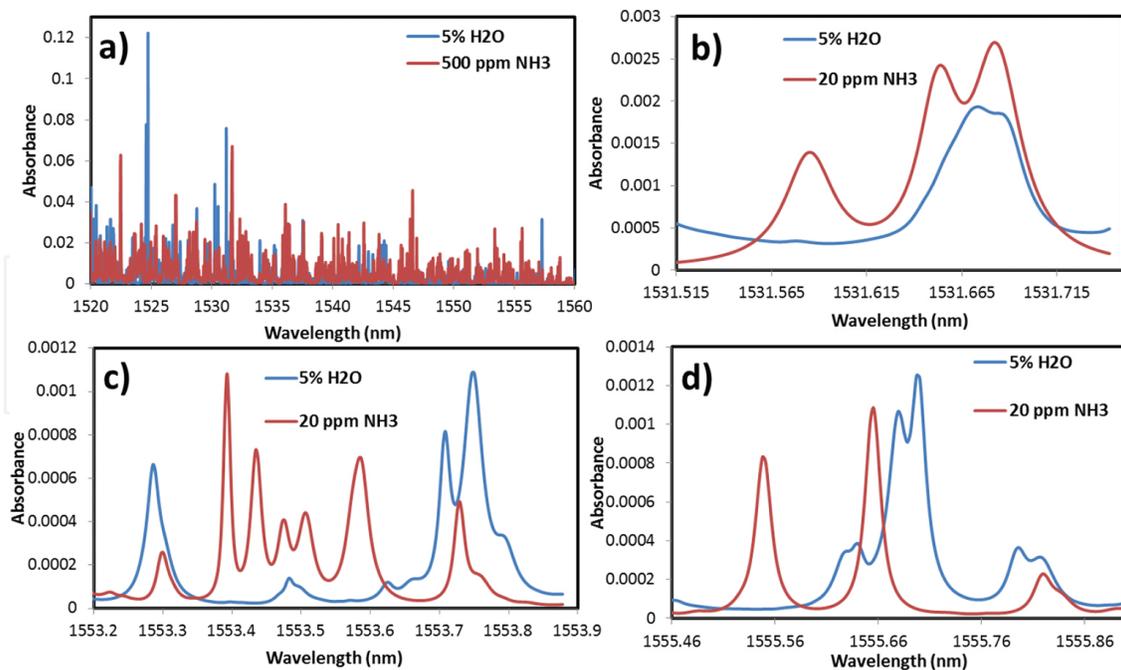


Figure 3. Spectroscopic absorbance simulations at 1.5 μm for pressure = 1 Bar, temperature = 500 K and path length = 10 m. (a) H_2O = 5%, NH_3 = 500 ppm. (b) H_2O = 5%, NH_3 = 20 ppm. (c) H_2O = 5%, NH_3 = 20 ppm. (d) H_2O = 5%, NH_3 = 20 ppm. Figures taken with permission from SPIE (From our published paper).

Assume a typical power plant emissions control application which requires measurement of ammonia (NH_3) with a sensitivity of <1 ppm at a path length of 10 m and sample gas temperature of 500 K. The average moisture level in the exhaust stream can be up to 5%. **Figure 3** shows the HITRAN spectral simulations for absorption line selection for this particular application. The spectral region around 1500 nm is good for ammonia detection because it covers strong absorption bands of ammonia. Also, this region allows for remote sensing as wavelengths around 1500 nm can be transmitted over fiber optics with low loss. **Figure 3a** shows a coarse simulation of ammonia lines (at the application conditions), with the appropriate moisture concentration. It is clear that many moisture lines are present which can potentially worsen the ammonia measurement fidelity. High-resolution simulations in shorter wavelength spans are conducted to identify three spectral lines at 1531.59, 1553.4, and 1555.56 nm where the spectral contribution of moisture is minimal. These are shown in **Figure 3b–d**, respectively. It should be noted that in all these regions, the moisture absorbance is nonzero but the spectra are relatively broader than the ammonia line. This is an acceptable solution when regions of zero background gas absorbance cannot be found. This is because, as explained in Section 2.2, WMS has the capability to be more sensitive toward sharp spectral features and can reject contributions from broad background gas features, like in this case. Once the absorption line is selected, the process of instrument development can be started as explained in the next subsection.

3.2. Optomechanical assembly and instrumentation

A well designed optomechanical assembly is crucial toward obtaining the optimum performance out of a TDLAS system and involves the following key considerations. All optical surfaces through which the laser passes, such as the laser window, the absorption cell window, and detector window, should have the appropriate antireflection (AR) coating for the laser wavelength. This ensures minimization of backscattering of photons into the laser which can severely increase the laser's excess noise. In case of fiber-coupled lasers, incorporation of an optical isolator in laser package (or right after the laser) is often a good idea to keep the excess noise in check. Furthermore, effort should be made to keep all windows wedged and tilted. This decreases the interference noise created by multiple reflections from parallel surfaces. In addition, in case of dual-pass or multipass systems, care should be taken to avoid the overlap of the different passes. This can also lead to significant interference noise in the system. Finally, all optical surfaces should be kept clean to the extent allowed by the application. It should be noted that some level of interference noise (also known as etalon noise [28]) will always be present in any practical TDLAS system as it cannot be completely avoided. However, if proper care is taken, as mentioned above, the absorbance noise level can typically be brought down to 10^{-4} – 10^{-5} , which is sufficient for most industrial applications.

On the instrumentation, front, low noise laser current drivers are recommended. However, one must remember that the system noise level is often limited by the etalon noise. So, it is often sufficient if the stability of the current driver is enough to keep itself from becoming the dominant noise source. Typically, it is acceptable to have the noise induced by current drivers at about two orders of magnitude lower than etalon noise. Similar requirements apply to the

detector as well where the thermal noise should be at least 10^{-7} – 10^{-8} in equivalent absorbance or less.

The harsh environment implementation of the system depends on the application. Free space systems [23, 24] employ a transmitter (or pitch) to launch the laser into the harsh environment and a receiver (or catch) to collect the transmitted radiation. The design of the transmitter assembly can include refractive or reflective optics to ensure that the laser is launched with the required diameter and divergence. Similarly, the design of the receiver includes optics to collect the transmitted laser and direct it to the detector. Multiple lasers can be incorporated into the transmitter through optical multiplexing. On the receiver side, these lasers can be demultiplexed using dichroic mirrors or beam splitters or other similar optical elements. Other advanced techniques, such as time division multiplexing (TDM) and frequency division multiplexing (FDM), are also employed when demanded by the application [37]. In some free space configurations, the transmitter and receiver are packaged into a single assembly, and the laser is reflected back using a retroreflector located across the sample on the other side. This typically enables a dual pass system. While free space TDLAS systems are generally used to measure the line-of-sight average species concentration or temperature, some applications toward temperature profiling have also been reported [38, 39].

Applications where a line of sight or retroreflector is not possible, TDLAS in standoff mode [25] is often employed. This approach is similar to the retroreflector configuration described above except that the return signal is due to the backscattering from the sample gas. One expected challenge in the standoff mode is to get enough backscattered signal to do a meaningful analysis. Narrowband filters are often used in front of the detector to selectively separate the detection laser from the ambient radiation. Also, large area optics (typical diameter 2–4 inches) is often employed for optimum collection of the backscattered signal. Similar to free space systems, standoff systems also measure path average concentration or temperature value.

Sampling-based systems, which use multipass absorption cells, are also used for harsh environment applications. Herriott-type [40], White-type [41], and Chernin-type [42] cells are the most well-known ones. When absorption cells are used to analyze harsh environment gases, it is a key requirement to maintain the properties of the gas mixture (to the extent possible) during sampling and analysis. This is because the change in gas properties, such as cooling, can change the concentration of the species of interest. For example, if an exhaust gas sample is allowed to cool, then the water vapor would condense out taking with it a significant amount of exhaust gases. High-temperature multipass cells [43], in combination with a heated sampling line, serve as a good solution in such cases.

Since most TDLAS applications require fast response, a real-time data acquisition system can be highly beneficial. In WMS, the detector data are collected at a high sampling frequency, at least 20–50 times the modulation frequency (f) of the system. In case of DAS, as expected, this requirement is relaxed based on the scan frequency. In WMS, the acquired data can be processed using a hardware or software lock-in amplifier to generate the $2f$ and $1f$ signals. The choice of hardware vs software lock-in amplifier depends on the application. For applications with 1 or 2 lasers, a compact hardware lock-in amplifier can be optimal. However, for

applications involving multiple lasers, the use of hardware lock-in amplifiers can be cumbersome and bulky. In such cases, an onboard PC/processor with software lock-in feature can be a much better solution. It should be noted that software lock-in features are commonly implemented in development environments such as National Instruments Labview and MATLAB. This concludes the basic overview of TDLAS sensor design and the following section will discuss some examples of how this technology is enabling real-world solutions to challenging industrial problems.

4. Harsh environment applications and examples

The applications of TDLAS and QCLAS techniques in harsh environment conditions are well known and widely discussed in the literature. The most common applications include measurement of trace gas concentrations [44–46], temperature [19, 47], combustion control [48], and plasma diagnostics [49]. It is beyond the scope of this chapter to discuss all these applications in detail. In the following subsections, two specific examples will be discussed which demonstrate the power of this technology in tackling real-world challenges where conventional techniques fail to perform well.

4.1. Steam quality sensor for steam turbine applications

This subsection is a summarized excerpt of the work published in reference [22]. Steam quality or steam wetness fraction is a critical operational parameter in steam turbines and is used in estimation of turbine efficiency and remaining life. It is a quantitative measure of the amount of water vapor and liquid water (usually microdroplets) present in the process steam. Steam quality or wetness fraction (X) is defined as follows

$$X = \frac{m_{\text{vapor}}}{m_{\text{vapor}} + m_{\text{liquid}}} \quad (5)$$

where m_{vapor} and m_{liquid} are the mass of vapor phase and mass of liquid phase, respectively.

The steam quality in a steam turbine needs to be closely monitored as an indicator of wear and tear of the machinery. The architecture of a steam turbine mainly includes three sections: HP (high pressure), IP (intermediate pressure), and LP (low pressure) respectively. The steam in HP and IP sections has little liquid water content, and therefore, the efficiency of these sections can be measured using standard temperature and pressure measurements. The LP section, however, can have steam with significant liquid water content (also known as wet steam), which can cause significant erosional damage to the rotating components [50, 51]. Therefore, the accurate measurement of steam wetness in the LP section becomes extremely critical. Most conventional methods are either based on steam sampling or based on calculations involving machine parameters (such as power output), both of which have low accuracy [22].

Therefore, a diode laser-based sensor capable of direct in situ measurement of steam quality in the hot and harsh LP section would be an ideal solution to this challenge.

As shown in Eq. (5), estimation of steam quality requires a quantitative measurement of water in liquid and vapor phases. **Figure 4** shows the schematic of a steam quality measurement system designed using two fixed wavelength broadband diode lasers. A laser at 945 nm (power 20 mW, spectral width ~ 2 nm) is used to probe the absorption of water vapor. Similarly, a laser at 1560 nm (20 mW, spectral width ~ 10 nm) is used for liquid water. Both lasers are passed through a steam chamber, which is capable of generating known vapor/liquid ratios. The path length of the steam chamber is predetermined. The intensities of both lasers before and after passage through the steam chamber are measured with Indium Gallium Arsenide (InGaAs) detectors. A comparison of the intensity loss is used to generate a quantitative measurement of the vapor and liquid concentrations respectively and hence, to estimate the steam quality, according to Eqs. (1) and (4).

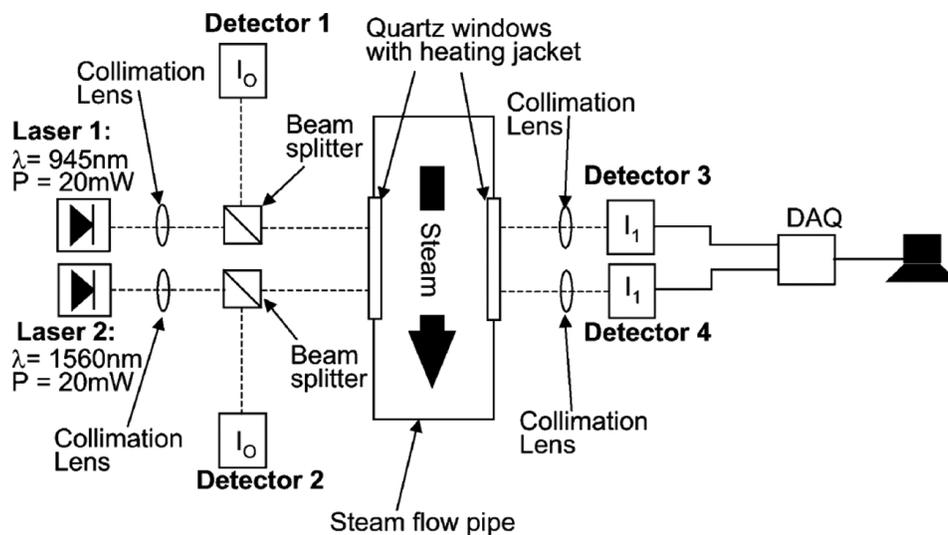


Figure 4. Schematic of the experimental setup for steam quality measurement. Figure taken with permission from IEEE (From our published paper).

Figure 5a and **b** shows a comparison of the laser-based steam quality measurement with the mass flow rate-based method under different water spray conditions. A reasonably good match is found between the two techniques and further improvements are possible through improvement of analysis algorithms for different temperature, pressure, and flow conditions. However, these results certainly demonstrate the power of laser-based techniques and the three main advantages offered in this particular application. First, this is a direct measurement of steam quality without any extraction or conditioning of the sample. The only inputs required in the method are temperature, pressure, and other standard operating parameters of the steam turbine. Second, the steam quality can be measured over a wide range (100–10%). This is a unique capability over conventional steam calorimeters which have a much smaller range of a (100–80%). Last but not the least, the measurement is real-time and can be used for better process optimization and steam turbine prognostics.

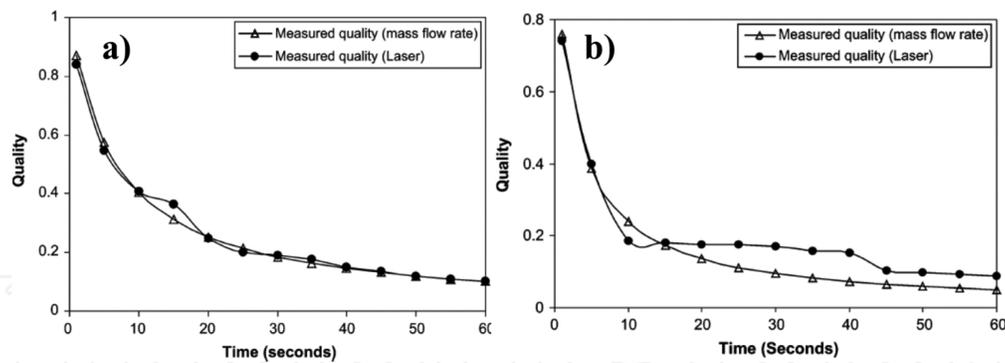


Figure 5. (a) Variation of steam quality with water spray in the steam flow pipe and comparison with calculation using mass flow rate. (b) Variation of steam quality with water spray in the steam flow pipe and comparison with calculation using mass flow rate at a different temperature, pressure, and flow rate condition. Figures taken with permission from IEEE (From our published paper).

4.2. Ammonia slip sensor for gas turbine applications

This subsection is a summarized excerpt of the work published in reference [14]. Gaseous emissions, such as NO_x , SO_x , and CO are strictly regulated by the environmental protection agency (EPA) in the United States and similar agencies around the world. To minimize NO_x emissions, a selective catalytic reduction (SCR) unit is commonly introduced in the exhaust gas path [52]. The gas temperatures in the harsh SCR exhaust environment are typically of the order of 250–380°C. The functioning of an SCR unit includes injection of ammonia (NH_3) gas to cause chemical reactions leading to reduction of NO_x into N_2 and H_2O . This process is depicted in **Figure 6**.

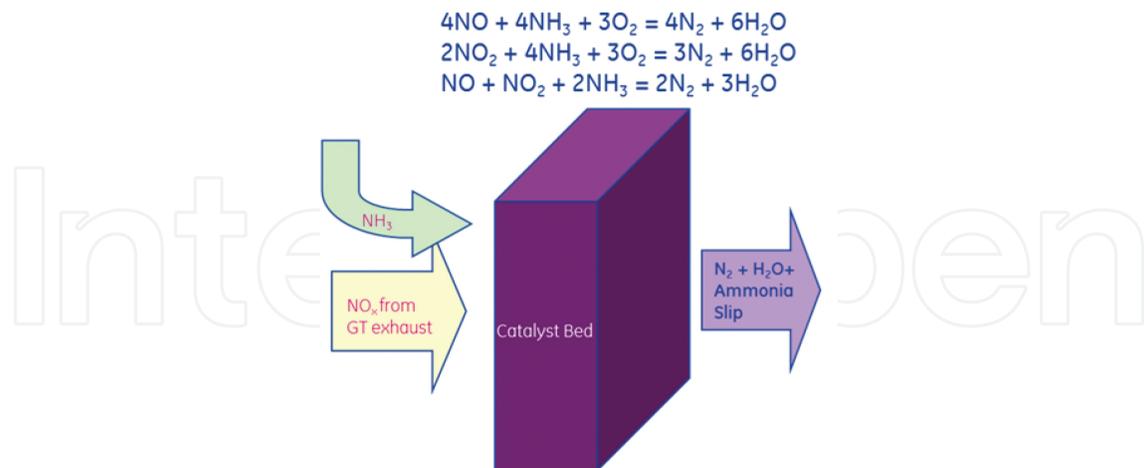


Figure 6. Schematic showing the function of a selective catalytic reduction unit in a power plant. (Figure taken with permission from Sharma et al. [14]).

The equations embedded in **Figure 6** suggest that the optimal performance of an SCR would require ammonia injection amount to vary with the NO_x generated. Too much ammonia injection leads to incomplete reaction and too little leads to residual ammonia (ammonia slip)

in the exhaust. The amount of ammonia injected is typically controlled by monitoring and minimizing the ammonia slip. The conventional sampling-based continuous emissions monitoring system (CEMS) [15] is the state-of-the-art for this application and is often believed to be suboptimal due to sampling-related measurement lags of up to 2–3 min. The most efficient and desired way of controlling the SCR is to directly measure the ammonia slip in the harsh SCR environment (without sampling). An example of how a TDLAS-based sensor can address this highly challenging real-world problem follows here.

The TDLAS sensor discussed here is designed for direct operation in an SCR exhaust so that measurement lag time is minimized. The sensor is based on a free space line-of-sight methodology employing a laser transmitter (pitch) to emit the laser radiation and a receiver (catch) to collect the radiation after passage through the SCR exhaust. A diode laser around 1.5 μm is chosen to sense ammonia. Details on spectral analysis and line selection have been presented in the Section 3.1. In a combined cycle power plant, the SCR exhaust is usually into a heat recovery steam generator (HRSG). The environment inside a HRSG is fairly harsh due to high temperatures, engine vibrations, and floating dust or impurities. The challenges around beam steering caused by temperature gradients and transmission losses due to dust particles are addressed using the $2f/1f$ WMS methodology described in the Section 2.2. A major challenge specific to this application is the thermally induced misalignment of the beam since the typical line-of-sight path length in a HRSG can be up to 10 m. Therefore, maintaining alignment through all engine-operating conditions is critical toward achieving long-term reliability.

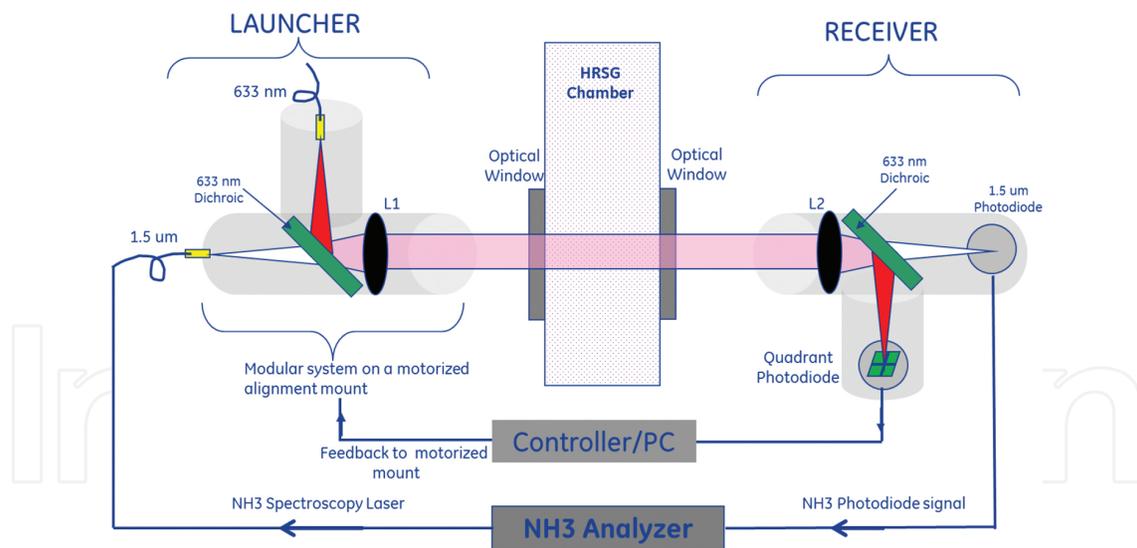


Figure 7. Schematic showing the hybrid ammonia slip sensor with alignment control and implementation in a HRSG. Figure taken with permission from SPIE (From our published paper).

The hybrid sensor, shown in **Figure 7**, is developed to address the misalignment challenge. A 633 nm fixed wavelength laser is multiplexed with the 1.5 μm ammonia spectroscopy laser at the transmitter (launcher) and demultiplexed at the receiver by using appropriate dichroic mirrors. The 633 nm laser wavelength is chosen because of two reasons: no absorption by exhaust gases and visibility to the human eye (helps in initial alignment of the system). As

shown, the launcher optical assembly is mounted on a motion control stage. The demultiplexed red laser is made incident on a quadrant photodiode which serves as a position sensitive detector. The error signal generated by the quadrant photodiode is used as a feedback signal to actively align the motion control stage to keep the red beam centered on the quadrant photodiode. As a consequence, the ammonia spectroscopy beam also remains centered on the $1.5\ \mu\text{m}$ photodiode. This leads to overcoming of measurement errors induced by thermal misalignment and enables long-term reliable operation of the sensor.

Experimental results demonstrating the performance and value of the alignment control system are shown in **Figure 8**. **Figure 8a** shows the scenario with no vibrations/misalignments. As expected, the $2f/1f$ signal stability is the same with the alignment control system on or off. This is a key check to ensure that the alignment control system does not introduce any artifacts or errors by itself. **Figure 8b** shows the scenario under induced vibrations/misalignments. With the alignment control off, the total normalized transmitted power drops close to zero in a matter of seconds, hence indicating a severe misalignment of the system. However, with the alignment control on, the system is able to actively maintain alignment over time. About 20–25% power fluctuations are still observed which are experimentally found to be well within the correction capability of the $2f/1f$ WMS technique. For more details on the tests demonstrating performance of the hybrid sensor, the reader is advised to refer to reference [14].

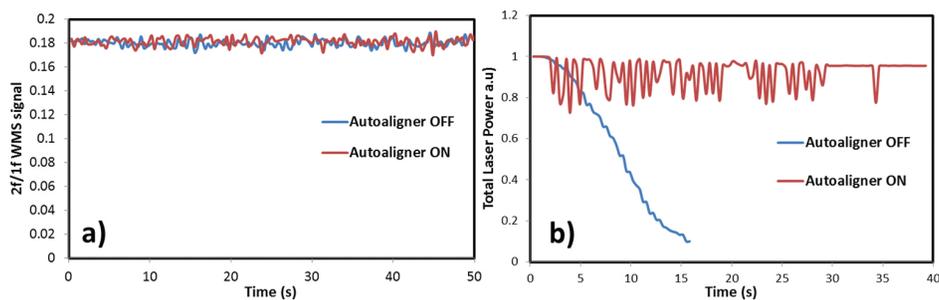


Figure 8. Experimental results showing the performance of the alignment control system. (a) $2f/1f$ WMS signals (with and without alignment control) as a function of time under no vibrations. (b) Transmitted spectroscopy laser power (with and without alignment control) as a function of time under induced vibrations. Figure taken with permission from SPIE (From our published paper).

5. Summary

In summary, this chapter presented the value and potential benefits of diode laser-based industrial harsh environment sensors. The chapter started with an overview of the industrial Internet and discussed the importance of sensors toward achieving enhanced output from industrial assets such as gas turbines, aircraft engines, and turbomachinery equipment. The discussion showed that real-time decision making through online sensors (that monitor the desired machine parameters) can enable optimized operation, performance enhancement, and extension of asset life. Subsequently, optical harsh environment sensors were introduced and the capabilities of diode laser-based techniques, that is TDLAS and QCLAS, were discussed.

The discussion was kept focused on these two most promising techniques (compared to other optical techniques) to remain within the scope of this chapter. The common implementation of TDLAS/QCLAS methodologies, that is direct absorption spectroscopy (DAS) and wavelength modulation spectroscopy (WMS), were discussed from an applied experimental perspective. The intention was to equip the reader with just the right level of information required to set up and carry out application-specific experiments. Appropriate references were provided for readers who wish to go deeper into these techniques. Next, the design philosophy and methodology behind a TDLAS sensor were discussed. Laser wavelength selection was presented as a crucial step where careful consideration to process temperature, pressure, and background gas interference needs to be given. Optomechanical configurations, namely line of sight, standoff, and extractive sampling, were then discussed followed by instrumentation and data acquisition basics. Finally, the power of diode laser technology in tackling real-world challenges was discussed using real-world examples. An in situ sensor for measurement of steam quality in the hot and harsh low pressure (LP) section of a steam turbine was presented. A solution based on two diode lasers, each targeted toward water in liquid phase and vapor phase, respectively, was discussed. Last but not the least, the chapter concluded with the discussion on a hybrid in situ ammonia slip sensor for power plant SCR control applications. A novel alignment control methodology in combination with a 2f/1f WMS scheme was shown to be an effective tool toward measuring gas concentrations in hot and harsh vibrating environments.

The field of optical and diode laser-based harsh environment sensing is rapidly evolving and is currently an area of active research in academia as well as industry. The various aspects of this technology space are being studied in details by different groups around the world and this chapter has, by no means, touched upon all of them. However, the authors do hope that this chapter has motivated the reader to think of new ideas and concepts that can advance the state-of-the-art and application areas in this space and help the industrial community realize the full potential of their valuable assets.

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