RICE UNIVERSITY

Laser Spectroscopic Trace Chemical Sensors for Environmental Sensor Networks and Portable Medical Devices

by

Stephen G. So

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

Doctor of Philosophy

APPROVED, THESIS COMMITTEE:

[Signatures]

Frank K. Tittel, J.S. Abercrombie
Professor of Electrical and Computer Engineering, Chair

Robert F. Curl, Pitzer-Schlumberger Professor of Natural Sciences Emeritus

Gerard Wysocki, Assistant Professor of Electrical Engineering, Princeton University

HOUSTON, TEXAS

MAY 2008
INFORMATION TO USERS

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleed-through, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.
Abstract

This thesis represents the development of the first laser spectroscopy based trace-gas sensors with sensor characteristics which simultaneously satisfy low cost, handheld footprint, low power, and long term autonomous operation while still providing part-per-billion detection sensitivity and negligible interference to enable trace gas sensor networks and wearable sensors. In order to realize these demanding criteria, this work describes the development of a complete laser spectroscopic sensor platform from the ground up to determine all of the tradeoffs inherent to photonic chemical sensing, and presents a sensor platform with a configuration to meet as many application requirements as possible. Specifically, complete photonic sensor integration and design optimization (e.g. digital signal processing, low power analog, digital control technology, high speed digital design, efficient programming, infrared laser technology, mechanical design) provides sensor characteristics which are significantly improved over the current sensor technology. These sensors can permit the portable deployment of trace gas sensors and enable applications previously unattainable with any other gas sensing method. A performance comparison of the various different types of sensors measured according to these new metrics of cost, size, power consumption in addition to standard metrics (such as sensitivity and specificity) will provide a complete description of advantages and disadvantages of each trace gas sensing technique. Performance characteristics of an open-access handheld sensor platform also provide the baseline for comparison in terms of all of these new criteria. This work will also detail the development path of each major sensor component to allow new technologies to update the original modules. This thesis also describes a scalable network of high sensitivity trace gas sensors, something which
has not been achieved to-date. Additionally, issues such as variable-power consumption sensor management and gas sensor data harvesting and analysis will be addressed. Several new applications will be described which may be performed with the optimized sensors which were difficult to perform previously. Finally, this thesis will extrapolate future optimal sensor configurations based on current research in MEMS, photonics, networking, integration, and sensing and will conclude with a discussion of the impact of the various advances achieved in this work.
### Table of Contents

Chapter 1. Introduction/Overview ................................................................. 1

Chapter 2. Background, Motivation, Current State of the Art ......................... 4
   A. Background: Wireless Sensor Networks (WSN) .................................. 7
   B. Background: Portable Medical Devices (PMD) ................................. 9
   C. Background: Chemical Sensing Technologies .................................. 12
   D. Background: Laser Spectroscopy .................................................. 16

Chapter 3. Optimizations of Trace Gas Sensor Characteristics .................... 19
   A. Optimization of Sensor Power Consumption ................................... 19
      1. Low Power Control Systems, Data Acquisition, and Processing ..... 21
      2. Optical Techniques .......................................................... 39
      3. High Efficiency Power Circuits .......................................... 43
   B. Sensor Size Optimization ......................................................... 49
      1. Optics Module .................................................................... 50
      2. Electronic Module .......................................................... 54
   C. Sensor Cost Optimization ........................................................... 58
      1. Laser Cost ....................................................................... 59
      2. Optics Cost .................................................................... 60
      3. Detector Cost .............................................................. 61
      4. Electronics Cost ............................................................ 61

Chapter 4. Implementation of PHOTONS Architectures .............................. 65
   A. The PHOTONS platform .............................................................. 65
      1. Frequency Synthesis and Lock-In Amplifiers .......................... 65
      2. Embedded Temperature Controller ....................................... 72
      3. Analog Front End ................................................................ 80
      4. Power Supplies and Laser Driver ........................................ 83
      5. Software and Firmware .................................................... 88
      6. Networking and Energy Storage .......................................... 90
   B. TDLAS Pulsed 4.6 μm QCL for CO .............................................. 91
   C. PHOTONS v1.0 - QEPAS at 1.5 μm for CO₂ .................................. 94
   D. PHOTONS v2.0 - QEPAS at 2.0 μm for CO₂ ................................ 97
   E. PHOTONS v3.0 - TDLAS at 2.7 μm for CO₂ ................................ 103
   F. Performance Comparisons ........................................................ 108
      1. System Metrics .................................................................. 109
      2. WSN and PMD Sensor Characteristics .................................... 115

Chapter 5. Developing with the PHOTONS platform ................................. 117
   A. Sensor Hardware Adjustments ................................................... 117
   B. Sensor Deployment ................................................................. 121

Chapter 6. Future implementations ......................................................... 122

Chapter 7. Future Prospects and Conclusions ......................................... 127

References ......................................................................................... 130

Appendix A: Acronyms ......................................................................... 136
Chapter 1. Introduction/Overview

Ideal trace gas sensors have the following characteristics: 1) a sensor with minimum size, 2) sensing that does not affect the conditions being sensed, 3) sensing with minimum power requirements, 4) sensing with maximum precision and accuracy, and 5) sensors with minimal cost. When designing a specific trace gas sensor, the degrees to which all of these characteristics can be met will determine which sensors will have the optimum level of performance for a certain application.

Trace gas sensing based on laser absorption spectroscopy (LAS) provides high performance in many of the desired sensor characteristics, which allows a wide variety of applications. The LAS methodology results in a sensor which is robust, sensitive, and selective. By fully exploiting these characteristics, these sensors have the potential to provide new applications.

Generally, sensitive and specific trace-gas sensing to measure small concentrations of a target chemical species has been difficult to achieve. Typically, the concentration of target molecules are part-per-million (ppm), per-billion (ppb), and even per-trillion (ppt), which must be measured in short timescales without interference from other molecules (high specificity). Thus, most sensors either require complex instrumentation to separate the target molecule from the mixture, or require consumable materials to interact with the sample. They also may require large changes to the sensor architecture when targeting a different molecule. Laser absorption spectroscopy offers a unique technique that provides a sensor platform which can simply change wavelengths to target different molecules
with no maintenance, no consumables, no sample preparation, and minimal interaction with the target sample.

The limiting factors in the scope of applications for laser spectroscopy are energy efficiency, cost of the sensor, and availability of lasers with the desired operating characteristics. Energy efficiency affects how much energy must be stored for the sensor to measure the target gas, affecting the deployment in applications that do not permit standard wall power. The cost of the sensor affects the scalability of sensors. Non-optimized sensor electronic systems draw unnecessary power and increase cost while lowering robustness. This thesis addresses these issues directly in order to improve the scope of applications of laser spectroscopic trace gas sensors.

The goal of this thesis is to describe the various issues in developing ultra-compact, high-efficiency, low cost laser spectroscopic sensors suitable for wireless sensor networks (WSN) and portable medical devices (PMD). Tradeoffs between sensor flexibility, sensitivity, size, and cost will be explored in detail in order to provide a framework for a portable laser spectroscopic chemical sensor platform. This thesis will also describe the implementation of various test sensors, and the ideal path of development to improve these sensors.

Exploiting the optimized technology described in this work will lead to novel applications in many areas, especially in environmental monitoring and medical diagnostics.

This thesis will be organized in the following manner: Chapter 2 provides the motivation for WSNs and PMDs, the current state of the art chemical sensing techniques available
for implementation into specific applications, and a discussion of laser spectroscopic
techniques which will provide the best performance for specific applications. Chapter 3
will describe the techniques which may be used to optimize laser spectroscopy for the
lowest electronic power consumption, the smallest size, and the lowest cost. Chapter 4
will describe the final subset of optimizations chosen from the techniques in the previous
chapter in order to develop a single sensor platform PHOTONS (PHOTOnic Networked
Sensors) for laser spectroscopy. This chapter will also discuss the experimental results for
the four different sensor architectures, which led to the final optimizations and provide a
comparison of the systems. Chapter 5 will demonstrate how to develop a sensor using the
PHOTONS platform. Chapter 6 uses the PHOTONS platform to create different
applications including WSN and PMD deployments. Chapter 7 concludes with a
summary of results and future prospects for LAS based sensors capable of low power
consumption, an ultra-compact footprint, and low cost.
Chapter 2. Background, Motivation, Current State of the Art

Trace-gas sensors based on laser spectroscopy particularly find use in environmental, medical, industrial, and security applications. Environmental sensors for methane, carbon dioxide, carbon monoxide, and water vapor [1,2,3] currently provide scientifically useful sensors, and have demonstrated high sensitivity for molecules important for atmospheric chemistry such as formaldehyde and ethylene [4,5]. LAS sensors have also seen use in medical applications in a laboratory setting, such as cell culture monitoring of carbon monoxide [6], and preliminary breath analysis studies [7,8]. Various industries have implemented laser spectroscopic chemical sensing, such as ammonia monitoring in semiconductor foundries [9], and natural gas leak detection in the oil and gas industry [10], and pharmaceuticals [11]. There has been significant research towards the detection of explosives and chemical warfare agents [12].

Deployments of these sensors are usually restricted to single point measurement, as they have been generally perceived as an alternative to laboratory instrumentation such as Fourier transform interferometers (FTIR), gas chromatography (GC), or mass spectroscopy (MS). Power consumption is typically not an issue, as laboratories have access to readily available power. A desired feature for laser spectroscopic sensors is compactness and transportability, but the footprints of typical LAS sensors are not portable in the current consumer electronic sense. Recent literature shows a push toward backpack and shoebox sized sensors [13], but this is still not suitable for wireless sensor networks (WSN) and portable medical devices (PMD). This focus on complete replacement for laboratory equipment architectures has precluded applications which
require cost-effective sensors. In this thesis, we change the target deployment from single-point sensing to the multi-point methodology of sensor networks, providing new opportunities and directions to improve gas sensing technology.

In changing to sensor network implementations (Figure 1), there is an opportunity for innovation, due to stringent requirements which have not been met. These requirements are as follows: 1) sensor networks are commonly implemented as wireless sensor networks (WSNs) since the idea is to cover a large area with sensing nodes and are usually deployed in areas without possibility for wired infrastructure. Thus, they must be deployed with batteries, solar panels, energy harvesting, or some other method of power supply and cannot draw more power than the environment can provide, since physical maintenance for many nodes is costly. 2) Sensors for WSNs must also possess an ultra-compact form factor which can be deployed anywhere. Designing and developing a dedicated infrastructure can be costly, 3) Sensors must be low cost and replicable, as resolution for real-time spatial mapping of data is directly dependent on node density, 4) Sensors must work autonomously and relay data wirelessly via radio from target nodes efficiently with no human interaction, since nodes may be numerous and sparsely located, and 5) Sensors must still provide adequate sensitivity and selectivity to satisfy trace sensing requirements.
Figure 1: A wireless sensor network (WSN) deployment creates an ad-hoc network and performs sensing at multiple locations.

Furthermore, the miniature low power framework required by the WSN technique also provides the same characteristics that portable health monitors require. Wireless battery powered operation while having cost and size suitable for the patient to handle throughout the day is the desired implementation by medical researchers in studying environmental health and disease progression. Also, being able to attach such sensors to portable electronics (i.e. cellular phones) will allow for analysis without a major departure from normal life, providing more accessible data. Such applications will lead to new body-area network applications [14].

Sensor network and portable medical applications would enable important high impact research, providing a large improvement in environmental and medical research methodologies. Since both of these applications are enabled by miniature, high efficiency, low cost sensors, the work described in this thesis will provide an optimized sensor platform targeting these three critical parameters. Each of these parameters can be optimized for singularly, but only their simultaneous combination will enable these types
of applications. Therefore, the methods to optimize for singular parameters will be described, and a carefully selected subset of these optimization procedures will be implemented in a test platform that enables WSN and PMD applications.

A. Background: Wireless Sensor Networks (WSN)

Sensor networks allow for spatially resolved long-term real-time information not possible from other types of monitoring. For environmental monitoring, the current research on greenhouse gases focuses on the carbon cycle and carbon flux sources and sinks [15,16]. One current method used to generate chemical emissions maps is self reporting by industry, which does not provide information about natural sources, and is prone to human sources of error. Another method to gather emissions source information is by ultra-high sensitivity instrumentation installed into vehicles (e.g. airplanes), and flown in cross patterns [17,18,19]. However, this technique is complex and expensive and not real-time since the vehicles cannot cover all points at a single time. Additionally, the sensitivity must be extremely high (ppt level) to detect the emissions at high altitudes after the gas has diffused. There exist field deployed carbon sensing networks deployed to measure chemical flux long term [20], but these sensors are very few in number and sparsely located. By providing a much larger number of low cost autonomous nodes which are wirelessly connected and battery powered, the nodes can be deployed without other infrastructure or maintenance, and can provide complete mapping information in real-time. This becomes important in monitoring hundreds of sq. km in carbon sequestration leak detection, industrial and natural emissions (especially methane) monitoring, agricultural monitoring [21], and volcanic emissions monitoring [22,23].
Furthermore, implementation of penalties for emissions or a carbon credit trading system (based on the Kyoto Protocol) will require precision real-time monitors with localization capability which is not currently possible [24] (see Figure 2).

![Figure 2: A map of emissions sources in the Greater Houston Area. The inset is the formaldehyde concentration measured at the University of Houston (star on map) versus wind source angle. This figure shows how single point sensing cannot distinguish spatial data, and the importance of dense wide area real-time sensing.](image)

The ideal sensor network deployment is the concept of numerous miniature "motes" creating a wireless communications mesh network, and cooperating to sense some phenomenon. Motes consist of a microcontroller, communications radio, energy source, and sensor (usually a simple sensor such as temperature, light intensity, humidity, or acceleration). Minimal further modules are embedded besides these main components, to make each mote as inexpensive and power efficient as possible.

One major missing capability which has been desired, but rarely implemented by the sensor networking community has been detection of chemicals [25,26]. Additionally, few sensors implemented into sensor networks have required such high precision control,
acquisition, and processing [27,28], making the direct adaptation of an available sensor platform to gas sensing difficult.

The WSN paradigm enables wide area monitoring with many monitoring points by targeting infrastructure [29]. By making the sensors low power, low cost, small sized, and wireless, the sensors can be deployed with a battery with optional energy harvesting to last essentially indefinitely, in a dense network to achieve high spatial resolution. They may also be deployed easily and inconspicuously due to its small size, without any wired infrastructure for power or communications.

Previous sensor networking literature has provided statistical algorithms to determine which nodes in the network should be measuring or communicating, in order to conserve overall sensor network energy stores [30]. With gas sensing, changes are typically slow and continuous (diffusion effects), providing opportunities for these sensors to interpolate data between themselves and turn off nodes which do not provide relevant information. They may also form ad-hoc relay networks to pass data wirelessly [31,32], an important feature for very long distances.

Scalability is an important issue in WSNs, and the communications protocols and hardware have been developed with hundreds of nodes in mind. The standard for WSN communication is the ZigBee alliance [33] IEEE 802.15.4 [34] standard for wireless mesh networks.

B. Background: Portable Medical Devices (PMD)

Chemical analysis is a powerful tool in modern medicine. However, there is a lack of sensors which may determine long term exposure to various chemical compounds.
Instead, medical exposures are usually determined through patient interviews [35,36]. This is unfortunate since exposure to certain chemicals may provide a trigger for various diseases, such as asthma, cancer, and autism. Studies on ground level ozone effects on asthma have been performed in [37,38]. Cancer also may have many different environmental risk factors related to dose effects which have not been precisely determined [39].

Breath analysis is a relatively new field of medical research, which allows non-invasive diagnostics of various diseases [40]. A breath test for exhaled Nitric Oxide (NO) to diagnose asthma has been approved by the Food and Drug Administration (FDA) [41]. Many other diseases have associated biomarker molecules at trace concentrations including diabetes, cancer, and organ rejection. With appropriate cost reduction and increases in robustness, the use of breath analysis can be as ubiquitous as blood pressure monitors (Figure 3). Furthermore, baseline levels may vary between different people, and long term changes may be more important for health monitoring.

Figure 3: Breath analysis will provide powerful new health diagnostic and monitoring tools. Portable laser spectroscopic sensors can provide disease state monitoring similar to portable blood sugar monitors for diabetics.
For example, with diabetes monitoring, blood glucose levels would vary throughout the day depending on diet, medicinal dosing, and physical activity. A non-invasive monitor may determine whether a standard blood test is necessary, or, if specific enough, may replace an invasive test altogether.

Industrial workers also have limits in the United States for their Occupational Health and Safety Administration (OHSA) Permissible Exposure Limit (PEL) to certain chemicals [42]. With personal monitors measuring in real-time with long term networked data logging, safety and efficiency of the workers will improve, and new guidelines can be generated based on the new data generated from such monitors.
C. Background: Chemical Sensing Technologies

Many chemical sensing methods have issues which may preclude their use in WSNs or PMDs. Currently, a majority of the methods for gas sensing have either had small size or high specificity, but not both simultaneously. A comparison of the methods is provided in Table 1.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Based</td>
<td>Small</td>
<td>&lt;$500</td>
<td>-</td>
<td>ppb</td>
<td>yes</td>
<td>Affects Conc.</td>
<td>Consumables</td>
</tr>
<tr>
<td>MS/GC-MS/IMS</td>
<td>Medium</td>
<td>$40k+</td>
<td>10W+</td>
<td>ppb/ppt</td>
<td>yes</td>
<td>Mass overlap</td>
<td>Sample Prep</td>
</tr>
<tr>
<td>Electro-chemical</td>
<td>Very small</td>
<td>&lt;$500</td>
<td>&lt;1-5W+</td>
<td>ppt</td>
<td>yes</td>
<td>Poor</td>
<td>Short Life</td>
</tr>
<tr>
<td>FTIR</td>
<td>Large</td>
<td>$40k+</td>
<td>10W+</td>
<td>ppt</td>
<td>no</td>
<td>Size Dep.</td>
<td></td>
</tr>
<tr>
<td>Raman</td>
<td>Small</td>
<td>$10k+</td>
<td>10W+</td>
<td>ppb</td>
<td>yes</td>
<td></td>
<td>Sample Contact</td>
</tr>
<tr>
<td>NDIR</td>
<td>Very small</td>
<td>$3k+</td>
<td>3W+</td>
<td>ppb/ppt</td>
<td>yes</td>
<td>Filter Dep.</td>
<td></td>
</tr>
<tr>
<td>TDLAS</td>
<td>Medium</td>
<td>$10k+</td>
<td>1-4W+</td>
<td>ppt</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavity Enhanced</td>
<td>Medium</td>
<td>$15k+</td>
<td>1-4W+</td>
<td>ppt</td>
<td>yes</td>
<td></td>
<td>Alignment</td>
</tr>
<tr>
<td>PAS/QEPAS</td>
<td>Small</td>
<td>$10k+</td>
<td>1-4W+</td>
<td>ppb</td>
<td>yes</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Chemical methods have the ability to measure minute concentrations. For example, a chemical test based on O-(2,3,4,5,6-pentafluorobenzyl) hydroxylamine (PFBHA) analysis can be used for detection of formaldehyde in air [43]. This method requires additional analysis by GC afterwards. Specificity is high as it targets molecules with carbonyl compounds, which can be separated from other species in the measurement phase. However, the measurement affects the concentration directly due to its destruction.
of the sample. Additionally, the reaction must be reversed to measure a new value, causing considerable autonomy issues. Some reactions are non-reversible, and thus would require considerable replacement for long term high temporal resolution measurements.

Another gas measurement method is Gas Chromatography (GC)/Mass Spectrometry (MS) which is the gold standard in gas phase chemical analysis. Additionally, there are Ion Mobility Spectrometer (IMS) based systems working on similar principles. These sensors provide high sensitivity and specificity for multiple species, but require sample preparation [44]. Additionally, there exist various molecules with similar atomic weights, causing mass overlap crosstalk between the chemical concentrations. There has been significant research towards miniaturized GC-MS [45], and the limiting factor is creating a path for the molecules long enough to separate similar sized molecules for high specificity. A miniaturized ion trap array spectrometer reported in [46] still required tabletop based footprint, and provided a relatively complicated sensor architecture. Additionally, the measurement frequently destroys the sample.

Electrochemical sensors are the current sensor of choice when considering small size and low cost. Commonly, metal-oxides are used for the sensor material [47], with very high sensitivity. Some sensors require a considerable electrical power to heat the sensor to 300-500+ °C [48] for optimum performance, causing other problems such as increased reactions and decomposition of chemical species. However, these sensors also have a short lifetime and are fragile. Since electrochemical sensors must be directly in contact with the analyte, they may corrode if the target species is reactive. Thus, these sensors are not suitable in applications requiring long-term operation. Furthermore, these sensors also have limited selectivity, typically sensing numerous other similar compounds resulting in
crosstalk. Thus, these sensors are deployed in large arrays when specificity is required to perform correlations between different sensors [49]. These sensors also require different materials to sense a different molecule, which is an issue when selecting another target chemical species. Additionally, the 500 °C temperature is not safe for portable medical applications.

Fourier Transform Infrared (FTIR) interferometry is the gold standard for optical techniques. FTIRs are highly sensitive and specific, and minimally affect the sample when measuring. However, a moving mirror Michelson interferometer is the basis of the FTIR design, and moving parts are undesirable in long term field deployable sensor applications. The FTIR spectral resolution is related to the optical path lengths of the Michelson interferometer. Thus, a FTIR based sensor requires a large size for high specificity [50]. The sensors also require processing power to decode the Fourier transform interferogram of the signal.

Raman spectroscopy can also provide gas concentration measurements. This involves measuring the Raman effect [51]. The optical power requirement to achieve good performance is large, and is not suitable for long term measurements in the field for WSNs. In Surface Enhanced Raman Spectroscopy (SERS) [52], the signal is amplified by ~$10^{11}$. However, surface enhancement only occurs on the surface of a material, which puts a component of the sensor in direct contact with an analyte, which may cause some of the same robustness issues as electrochemical sensors described above.

Non-dispersive Infrared sensors (NDIR) are another optical technique which is based on absorption spectroscopy, but typically uses a broadband IR source such as a lamp or LED. The radiation passes through the absorbing medium over a certain path, and the
wavelengths of light which are not absorption frequencies of the target molecule are filtered by a non-dispersive element. This requires calibration based on the zero-gas detector signal. These types of sensors possess limited specificity, with crosstalk due to the broadband radiation source, and the non-ideal bandpass filtering, a necessary characteristic of useful trace gas sensors. However, these sensors provide robust and simple maintenance free operation. Good examples of these types of sensors are produced by Vaisala [53], which have implemented the filter as a micromachined Fabry-Perot Interferometer, which allows applications targeting sensor networks [54].

The three types of laser absorption spectroscopy (LAS) [55] are TDLAS, cavity enhanced, and photoacoustic spectroscopy, which have been studied in this work. Sensors of this type are capable of excellent sensitivity, specificity, require no consumables, and can be made robust to most environments, including chemical process control environments. These LAS sensors are also frequently used in monitoring applications due to its ability to separate the active components of the sensor from the sample, such as in combustion diagnostics. Thus, such sensors offer the most suitable sensor architecture for WSN and PMD technologies. Background for these absorption techniques will be given in the next section.
D. Background: Laser Spectroscopy

Infrared laser spectroscopy has the potential to meet all of the requirements for WSNs and PMDs. The issues preventing implementation in these applications (which we address in this thesis) have been cost, size, and power consumption.

The two main types of laser spectroscopy are tunable diode laser absorption spectroscopy (TDLAS) and photoacoustic spectroscopy (PAS). The main physical phenomenon behind these types of sensing is the Beer-Lambert law of absorption:

\[ I = I_0 e^{-\alpha(v) \cdot l} \]

where \( I_0 \) is the initial intensity of light, \( l \) is the optical path length which the light intensity traverses, \( \alpha(v) \) is the absorption coefficient of the gas,

\[ \alpha(v) = C \cdot S \cdot g(v - v_0) \]

where \( C \) is number of molecules of absorbing gas per unit volume \([molecule \cdot cm^3]\), \( S \) is the molecular line intensity \([cm^{-1}/(molecule \cdot cm^{-2})]\) and \( g(v - v_0) \) is the normalized lineshape function of molecular absorption \([cm]\) which may be Gaussian, Lorentzian, or Voigt and \( C \) is the concentration of the trace species.

In the case of TDLAS, a photodetector is employed to directly measure \( I \). In the case of PAS, the absorbed radiation creates heating, and the heating is modulated to produce acoustic pressure waves that can be detected by an acoustic transducer.

Sensors based on infrared laser spectroscopy require 3 major modules which are 1) the laser source, 2) the absorbing medium, and 3) the detector (Figure 4). The infrared light source is typically a semiconductor laser. The absorbing medium is enclosed within a gas chamber, and in the case of TDLAS, some method of folding the optical path with
mirrors is also integrated. The detector is typically a photodiode for TDLAS, and a microphone in PAS.

![Diagram of laser absorption spectroscopy](image)

*Figure 4: Laser absorption spectroscopy over a path $L$ causes decay in intensity $I_0$ to $I$ due to a chemical's optical absorption spectrum.*

Cavity enhanced methods which use high reflectivity mirrors provide longer effective paths for TDLAS. Cavity enhanced methods include integrated cavity output spectroscopy (ICOS), cavity ring down spectroscopy (CRDS), and Noise-Immune Cavity-Enhanced Optical Heterodyne Molecular Spectroscopy (NICE-OHMS). These techniques are suitable for laboratory instrumentation, but not field deployable applications due to robustness issues. Small misalignments can cause changes in the cavity, requiring new calibrations, or even make the measurements impossible.

Another type of spectroscopy based on laser absorption is evanescent wave spectroscopy, which uses the electromagnetic (EM) fields which leak out of a waveguide or an optical fiber to provide the radiation to the absorbing medium [56]. The waveguide approach may also be used with hollow core photonic crystal fibers to allow the path to be contained within a photonic crystal fiber, with the gas injected into the hole structure [57]. These will be combined with standard TDLAS configurations.

Photoacoustic spectroscopy (PAS) techniques modulate the radiation around the absorption line to cause periodic heating in the sample, generating acoustic pressure waves [58]. The pressure waves are built up inside an acoustic resonator. These waves
may be detected by an audio microphone. These techniques can be very sensitive, although they can be affected by ambient vibration if not properly isolated [59].

The quartz-enhanced photoacoustic spectroscopy (QEPAS) technique [60] uses the same principle as standard PAS, but builds up the energy in a standard quartz piezoelectric crystal used for precision timing in wrist watches and electronic devices. The high Q factor of the resonator allows for a large energy storage capability.

It is desired that the laser used as a spectral source provides monochromatic light at a precisely selected wavelength. To achieve this, single mode operation of the laser is required. The main methods for wavelength selection are distributed feedback (DFB) gratings [61] and external cavity (EC) configurations [62]. DFBs are the wavelength selection method of choice for miniaturized sensors due to the simplicity and robustness of the controls necessary to target a specific wavelength within the lasers tuning range.

By varying the temperature of the laser via a Peltier element or Joule heating by current control, the grating period increases, which provides a longer resonant wavelength. In addition, lack of moving parts provides additional robustness for portable applications. On the other hand, EC configurations provide a wider tuning range to target many molecules, trading off complexity and robustness for sensor flexibility.

The advantages and drawbacks to the various types of laser spectroscopy for adaptation to WSNs and PMDs will be explored in the following chapters.
Chapter 3. Optimizations of Trace Gas Sensor Characteristics

This chapter will describe the various optimizations possible to decrease size, cost, and power consumption individually. Each sensor characteristic can be optimized to meet specific applications requirements, and this chapter will explain the advantages and drawbacks, the relative importance, and the effect on other sensor parameters for various optimization strategies.

A. Optimization of Sensor Power Consumption

Electrical power consumption is an often overlooked parameter for gas phase chemical sensors. However, power consumption directly affects deployment ability, especially when targeting portable and field deployable applications.

With low enough power consumption, energy harvesting (e.g. solar, piezoelectric) can power a sensor to operate continuously without recharging or replacing batteries, and without a wired infrastructure for power.

Power consumption of the sensor is one major advantage laser spectroscopic sensors should have versus other gas sensing methods; however, this requires adapting the TDLAS and PAS architectures to handle software and hardware optimizations available for embedded sensor systems.
The main power draw by laser spectroscopic sensors primarily comes from the control and acquisition systems, the efficiency of the firmware for those systems, and the laser power systems required for the different spectroscopic methods.

Power consumption in laser based trace gas sensors based on laser spectroscopy can be represented by the following the expression:

\[ P_{\text{total}} = P_{\text{bias}} + P_{\text{bias-loss}} + P_{\text{actrl}} + P_{\text{actrl-loss}} + P_{\text{acq}} + P_{\text{proc}} + P_{\text{loss}} + P_{\text{pump}} + P_{\text{det}} \]

\( P_{\text{bias}} \) is the power required to bias a specific semiconductor laser, which is currently \( \sim 0.25\)W for DFB diode lasers, \( \sim 0.05\)W for vertical cavity surface emitting lasers (VCSEL), and \( \sim 1\)W for high wall-plug efficiency continuous wave (CW) DFB quantum cascade lasers (QCL) [63]. \( P_{\text{bias-loss}} \) is the loss due to inefficiencies in supplying the voltage and current to the laser, typically 10-50% of \( P_{\text{bias}} \). \( P_{\text{actrl}} \) is the power used to reach a certain temperature using a Peltier thermoelectric cooler for DFB wavelength tuning, or external cavity tuning. If keeping the same temperature for the laser as ambient conditions, this power is equal to \( P_{\text{bias}} \) in order to prevent the temperature rise. However, TECs are non-ideal elements, and typically would double the required power to pump out an equivalent amount of heat power. Additionally, a term \( P_{\text{actrl-loss}} \) is associated with the power supply, acting similarly to \( P_{\text{bias-loss}} \). \( P_{\text{acq}} \) is the power required to generate and acquire the signal, which depends on the ADC and any support circuitry (clocks, amplifiers, glue logic). \( P_{\text{proc}} \) is the power required to process the resulting digital data (before this work \( 4\)W+) and perform control loops. \( P_{\text{loss}} \) is similar to \( P_{\text{bias-loss}} \) and \( P_{\text{actrl-loss}} \), except it is associated with loss attributed to providing \( P_{\text{acq}} \) and \( P_{\text{proc}} \) lumped
into a single term, since they usually share the same power supply. \( P_{\text{pump}} \) is the power required for any gas handling system required to pump the gas chamber. This power depends on the size of the chamber, and the efficiency of the pump. \( P_{\text{det}} \) is the power required to detect the radiation, which depends on amplifiers, bias current for the detectors, and temperature control of the detectors. Each of these sources may be targeted directly in order to reduce overall power consumption and these techniques will be described in the rest of the section.

1. **Low Power Control Systems, Data Acquisition, and Processing**

This section focuses on reducing \( P_{\text{acq}} + P_{\text{proc}} \). These two terms are typically the most important factors in overall sensor power consumption in the sensors described in the literature.

The main methods within the literature have so far centered on high speed digital implementations for the signal processing of laser spectroscopy, rather than efficient embedded approaches. The main methods in the laser spectroscopy literature for signal processing have been 1) Laptop computers or single board computers with interfaces to PCMCIA, ISA, USB, PCI, PCIe, PXI data acquisition cards [64], 2) field programmable gate arrays (FPGA) [65], and 3) High speed DSPs [66]. The first implementation by the author of this thesis for integration of laser spectroscopic sensors in [67] was a 150MHz pipelined 32 bit digital signal processor (DSP) implementation. Several references report microcontroller implementations [68,69,70], but use less sophisticated laser spectroscopic architectures since new electronic sensor architectures to accommodate
reduced processing resources are not straightforward. Those which provide microcontroller implementations while preserving sensor performance have not explored the latest power management methods. Consequently, before the work described in this thesis, control system power consumption was never reduced to $<1.5\text{W}$ [71,72,73] even using microcontroller implementations which specifically target low power, and a systematic analysis of laser spectroscopic power consumption has not been performed.

Issues with the current implementations of laser spectroscopic processing for use in WSNs and PMDs are numerous. Laptops and single board computers require wall plug power or exceedingly large batteries to last more than 1 day. The lowest power standard x86 computers require 5W with standby power of 0.1W, and have a high cost. This does not include the cost and power consumption of data acquisition systems. Examples of sensors which used this technique are described in [64]. FPGAs are an improvement in required power consumption, drawing 5 $\mu\text{W}$ in a static mode in the case of very low power FPGAs, and low power in active mode, depending on clock speed and capabilities [74]. However, a DSP core is required to perform the processing required for laser spectroscopy which increases power consumption over DSPs in actual silicon, due to overhead. Using actual DSPs with integrated peripherals reduces the overhead in generating a DSP core in FPGAs, and can provide processing power of 150 million instructions per second (MIPS) using $<0.5\text{W}$. Microcontrollers have much lower processing power which makes it difficult to directly process a data stream, especially at the higher frequencies necessary to reduce noise using direct sampling methods. However, ultra low power microcontrollers can have nW standby power and mW active power which is important for sensors capable of long term field deployment.
Power consumption in complementary metal oxide semiconductor (CMOS) systems increases with the following equation:

\[ P_{proc} \propto fV^2 \]

where \( f \) is the switching frequency and \( V \) is the voltage across the CMOS structure.

As virtually all processors use CMOS as their logic structure, this is currently one of the dominating power relationships in laser spectroscopic sensors. The laser spectroscopic community has stressed fast onboard processing, resulting in \( f \) being very high. In [67], \( f \) was 150MHz when using the TI TMS320F2812 processor. Some modern DSPs reach >1GHz [75]. In contrast, low power microcontrollers such as the TI MSP430 have clock speeds of 16 kHz to 16 MHz. Increased frequency also requires increased voltage to drive the logic levels faster, causing further increase in overall power consumption when requiring high speed processing.

Thus, power greatly increases with frequency, and the high clock rates will have processing power dominate over physical sensor power, as seen in most of the sensors in the literature. It is usually undesirable to decrease frequency, as the best performance of laser spectroscopic sensors occurs at high bandwidth. Fortunately, improvements to semiconductor process technology have led to lower power consumption. The current microcontroller technology semiconductor processes (typically 90nm) decreases processing power consumption by the application of Moore’s Law in general, since smaller transistors require less power. However, there are methods to improve power consumption faster than Moore’s Law, capitalizing on developments in embedded
systems research, signal processing, and considerable development in consumer portable electronic equipment.

*Data acquisition methods*

Methods for signal acquisition and processing in laser spectroscopic sensors have focused on two major approaches: 1) direct high speed sampling and processing and 2) lock-in detection. Data acquisition requirements for each laser spectroscopic technique are shown in Table 2.

<table>
<thead>
<tr>
<th>Spectroscopic Method</th>
<th>Requirements</th>
<th>Bandwidth</th>
<th>Resonant Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDLAS – Scan</td>
<td>Scan over 1/f noise</td>
<td>&gt;1kHz</td>
<td>N/A</td>
</tr>
<tr>
<td>TDLAS – WM</td>
<td>Lock-In, non-resonant</td>
<td>&gt;10kHz</td>
<td>N/A</td>
</tr>
<tr>
<td>PAS</td>
<td>Lock-In, resonant</td>
<td>10kHz</td>
<td>Q = ~200</td>
</tr>
<tr>
<td>QEPAS</td>
<td>Lock-In, sharp resonance</td>
<td>32kHz</td>
<td>Q=~10,000</td>
</tr>
<tr>
<td>ICOS – WM</td>
<td>Scan, optional Lock-In</td>
<td>10kHz</td>
<td>N/A</td>
</tr>
<tr>
<td>CRDS</td>
<td>Ultra fast sampling</td>
<td>25MHz</td>
<td>N/A</td>
</tr>
<tr>
<td>NICE-OHMS</td>
<td>High frequency Lock-In</td>
<td>400MHz</td>
<td>High</td>
</tr>
</tbody>
</table>

*Direct Sampling Methods*

Direct sampling methods sample the signal at high frequency, and usually provide a sawtooth waveform to periodically scan over the target absorption line at frequencies of 1-10kHz to sample the full spectrum of the target line. The photodiode signal is sampled by a high-bandwidth ADC, and the points are used to compare with reference spectra. This requires a high speed processor to perform least squares linear fitting in real-time to make full use of the entire spectral data set.

Direct sampling is effective in pulsed TDLAS configurations. Typically, a high speed ADC (>10MSPS) digitizes the high bandwidth signal to resolve multiple points of the pulse shape; otherwise a boxcar/gated integrator or sample-and-hold scheme is used to
extract the pulsed signal from the signal sections with minimal data [76]. In the case of TDLAS sensors which produce the pulsing externally to the acquisition system, a second time base to synchronize the sampling which is phase locked to the pulse time base must be generated.

Direct sampling is also used in CRDS, but in a different approach. The power built up in the cavity takes time to decay, depending on the concentration. Thus, the measurement needs to have extremely high time resolution to determine the decay time constant precisely. Hence, CRDS has one of the highest bandwidth requirements, and therefore an especially high processing power requirement.

Fast sawtooth methods rely on co-averaging of spectra by putting each result of a scan into a memory block and averaging each individual channel. To minimize power in sawtooth configurations, the hardware must be able to co-average spectra efficiently. Scans must occur relatively fast, and be aligned with previous scans to avoid electronic broadening of the spectrum.

A pulsed TDLAS system described in Chapter 4.B provided fast acquisition, co-averaging, and normalization, implemented using a DSP. Significant additional power optimization of this pulsed sensor is possible by using an FPGA or ASIC with parallel arithmetic logic units (ALUs), and streamlining the hardware to handle the spectral data which has periodic data locality and task parallelism (see Figure 5).
Figure 5: Data locality and task parallelism in sawtooth modulated laser spectroscopy. The data for a single point comes periodically, so providing normalization and fetching previous data for moving averages must be performed every point. A processor with parallel ALUs would allow for lower clock speeds without compromising latency. The capital letters denotes the independent signal channel spectra A, B, and C. The lower case a,b,c denote the reference channel.

The periodic data locality is due to sawtooth modulation using the same memory locations each time for each scan. The task parallelism is due to the co-averaging of a signal and reference channel, and various normalization tasks. By optimizing this type of system, the clock speed of the FPGA/ASIC can be lowered dramatically without compromising latency of the processed measurement result. Instead of re-calculating the signal average, the reference average, then the normalized result for each point in order, the algorithm may perform the averages and normalization in parallel. Assuming the ALU functions take equal time, the clock rate may be reduced by a factor of 3, providing
an immediate savings of power. Additionally, lower clock rates allow lower voltages for the processor, greatly reducing power consumption.

An external sample-and-hold is typically used when the ADC time base cannot be asynchronously triggered or if the ADC cannot sample fast enough to acquire 2 successive pulses with separate start-of-conversion (SOC) signals. Good examples of sensors which use this external sample-and-hold method are in [67,76]. One way to save processing power in pulsed configurations is to clock the pulse acquisition time base with a clock skewed ADC sampling signal, removing the necessity for external sample and hold capability. In a custom acquisition system, a second ADC is easily implemented since they are low power, low cost, and small, or pulsed versions of the SOC can be logical OR’d to use a single ADC, as long as it is fast enough to convert consecutive samples (see Figure 6). Thus, this is one case where direct translation of the circuits used in laboratory configurations does not provide optimized performance.
Figure 6: Comparing external sample and hold with internal methods for pulsed signal sampling. If the ADC is fast enough, a pulsed version of the ADC start signals can be logical OR'd to use a single ADC. Internal sample-and-hold uses less high bandwidth circuitry.

It is optimizations of this type which provide large amounts of power optimization by using less circuitry. This example presented a solution for pulsed mode; however, continuous wave (CW) methods generally achieve better detection limits in shorter times, which allow the processing and laser drive to go into an idle mode sooner.

Sawtooth scanning with direct sampling provides good performance; however, lock-in detection can provide much better performance in terms of power and noise immunity, while keeping the modulation frequencies high.
Many of the methods for laser spectroscopy require lock-in detection. Every laser spectroscopic method (except CRDS) would benefit from low power lock-in amplification, allowing for a single basic electronic architecture. For QEPAS and PAS, the periodic modulation provides a signal which can be demodulated at the second harmonic using lock-in amplifiers (LIA). For TDLAS, wavelength modulation provides high baseline fluctuation immunity which is also demodulated using LIA. Thus, a low power, low cost, miniature lock-in solution benefits the spectroscopic methods, and actually allows for almost identical implementations of electronics architectures.

*Lock-In amplifier methods*

Lock-in amplification provides a method to extract a signal buried in noise through phase sensitive detection. This method also moves the frequency band of the signal above any 1/f noise which may exist by modulating the signal at a high frequency. Lock-in amplification is a synchronous homodyne detection technique which mixes a local oscillator at the frequency of interest to down-convert the high frequency signal to DC.

Lock-in amplifiers mix the signal of interest $u(t)$ and local oscillator signal $v(t)$:

$$u(t) = a \sin(\omega * t + \varphi)$$

$$v(t) = B \sin(\gamma * t + \alpha)$$

so that

$$u(t) * v(t) = aB \frac{1}{2} (\cos[(\omega * t + \varphi) + (\gamma * t + \alpha)] + \cos[(\omega * t + \varphi) - (\gamma * t + \alpha)])$$

When $u(t)$ is matched in phase and frequency ($\omega = \gamma$, $\varphi = \alpha$) to $v(t)$ the resulting signal is:

$$a \cdot B \frac{1}{2} (\cos(2\omega t + 2\varphi) + 1)$$
which is then low pass filtered to remove the second harmonic signal to leave a DC signal with the signal amplitude $a$ multiplied by the constant $\frac{B}{2}$.

To minimize the amount of power loss from all sources, the most efficient method to sense the signal is to make sure the SNR is maximized at all times. This can be implemented by locking the center laser wavelength of the absorption peak, thereby reducing the amount of time in the spectral wings where the absorption is lower to reach the desired detection limit more quickly. This approach will allow the system to measure quickly and then immediately go into an idle mode. To lock the line, a useful error signal is the third harmonic $3f$ of the absorption signal. The $3f$ signal has a zero crossing in its spectrum at the absorption peak, and has a sharp slope, providing a suitable signal to provide compensation. The $1f$ signal also has a zero crossing, but can have an offset shift if the absorption peak is non-symmetric. The $3f$ signal has lower amplitude, but is less affected by baseline fluctuations.

There are various ways to implement a lock-in amplifier in a power efficient manner. These methods are 1) a DSP based solution using numerical multiplication of an ADC sampled signal using arithmetic logic units, 2) analog multiplier based solutions using special circuits such as four quadrant multipliers or Gilbert cells to multiply the LO waveform with the signal waveform, and 3) a switching configuration using inverting and non-inverting gain (Figure 7).
Figure 7: Basic LIA architectures based on DSP, analog multiplier, and switched gains.

A DSP based solution is the most common implementation in commercial laboratory instrumentation. The signal from a preamplifier is directly sampled by a wideband ADC. The digital signal is multiplied by a sinusoid at the LO frequency, and then filtered by a digital filter. The LO is generated from a reference clock or its harmonics, usually by PLL. Having quadrature phases requires twice the processing power to multiply the signals in real-time.

The second method for LIAs is to use an analog multiplier. Examples of analog multipliers are the Analog Devices AD835 [77], Texas Instruments MPY634 [78]. The basic circuit architecture of analog multipliers is the Gilbert cell, which is a cross-coupled differential amplifier. The signal is directly multiplied with an analog LO. The signal is low pass filtered, and sampled with an ADC which can have low bandwidth. Noise, offset, and drifts are issues with analog multipliers, which can be solved at a cost of complexity and size. Quadrature phases require a second analog multiplier.
Lock-in amplification using a switched gain configuration provides less complexity with a tradeoff of higher effective noise bandwidth (ENBW) due to detection of the odd harmonics of the lock-in reference frequency [79]. The odd harmonic detection is caused by the multiplication of a square wave LO instead of a sinusoid. Therefore, sinusoidal based multipliers are typically a better method for laboratory bench-top instrumentation where a wide variety of experimental setups must be accommodated. A laser spectroscopic wavelength modulation signal has very specific frequency characteristics, and the signal can be filtered to remove the harmonics outside the frequencies of interest, avoiding the higher ENBW. The resulting output signal is handled the same way as the analog multiplier method: low pass filtering and sampling with a low bandwidth ADC. Quadrature phases require double the switching circuitry. To implement one of these configurations, a Gilbert cell may be used with a digital clock signal instead of an analog signal, which saves power in generating clean synchronized sinusoidal waveforms from digital controllers. Another method is to provide a balanced inverting and non-inverting gain, and toggle between them using an analog switch.

One approach to saving power in LIAs is under-sampling the signal to provide a much slower data stream. According to the Nyquist criterion, to completely reconstruct a signal with energy contained within a bandwidth $BW$, the sampling rate $f_s$ must be $f_s = 2 \times BW$. However, knowledge of the signal's structure (a sinusoid) allows for a type of compressive sensing, significantly reducing the required rate of data acquisition. Putting this technique into practice can be demonstrated using a simple microcontroller example. To demonstrate an under-sampled LIA using the TI MSP430, an experimental lock-in measurement of the sinusoidal amplitude of a semiconductor laser current monitor is
described. The current monitor has a bandwidth higher than the modulation frequency of 16384 Hz. The ADC clock was set at some random non-integer multiple of the modulation frequency. The ADC was shared to measure multiple signals so that the effective sampling rate of the signal of interest was ~2.5 kHz. Each time the ADC took a sample, a processor interrupt was generated which noted the time of the sample, and converted the time base to an angle within a sinusoid look-up table (LUT) in memory (Figure 8).

![Figure 8: An example of a timer value to sine look-up table value mapping. The highlighted points named 'sampled' are the positions that are accessed when the sampling frequency is lower than the reference frequency.](image)

The signal and the sinusoid LUT value were then multiplied, and low pass filtered to yield the LIA result. The results showed that the signal was locked in using fewer samples than the Nyquist rate (Figure 9). The quadrature phase is also efficiently calculated by moving 90 degrees within the LUT.
Figure 9: Digital Lock-In of 16kHz bias current monitor by sampling at 2.5kHz. The AC component of the laser bias was enabled at ~800 points. The low pass filter was implemented using a moving 3 point average. The sinusoidal shape is due to the mismatch of the timing between the onboard clock divider and the DDS generation of the laser AC bias causing a slight heterodyne effect. Each point is ~0.1 seconds. The amplitude is the most-significant 16 bits of a 32 bit result.

The main issue with this sub-Nyquist frequency technique is aliasing of the signal. However, this has been solved using random sampling period techniques in [80], to provide no aliasing with minimal sampling rate. This technique can be implemented on the MSP430 (Figure 10). The other issue with this technique is the extent of digital filtering possible (number of filter taps) with a low power processor which can be solved with hand coding of the filter to maximize performance.
Figure 10: Block diagram of a random undersampling DSP LIA using MSP430. The timer keeps track of the time base, and the processor can provide random sampling by changing the timer compare registers. The red indicates blocks on the MSP.

Analog multiplier based LIA solutions are not simple to optimize for power. The only methods without changing the internal silicon configuration are to select off-the-shelf components with lower maximum bandwidth to prevent high quiescent currents, and to lower the voltage as much as possible.

To save power in the switched gain case, the balanced amplifiers may be shared between the two quadrature phases. Thus, instead of 2 sets of balanced amplifiers (totaling 4 amplifiers), a single set may be used, cutting power in half (Figure 11). The voltages should also be lowered to save power, at a cost of dynamic range. Dynamic range is reduced since the maximum voltage swings are lowered (best case to the voltage rails), while noise floor is relatively constant.
Figure 11: Sharing a matched pair of amplifiers for quadrature phases provides \( \frac{1}{2} \) the required number of amplifiers.

The electrical power levels for each of these 3 techniques either in simulation or actual experimentation are as follows: the DSP technique with LIA under-sampling for 2 channels of 2 quadrature phases required the MSP430 active mode power consumption, which at 8MHz was 5.3mA times 3.3V, or \( \approx 20mW \). However, the duty cycle for which the processor was actively performing LIA computations was \( \approx 1260 \) processor cycles out of 3200 cycles, or 40% when running at the fastest loop rate. Thus, the power consumption for one channel with two quadrature phases was \( \approx 4mW \). The analog multiplier technique was simulated for a single phase using an AD835, requiring 20mA at \( \pm 5.5V \), 110mW. Two phases would require 220mW. The switching gain method was implemented using AD8608 op amps and an analog switch, clocked by a digital output. This method required 1.2mA per amplifier at 3.0V, and used 4 amplifiers for quadrature phases. Thus the LIA power for the switched gain case was 14mW.
Data Processing and Embedded Programming Methods

Programming methods also have an impact on the power consumption. By having very efficient algorithms, the processor core can be freed for other tasks, or even shut off. Additionally, lower processing requirements can lower the required clock speeds or voltages to the processor, cutting power consumption even further. In modern low power processors, spending most of the time in a standby mode with a clock speed on the order of kHz is the method of choice.

Instruction set architectures also improve with each successive processor generation, adding various peripherals and more powerful instructions optimized to sensor DSP applications. Examples of this are hardware multipliers, direct memory access (DMA), multiply-accumulate (MAC), and floating point co-processors.

Hardware multipliers allow for low latency fixed point multiplication, improving performance of intensive processing applications. HW multipliers combined with MAC instructions improve code density and execution speed for digital finite-impulse response (FIR) and infinite-impulse response (IIR) filters, necessary in digital lock-in amplifiers. DMA allows for the processor to move data from peripherals to other memory locations quickly (Figure 12). Floating point co-processors and other mathematics related hardware allow for large dynamic range and fast execution, at a price of complexity in the processor.
Figure 12: Direct memory access capability with interrupt triggering provides movement of data with minimal intervention by the processor. This provides better latency than waiting for the data to be transmitted/acquired in a single block which is necessary for control loops.

Another important software issue affecting power consumption of these digital implementations is the overhead of mapping high level languages to the processor instructions. Software and firmware are typically created in Labview, Matlab, or C, and rely on efficient compilers to map to assembly language or hardware descriptor language (HDL) such as VHDL and Verilog. Systems developed on platforms running on standard PCs further suffer from modern operating system overhead (from implementing virtual memory, video displays, etc.). Thus, there is a tradeoff between ease-of-implementation and efficiency. Porting typical laser spectroscopic software written in LabVIEW or other x86 PC based software to run on embedded systems requires major modifications to accommodate smaller RAM and non-volatile memory, interrupt driven processing, and minimal floating point performance. For highest efficiency, or to meet real-time deadlines, a complete hand coding in assembly or HDL is necessary.

Laser spectroscopy also requires high precision controls to keep the sensor parameters stable. Digital control loops are replacing most analog control loops due to higher integration and lower complexity and power consumption. To enable high precision, a fractional number system is required. However, low power processors typically lack floating point processing units. A fixed point implementation should be used whenever
possible to perform computation on fractional numbers using integer arithmetic logic units (ALU). This is opposed to emulating floating point (if the processor does not have a floating point ALU), providing a large reduction in the number of instructions and latency. With low instruction count and low latency, more time in low power modes or faster control loops are possible.

The most complicated processing (chemimetrics, beamforming, spectral fitting) can be performed at the base station to save energy on the battery powered nodes. However, offloading processing must be weighed against the power consumption in transmitting all of the data over the radio. Providing the raw data to the central base station to perform processing and to centralize user interfaces and data displays also avoids requiring the sensors themselves from requiring buttons, LCDs, and LEDs.

2. **Optical Techniques**

The semiconductor laser architecture also affects the power consumption. The laser power consumption contribution is contained within the $P_{bias} + P_{actrl} + P_{det}$ terms. The main laser types used in infrared laser spectroscopy are diode lasers, VCSELs, DFG sources, and quantum cascade and interband cascade lasers. Optimization of wavelength, output power, wall plug efficiency, wavelength selection method, detectors, and temperature control all affect the electrical power consumption.

The wavelength choice is the first major factor in sensor power consumption performance. In the telecom near-IR region, VCSELs are available, which are capable of high efficiency and can be made at low cost, but provide only modest amounts of output power. They dissipate $\sim 5 \text{ mW}$ to produce about 0.5 mW of optical power. Output powers
of microwatts can provide TDLAS spectroscopic information provided the source provides enough power to accommodate detection after reflection off non-ideal mirrors. Telecom diode lasers are also available in the near-IR region, with maximum input bias of 1.25W, producing a max of 85mW of output power. In the mid-IR wavelengths, line strengths are orders of magnitude stronger compared to the near-IR. Lead salt (IV-VI) material diode lasers can provide CW mid-IR radiation, but with the requirement of cryogenic cooling [81]. Stirling engines which provide continuous cryogenic temperatures drain 55W of power to achieve 80K and require moving parts [82,83]. Another option in the mid-IR is a DFG source, mixing the output of two near-IR diode laser or solid state state lasers operating at two wavelengths in a non-linear crystal. This process is not efficient in terms of nonlinear optical conversion, and may require pumped fiber amplifiers which dissipate multiple watts each [84]. The most useful lasers for portable sensors providing mid-IR radiation at room temperature are DFB QCLs, which have recently achieved 1mW optical power while dissipating 1W in electronic energy [63,85]. This power consumption in creating the radiation is contained within $P_{bias}$.

In direct absorption spectroscopy, the amount of optical power is related to the detection limit. The light impinging on the detector must be high enough to overcome various noise sources. This will determine the SNR of the signal, barring any etalon effects.

Since optical power is directly related to the bias power, being able to use lower initial intensities can lower the minimum power consumption necessary to reach a certain minimum detection limit. Optimization of the reflection and transmission losses for lenses, windows, and mirrors is necessary to maximize throughput. If using optics of lower quality, the SNR suffers due to the lower power, or requires driving the laser with
more electrical pump power to compensate. In QEPAS or PAS configurations, sensitivity scales directly with optical power [86], making optical power loss considerations even more important.

Wavelength control power consumption is contained in $P_{\text{actr}}$. This source of power is attributed to the physical power required to control the wavelength of the laser (excluding control loop power). For DFB lasers, this term is the power injected into a Peltier TEC (thermoelectric cooler). For cryogenically cooled lasers with heaters, this power is the heating power required to stabilize the temperature, and for refilling or recycling the cryogen. For external cavity lasers, this is the power necessary to move mirrors and gratings using piezoelectric transducers for the laser cavity length. In DFB lasers, reaching the target absorption wavelength at its steady-state temperature without cooling will allow the TEC to dissipate minimal average power in controlling the wavelength, due to having no steady-state current required. Therefore, with the correct selection of wavelength versus temperature and bias power in the laser, $P_{\text{actr}}$ can reach negligible levels only related to temperature isolation of the laser. With good temperature isolation of the laser, less RMS power can be dissipated to control the laser since environmental effects of ambient convection are minimized.

Pulsing the laser and detecting the amplitude modulation signal using lock-in detection can achieve even lower power consumption. The drawback to amplitude modulation is reduced noise immunity to background signals. With typical telecom DFB diode bias levels of 150mA @ 1.5V the laser dissipates 0.225W and ~0.113W average at 50% duty cycle. The TEC requires a minimum of 0.45W at 100% duty cycle and 0.225W at 50% duty cycle to compensate heating, assuming a TEC efficiency of 50%. Thus, the total
dissipated power decreases in relation to short duty cycles, but noise immunity and overall stability of the wavelength and power decrease as well.

\( P_{\text{det}} \) is the power consumed by the detector. This power is dissipated by any bias currents necessary for the detector, cooling to improve \( D^* \), and any amplification of the signal. Different wavelength ranges require different detector materials to detect the radiation efficiently. The formula for detectivity which defines the performance of the various detector materials with respect to noise is

\[
D^* = \frac{\sqrt{A \Delta f}}{NEP}
\]

Where \( A \) is the area of the detector, \( \Delta f \) is the effective noise bandwidth, and \( NEP \) is the noise equivalent power, the optical power necessary to achieve a signal to noise ratio of 1.

Another way to increase \( D^* \) is to cool the detector. The cooling of the detector reduces the dark current/thermal noise. When this occurs, \( P_{\text{det}} \) additionally requires power along the lines of \( P_{\text{det}_{\text{cryo}}} \), in that cryogenically cooled detectors require power for refrigeration, and TEC cooled detectors must inject power into the Peltier element to stabilize the temperature or reach a certain offset temperature.

If a detector with a TEC is implemented, an analysis should be performed to determine whether increasing power consumption via detector cooling or increasing laser bias power is more efficient to improve the minimum detection limit. Additional power consumption to provide control of the detector temperature is also necessary, and must be taken into account.

For 0.75A at 1.5V using a 1 stage TEC, a 2.8 micron optimized MCT detector drops from 27 to -20 C. This provides \( \sim 5 \times \) increase from \( D^* \approx 2.0 \times 10^9 \) to \( 1.1 \times 10^{10} \) for 1.125W of
electrical power consumption, although etalon effects may dominate the noise, causing negligible improvement in SNR.

When using very high modulation frequencies, a bias current is typically necessary to improve the frequency response of the detector, which increases dark current and power consumption. Pulsed configurations may require increased frequency performance as well, since the signal at the pulse edges has high frequency content. In CW operation for absorption methods, the modulation frequency is usually low, so no bias current is required.

Amplification of the detector signal requires power. For photodiodes, this usually entails a transimpedance amplifier. The amplifier must provide enough gain at the frequency of interest. A amplifier corresponding to the gain-bandwidth (GBW) required should be implemented to prevent excessive quiescent bias current. Amplifiers which have a GBW of 50MHz currently have a quiescent current around 10mA, while GBW of 10MHz are around 1mA. For PAS and QEPAS, the detector is an acoustic transducer at audio frequencies, and similar optimizations of the amplifier must be provided to minimize power consumption.

3. High Efficiency Power Circuits

The power supply choices also directly affect power consumption. The two types of power supply are linear and switching, each with advantages and disadvantages. In this work, power supplies are used to deliver energy for laser bias, wavelength control, and electronics power rails. This power is contained in the terms

\[ P_{\text{bias-loss}}, P_{\text{actvl-loss}}, P_{\text{loss}} \]
Linear power supplies regulate power supply voltage or current by converting the excess energy into heat by means of variable impedance. Linear supplies can have very high bandwidth and low noise, and are simple and cost efficient. However, DC-DC linear power supplies (usually low drop out regulators or LDOs) should be fed input voltages only slightly higher than the drop-out voltage + output voltage to minimize loss (Figure 13). Increased current causes an increased power loss due to the drop out voltage, causing an efficiency loss.

![Diagram of LDO regulator schematic](image)

**Figure 13:** An LDO regulator schematic diagram. The drop out voltage multiplied by the load current determines the energy loss. LDOs have low noise since they are a linear topology. For highest efficiency, a SMPS source must be provided to Vin to minimize drop out.

Switched mode power supplies (SMPS) deliver the energy into a low loss power system. By having the system either completely turned on or off, negligible wasted heat can be achieved with close-to-idealized circuit components. An output LC filter smoothes the power output to suppress the switching frequency. SMPS allow for both lower and higher voltages than the input voltage. The drawback to SMPS is the complexity, radiated electromagnetic interference (EMI) and conducted noise, and cost.
To minimize power consumption in portable laser spectroscopic sensors, a SMPS is generally preferred. SMPS is desirable due to higher efficiency at larger current loads (typically max ~95% compared to max ~60% for linear supplies). SMPS is not typically used in telecom laser drivers since the bandwidth for communication (up to 10Gbps) is much higher than the switching frequencies of the power supplies (500kHz-8MHz), and any switching noise is directly coupled into the transmitted signal. However, the moderate modulation frequencies (1-40kHz) used with laser spectroscopy are at least an order of magnitude lower than the SMPS frequency, allowing the output filter to smooth out the current and voltage ripples effectively.

To achieve the maximum efficiency from SMPS, the components must be chosen carefully. First, the SMPS controller must provide low quiescent current. Second, the switch transistors chosen must have low on resistance (typically MOSFETs) $r_{ds}$, and should have low gate charge and capacitance to minimize the required power for dynamic switching. Third, the inductor for the output filter must have extremely low, DC resistance (DCR) as this is where the majority of the loss originates in SMPS (see Table 3). Finally, the capacitor must have low effective series resistance (ESR) as well, as this provides some loss, as well as becoming one of the limiting factors in post filter output voltage ripple noise [87].
Table 3: Effect of inductor choice on power loss. All inductors are 10 μH. A tradeoff of size, power loss, and current handling capability exists. L2 was used in the final designs.

<table>
<thead>
<tr>
<th></th>
<th>DCR [ohm]</th>
<th>I_{sat} [A]</th>
<th>Vol. [mm^3]</th>
<th>Loss @ 0.1A [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>1.51</td>
<td>0.27</td>
<td>20.2</td>
<td>0.0151</td>
</tr>
<tr>
<td>L2</td>
<td>0.65</td>
<td>0.5</td>
<td>7.2</td>
<td>0.0065</td>
</tr>
<tr>
<td>L3</td>
<td>0.17</td>
<td>0.9</td>
<td>111</td>
<td>0.0017</td>
</tr>
<tr>
<td>L4</td>
<td>0.35</td>
<td>1</td>
<td>16</td>
<td>0.0035</td>
</tr>
</tbody>
</table>

At very high laser current loads, the efficiency becomes critical. In many of the current QCL devices, the bias power can be >5W. If a 50% efficient power supply were used, the total dissipated power is more than doubled, while requiring increased size and cost to improve current and heat handling capabilities.

For a low noise high efficiency requirement, a power topology which combines a SMPS and LDO minimizes the drop out voltage and minimizes switching noise. A simulation was performed with 1) a 4.2V battery feeding a 3.0V LDO compared to 3) the 4.2V battery feeding a 3.3V SMPS before the LDO with 0.2V drop out. The set current was 0.1A. The waste power to heat in the first case was 0.12W, compared to 0.066W in the second case (Figure 14).
Figure 14: A SMPS provides buck regulation with output at +3.3V_SMP. An LDO then provides linear regulation for +3.0V_LDO.

There are two main methods for supply of the pulse energy into SMPS, pulse width modulation (PWM) and pulse frequency modulation (PFM). Pulse width modulation is the method of choice which varies the duty cycle of a fixed frequency. Pulse frequency modulation (PFM) is a method which provides an efficiency improvement in light load situations. PFM varies the frequency of a fixed pulse width by changing the timing between pulses. This method achieves higher efficiency by injecting power only when necessary, providing “pulse skipping”.
Figure 15: Difference between PWM mode and PFM mode. PFM mode provides better efficiency at light loads.

Power supplies based on SMPS sometimes provide PFM mode to improve efficiency at light load. Maximum power delivery is reduced in PFM mode. When a high efficiency laser is operated at near room temperature, the load requirement to the TEC is reduced providing a case where PFM would provide improved performance. To provide highest efficiency and highest disturbance rejection, a controller capable of switching between PFM and PWM allows maximum performance.

Throughout the versions of the sensor, the absolute power consumption due to all of the optimizations listed before have improved by orders of magnitude (Figure 16).
Figure 16: Various power topologies implemented in this work. Top Left) Pulsed QCL TDLAS with all linear supplies, Top Right) PHOTONS v1.0 where power consumption of electronics were directly addressed, with linear supplies, Bottom Left) PHOTONS v2.0 where switching supplies and LDOs were combined for high efficiency and low noise, Bottom Right) PHOTONS v3.0, a revision capable of high power and high efficiency

B. Sensor Size Optimization

The sensor size comes from 3 main modules of the sensor. These are 1) the optics module, 2) electronics module, and 3) energy module. This section will describe reducing the size and weight of the sensor.
1. **Optics Module**

The optics module consists of the laser and its mount, the absorbance detection unit, associated beam steering optics, and the detector. The absorbance detection module is the folded optical path multipass optics for direct absorption methods and the acoustic module for PAS and QEPAS.

*Laser Module Size Reduction*

Of the lasers available for IR laser spectroscopy, the DFB laser provides the smallest possible complete laser module. Telecom DFB diode lasers have the most integration available, including a diode laser, Peltier TEC element, thermistor, and back facet photodiode monitoring into a hermetically sealed package. Diode lasers may also integrate etalon structures to monitor wavelength. However, some packages only provide the sealed DFB diode, which must be attached to an external TEC and temperature sensor. This increases the size of the laser module. With cryogenically cooled lasers, a dewar is required to retain sufficient liquid cryogen in reserve, while isolating it from any heat. An external cavity laser must provide space for the grating, the length of the cavity, and the tuning mechanism.

The standard package for near-IR DFB telecommunications lasers is a fiber coupled dual in-line (DIL) butterfly package. Smaller packages come in transistor outline (TO) metal canisters, with less heat sinking capacity. This is due to the large flat area on the bottom of butterfly packages, providing lower thermal resistance than TO canisters. By lowering the amount of optical power required, and providing lasers with higher wall-plug efficiency, the large heat sinking capability of the larger telecom packages become
unnecessary, allowing the use of the smaller TO packages. As mentioned previously, the minimum detection limit of QEPAS and PAS scales directly with power. Therefore these sensors should be analyzed to determine which package is optimal. Standard commercial packaging is currently limited by the TEC height, but new thermoelectric cooler developments related to Peltier cooling [88] have the potential to be implemented in lower profile packages.

The pin configuration for the laser also affects miniaturization. The main butterfly DIL package, takes 1/3 of the 2D footprint, while the other 2/3 is used for pins, which are latched into place on a telecom butterfly mount, as shown in Figure 17.

![Figure 17: Left: Photograph of a telecom butterfly DIL package with US penny, Right: Photograph of a typical telecom laser mount [89].](image)

The standard latches are also very large, and approximately double the size of the pin connectors required. TO packaged lasers have much smaller footprint and standard sockets are available. The ideal laser packaging footprint for size would be a surface mount leadless chip scale package such as a quad flat no-lead (QFN) or ball grid array (BGA) with thermal balls/pads. Some development has been reported for BGA based optoelectronic packages [90]. However, commercial lasers are typically available in
packages which can be easily socketed. The exception has been highly integrated telecom photonic integrated circuits [91].

Fiber coupling in the near-IR provides extra robustness for optical power delivery, and can be applied to both butterfly and TO packaged lasers. With smaller sensors and higher integration, the laser source, drive circuitry, and the absorption path are closely coupled. When this situation occurs, the advantages of fiber coupling become negligible, unless a hollow core waveguide absorption cell is used. Fiber coupling is useful in situations where the ADM must be far away from the sensor electronics and laser source, such as industrial process control in harsh environments. In the WSN paradigm, the entire sensor self contained and environmentally hardened, so no outside connections are necessary.

The laser beam must also be collimated in order to minimize divergence before, inside, and after the ADM. In the near-IR, fiber coupled gradient index (GRIN) lenses are available commercially which can be spliced with fibers to collimate the beam. In non-fiber coupled cases, the laser must be collimated to provide smaller beam diameter, which enables the use of smaller optics. Again, the near-IR provides the best solutions in terms of size, and offer aspheric lenses that are readily available with good transparency, AR coatings, and small diameters. In the mid-IR, aspheric lenses made of materials such as CaF₂, ZnSe, and MgF₂ with high transparency at the target wavelengths are used, but are not commonly available off-the-shelf.

Absorbance Detection Module Miniaturization

TDLAS uses multipass cell mirror configurations to increase pathlength. The main types of multipass cells are the White cell [92], the Herriott cell [93], Chernin cell [94], the astigmatic Herriott cell [95], and recently chaotic multipass cells [96]. These multipass
cells provide small volumes with long optical paths. Using cavity enhanced techniques also increases the effective optical pathlength within the volume, with kilometers of path attainable with high reflectivity mirrors.

In addition to direct reduction of the volume of the gas chamber, folded optical paths allow smaller pumps to be used. The volume reduction is the most pronounced with QEPAS. The gas chamber can be miniaturized to the size of the tuning fork of about 4 mm x 2 mm, the smallest of all of the laser spectroscopic techniques. The pump volume also becomes extremely small, allowing use of ultra miniature pumps.

However, beam steering and mode matching optics are required to couple into the various types of ADMs. Alignment using standard laboratory optical kinematic mounts can lead to a bulky configuration. This can be solved by providing custom adjustment stages. Using simple flexure modules can provide adequate adjustment to align the optical system, while reducing the size significantly. An example is shown in Figure 18.

![Flexure mount](image)

*Figure 18: Flexure mount providing displacement in 2 directions. Screws are inserted into threaded bushings or the material itself with tapped holes machined in post processing.*
Detector Miniaturization

The detector should also be miniaturized, and detector size reduction techniques are similar to the laser module techniques. TO package detectors are optimal, and any temperature control should be integrated into the package. When the optical beam diameter is small, or the beam can be tightly focused and steered precisely, a smaller active area detector can be used, allowing even smaller packages.

2. Electronic Module

The electronic sections of the sensor are another major component of the sensor which can be optimized for size. The main techniques for miniaturization are 1) using smaller electronic packages, 2) systems integration, and 3) printed circuit board (PCB) optimizations.

Electronic Packages

Electronic packages have reached ultra miniature sizes, and PCB manufacturing and assembly techniques can mount these components precisely and efficiently. Previously, dual inline packages (DIP) and transistor outline (TO) canister packages were the prevalent package, due to ease of handling and prototyping circuits. Sockets are readily available, allowing for hand assembly of electronic circuits. DIP packages typically require holes in the PCB.

Since the number of through holes with plating typically dictates the cost of PCBs, surface mount technology has replaced DIP packages. Additionally, the parasitic capacitance and inductance of the pin leads causes poor high frequency performance, another reason DIP packages are seeing less use. Surface mount parts simply require
metal pads on the board with a solder mask opening, removing the requirement for through holes, and allowing no wasted PCB area on the other side of the board to accommodate the plated holes. Passive components such as capacitors, resistors, and inductors have many standard sizes (1206, 0805, 0603, 0402 in decreasing size), and 0402 (0.040 inch x 0.020 inch or 1 mm x 0.5 mm) components are routinely machine placed by prototype board assembly companies. Amplifiers have standard surface mount sizes and pin-outs (small outline integrated circuit SOIC, thin shrink small outline package TSSOP, mini small outline package MSOP in decreasing size). These leaded surface mount parts are robust and easily soldered by hand or machine.

The next levels of technology are leadless and ball grid array packaging technologies. Leadless packages place the pins directly on underside of the package. Thus, no space is wasted outside of the outline of the package for leads to extend outward. These packages are Quad Flat No-Lead (QFN) packages. Ball grid arrays (BGA) have metal bumps on the bottom of the package in an array configuration, allowing the entire bottom area of the package to provide pin connections. These QFN and BGA packages are much smaller, so they should be used whenever size and weight reduction are the most important features of the sensor. However, QFN and BGAs require thorough inspection to make sure the PCB pads are in contact with the QFN pads or the BGA bumps. These are typically machine placed.

Certain packages also provide a thermal pad to solder directly to the board to provide heat sinking. When soldered to the board, they provide a lower thermal resistance, removing any external heat sinks connected to the top of the chip. These packages require
less surface area from the package to dissipate the heat into the surrounding air, and can be made smaller.

**PCB Optimizations**

Integrated circuits which are designed to perform high precision control and acquisition require some support components, such as precision resistors, bypass capacitors, inductors, clock sources, and connectors, currently making full integration on a chip difficult. Signal routing also becomes an issue with large pin counts (for more peripherals and I/O), requiring higher resolution printed circuit boards (PCB), and more routing layers.

PCB boards can have many layers, but 2 and 4 layer boards are common for boards using simple low pin count IC packages. When pins are densely spaced (as in ball-grid array packages), they require better PCB technologies such as 6 layers and up, blind vias, and some attention to structural stability. When routing many signals around a dense board, smaller vias may be necessary to accommodate crossing signals. Higher density routing also usually necessitates more vias/area, sometimes requiring an additional cost to produce high density via patterns. High speed DSPs, FPGAs, and other I/O intensive high frequency ICs typically use BGAs with very high pin density. High speed ICs also require bypass capacitors to be close to the pins increasing necessary PCB space for the single IC.

With dense electronic component layouts, crosstalk and noise coupling become more of an issue. High frequency current loops can cause strong electromagnetic interference (EMI) which can couple easily to sensitive analog circuits. Crosstalk is very important when high gain amplifiers coexist on the same board (or die) as power electronics. Some
methods to avoid this are to use more PCB layers as signal shielding or adding external shielding, but at the expense of increased size and cost. Thus, to decrease size to the minimum level, the lowest digital clock speeds should be used and steps to lower bias powers in the circuits should be taken in order to prevent EM emissions from coupling to the sensitive portions of the circuit.

Power plane and ground plane splitting prevents noise coupling into circuitry which needs clean power, such as crystal clocks, amplifiers, and laser power supply. High power current loops on the ground plane should be isolated, which is what a configuration such as star grounding accomplishes.

Localized heating also provides some noise issues when power electronics are integrated on the same board as sensitive analog electronics and inter-module distances are reduced. One method to reduce this heating is to increase the copper weight that the board is made of. Standard copper is 1 ounce per square foot (0.3 kg / m²) on the outer layers, and 0.5 (0.15 kg / m²) ounces on the inner layers. By increasing the weight to 2 or 3 (0.6-0.9 kg / m²) ounces, the thermal mass is higher, requiring more heat energy to cause a rise in temperature. The boards are slightly thicker and have a slightly higher mass, but this is negligible compared to component heights. The use of thermal vias also provides a large improvement in heat sinking. Thermal vias are drilled plated through holes connecting large copper areas (copper pours) on the board together to increase the amount of copper which is conducting heat. Thermal vias also provide a larger surface area for convection to remove heat, since they are plated. These thermal vias must not have any thermal relief structures (a void of copper around the via which minimizes conduction of heat to make soldering components connected to ground planes easier).
Thus, lowering power consumption is required to achieve the smallest electronic size, as heating and noise from current loops are enough to cause problems with miniaturization (Table 4). Lowering the frequency also avoids the necessity of having a larger number of high frequency bypass capacitors and shielding to block EMI coupling.

Table 4: Power consumption per volume for each sensor. With smaller sizes, even with power dissipation reduction, the average power density is greatly increased, necessitating thermal management techniques.

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Power [W]</th>
<th>mW/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDLAS pulsed 100m</td>
<td>170</td>
<td>0.994152047</td>
</tr>
<tr>
<td>QEPAS 1.5</td>
<td>5</td>
<td>0.644246875</td>
</tr>
<tr>
<td>QEPAS 2.0</td>
<td>1</td>
<td>2.777777778</td>
</tr>
<tr>
<td>TDLAS 2.7 0.1m</td>
<td>0.75</td>
<td>4.761904762</td>
</tr>
</tbody>
</table>

**C. Sensor Cost Optimization**

The sensor total price is determined by cost of 1) laser, 2) optics, and 3) detector. Currently, the laser cost is the dominating factor at $500-20,000. Detector cost is low compared to the other sensor components at $30-500. However, non-optimized electronics cost may actually exceed the laser cost, since single board computers with data acquisition and software can require >$14,000. Furthermore, certain optical configurations such as astigmatic Herriott cells with large mirror diameters or high reflectivity mirrors exceed laser cost in the near-IR. In [71], the target was a sensor with cost of a few thousand dollars in the near-IR in bulk quantities, but this is still too high for many applications. Therefore, to achieve costs suitable for WSNs and PMDs, major optimization for all components of the sensor is necessary. In this way, sensor cost may be reduced, while maintaining sensor performance.
1. **Laser Cost**

The laser cost varies for the different types of lasers and the different spectral ranges. To minimize the cost of the lasers, they should provide at least room temperature lasing to avoid complicated temperature control equipment such as cryogenic cooling, complicated power supplies for powering larger TECs, and large heat sinks, radiators, and liquid pumps for thermal management of waste heat.

Another cost reduction is to move to near-IR wavelengths from the mid-IR, and sacrifice size of the optical configuration in order to get longer paths from MPCs to make up for decreased line intensity. However, this only works until reflection loss dominates and detector SNR decreases [97]. Fixing this problem with higher reflectivity mirrors increases cost, and may be more costly than switching to lasers in the mid-IR. Therefore, there are situations where no cost reduction in the laser source is possible since some molecules may only provide adequate performance in the mid-IR.

To lower costs further, a custom TEC laser mount can be implemented. A 320W TEC designed for electronics cooling is only $25 in 2008. Negative temperature coefficient (NTC) thermistors can cost less than $0.10. On the other hand, a commercial laser diode mount designed for diode lasers with integrated TEC and thermistor costs $300 [98].

Angled caps to reduce reflection loss from the laser window are available, but increase cost. Hermetic sealing also increases cost, so a cap-less laser would provide the lowest cost possible.

VCSELs have the lowest potential cost, since they are produced and operated vertically and can be made in large quantities on a single wafer. The drawbacks of VCSELs are low optical powers.
QCLs are more difficult to manufacture, since many layers must be grown with good quality. Due to the relative infancy of QCLs, growth of these lasers using metal-organic chemical vapor deposition (MOCVD) for mass production is just beginning to be developed. Mass produced QCLs have the potential to provide a sensor with the best size, cost, and power consumption characteristics, as will be seen in the analysis in Chapter 4.F.1.

2. Optics Cost

Optical cost is also a major factor in overall sensor cost. Near-IR optics are available at low cost, even with AR coatings. The near-IR has many glass materials developed for transparency in the wavelength range, and come coated with MgF₂ AR coatings. An aspheric lens with AR coating at 1.5 microns typically costs $100. However, in the 2+ micron range, these low cost materials start to become opaque. Avoiding configurations with many optical elements is the main method to reduce optical costs. Any unnecessary optical adjustment axes should also be removed from designs to ensure lowest cost. Optical kinematic mounts are also expensive individually. These optical mounts are designed for quick prototyping and multipurpose use, and should be minimized in number. Also, high optical quality, large diameter surfaces require high cost so the beam diameters should be minimized as much as possible. Lasers with small beam divergence angles are important to keep optical costs down by allowing lenses with small diameter.
Smaller beam diameters allow for tighter spacing within multipass cell spot patterns, permitting smaller optics and smaller footprints.

An important optimization which can provide lower costs is to use reflective optics rather than refractive optics. Reflective optics provide broadband reflection with minimal aberration, and the same optical system can be used for many different wavelength sensors. However, most off the shelf reflective optics have relatively long focal lengths.

3. Detector Cost

QEPAS cost for simple detection is much lower than TDLAS. This is especially true if the laser has an integrated photodiode and wavelength locker etalon, as no external power monitor is necessary.

A detector for TDLAS with an integrated TEC will cost more, but provide better noise performance. Depending on the wavelength range, this detector with TEC cost plus an extra temperature control circuit may be lower than the cost increase to improve the laser output power and noise level.

Angled windows and other special configurations are also available for detection, and the benefits of reduced reflection, laser feedback, or increased output power may outweigh the increased cost.

4. Electronics Cost

The electronics cost can be very high if not properly addressed. However, minimizing the cost can cause a drop in sensor detection performance, and therefore the cost reduction
must be carefully optimized. For example, a dedicated normal PC ($500) for each sensor [99] with data acquisition hardware ($1,500) [100], commercial acquisition software ($2,000) [100, 101], lock-in amplifiers for 2f and 3f ($4,500 \times 2) [102] and separate controllers for temperature ($350) and laser drive ($500) [103], and pressure ($300) [104]. This comes to a total of $14,150, not including the optical sensor modules. This work employs a $250 embedded sensor platform with full processing capability, smaller size, and dramatically lower power consumption.

This section will describe the custom embedded design techniques which provide low cost capability to enable the large numbers of sensors required by WSN applications. Lowest cost comes with the economies of scale associated with potentially large numbers of sensor nodes. The use of components off the shelf is the best way to minimize the cost of the electronics. Furthermore, using the most common ICs possible will assure supply for the parts, and will have a higher likelihood of being replaced by a new design if a part actually becomes obsolete.

With increased heat production of non-optimized sensors a fan, external heat sink, or extra thermal surface area may be required to spread the heat. A fan is undesirable in a field deployment since it is a moving part, so the only option is an external heat sink or increasing the surface area of exposed metal for convection to take place. A larger thermal mass is also possible with increased copper weight used on the PCB, discussed in Chapter 3.B.2. The increase in cost from increased copper weight is negligible compared to custom mounts for fans and radiators. Parts with thermal pads can be more costly to attach to a PCB, requiring a solder paste stencil to place the correct amount of solder to ensure good seating of the electronic package against the PCB.
Shielding is another cost for the electronics. With appropriate noise reduction techniques such as continuous ground planes with ground loop analysis, the EM susceptibility decreases, relaxing some shielding requirements. With poor noise performance, the circuits must be individually shielded on the same board from one another, requiring multi-chamber shields, and a grounded metal enclosure completely surrounding the circuit must be implemented.

The cost of wiring separate parts and components together by hand is also a major factor in the scalability of a sensor to large numbers. Thus, the optimal way to minimize this cost is to attempt to integrate all of the components into a monolithic unit. Otherwise, to optimize this source of cost, standard connectors such as 0.1 inch or 2 mm header sockets and plugs should be used, with minimum wiring requirements. When any wiring is required, the part must also be heat-shrink wrapped or crimped and sealed, to ensure robust environmentally isolated contact increasing assembly costs.

With a highly complex circuit, the number of parts and interconnections on the PCB increases. This can require extra space for wire buses, vias, and buffer zones between chips for assembly. Larger number of PCBs and vias cost more. Any extra layers in the PCB also increase cost, as well as any special features required of some packages such as blind vias.

The energy module cost is also a factor in total sensor cost. In a WSN application, if the sensor requires a large amount of energy harvesting to keep transmitting real-time information, the cost of a solar panel harvesting element with larger areas and greater efficiencies can quickly escalate.
Reducing the cost of the main processing unit is possible when further optimizations of the algorithm are performed. For instance, using the modern single board computer/PC method would take advantage of the economies of scale for PC computing, but a low cost microcontroller will always cost less due to the complexity of modern PC architectures. Additionally, the Moore’s Law improvements also apply to microcontrollers allowing higher transistor density and consequently smaller chips and higher yield.
Chapter 4. Implementation of PHOTONS Architectures

The optimizations used for the PHOTONS sensor platform will be described in this chapter, followed by the results from the testbed systems to provide the reasoning for the final platform architecture. The platform can be used for TDLAS and PAS configurations. Since all of the power, size, and cost optimizations interplay, the optimizations for the major modules determined from behavior of previous versions will be described.

A. The PHOTONS platform

All of the electronic systems were custom developed in order to satisfy all of power consumption, size, and cost requirements for WSN and PMD applications. The platform allows implementation of both TDLAS and QEPAS without requiring a large amount of modification to the sensor. A typical method used in all three spectroscopic methods is wavelength modulation with 2f LIA, with optional line locking, power normalization, and temperature or current scanning.

1. Frequency Synthesis and Lock-In Amplifiers

QEPAS sensors posses high Q-factor and therefore allows little margin of error for the resonant condition. A straightforward implementation to provide f, 2f, 3f synchronized local oscillators is to generate f, and use phase locked loops using integer-n factors with
phase lag circuits for phase tuning. Quadrature generation to perform real-time quadrature detection is more difficult in this case.

An enhanced method for harmonic quadrature frequency generation is to directly synthesize all of the waveforms using a custom DDS from a DSP or FPGA. This entails setting starting phases at either 0 or 90 degrees, and keeping separate angle information for each frequency. The first implementation of the PHOTONS platform used this method to provide $f$, $2f$, $2f+90$, $3f$, and $3f+90$ using direct digital synthesis on dual microcontrollers. The first processor generated $2f$, $2f + 90$, and $f$. The second processor generated $3f$ and $3f+90$. These were output as quantized sinusoids using the onboard DACs. Switched capacitor filters then filtered the sinusoids to eliminate the sampling frequency, and the signals were directly used with mixers performing lock-in detection. This was fed into a difference amplifier followed by a switched capacitor filter for the final low pass filtering before the onboard ADC.

Direct synthesis of multiple signals requires a substantial amount of processing power and thus increases cost and power consumption. A significant improvement of the system performance was achieved by optimization of the signal generation method. By generating a waveform at a multiple of all of the waveforms and using embedded asynchronous digital counters available on the MSP430, the processing requirements are decreased, providing a significant improvement in terms of power consumption, size, and cost. Thus it was possible to develop an effective sensor architecture for high Q-factor QEPAS using standard microcontroller peripherals.

For the initial implementation of this single waveform generation technique, the processing for the DDS algorithm was performed on one MSP430 processor. The entire
algorithm was digital and provided high clocking stability. The 31 bit phase accumulator provided the angle within the output waveform. The number of bits for the angular resolution needed to be as high as possible to provide adequate frequency dynamic range. The 31 bit limitation was due to the memory constraints of the processor. The MSP430F1612 had 55KB flash memory to store the sine LUT which was accessed with the top 15 bits of the phase accumulator. The LUT value was sent to an onboard DAC. The DAC output update rate was 667kHz, 3 times the 12f signal and filtered by a 4\textsuperscript{th} order Butterworth filter. The DAC output was filtered, sent to an onboard comparator, converted to a digital clock, and divided down by timers on each of the 2 processors. This firmware based generation (Figure 19) required a large amount of processing power, almost 100\% of the processing resources of an 8MHz MSP430F16x. This left no processing power for the other required functionality, necessitating another processor. Results are shown in Figure 20. This microcontroller method provides the best integration for the clock generation, which may be improved by increasing the output sampling frequency.
Figure 19: Direct Digital Synthesis algorithm in MSP430 assembly language. The comments list the number of processor cycles each instruction requires. The phase accumulator and phase increment are 32 bits, and the phase increment controls the frequency.

Figure 20: Oscilloscope trace of DDS waveform generation by an MSP430 processor and onboard peripherals. A harmonic was generated of all required local oscillators for lock-in amplifiers, and used to clock asynchronous counter timer outputs.

An analysis was then performed in order to determine what resolution of the DDS is necessary. When the Q factor of the resonance defined by:
must be matched by the frequency generation produced via DDS, the frequency resolution $\Delta f_{dds}$ is matched to the width of the resonance when

$$\Delta f_{dds} = \frac{f_{sclk}}{2^B k} = \Delta f$$

where the value $k$ is the multiplier to provide the common factor of frequencies which can be divided into separate integer-multiple waveforms, $B$ is the number of bits of resolution, and $f_{sclk}$ is the system reference frequency. The $f_{sclk}$ clock rate is usually high to provide better sampling performance. This provides the number of required bits of frequency resolution:

$$B > \log_2\left(\frac{f_{sclk} nQ}{f_0 k}\right)$$

where $n$ scales $Q$ to assure adequate number of points of tuning within the resonance. Here $k = 12$, and a value of $n = 100$ provides sufficient frequency resolution within the resonance. When $f_{sclk} = 8$ MHz, $f_0 = 32768$ Hz, the required $B$ is >25 bits for $Q = 20,000$, and $B$ is >27.6 bits for $Q = 100,000$. An illustration of the frequency generation is provided in Figure 21.
Using the results of this DDS resolution analysis, a revised implementation used a standalone 28 bit DDS chip (AD9833) controlled by an MSP430 removed the necessity of a second processor. The MSP430 clock of 8 MHz was sent to the DDS, and created a sinusoidal waveform at a frequency which was a multiple of all LO waveforms required (in this case 24f). The sinusoid was sent to the onboard ComparatorA module of the MSP430 for conversion to digital. The resulting DDS clock was sent to the two timer units on the MSP430 and the timer outputs were set to generate the 5 required waveforms simultaneously without any extra processing. This method was compared to the processor software based DDS in terms of spurious free dynamic range in Figure 22.
Figure 22: Oscilloscope generated FFTs for A) Software DDS of a 12f signal at 196,608Hz with output sampling rate ~3x higher, B) DDS of a 24f signal with AD9833. The largest spurs are labeled with their relative frequency compared to the fundamental.
The final iteration of the LIA frequency generation was to generate a DDS signal at a multiple of the desired reference frequency, and use it as a time base for a DSP based digital LIA. This method (as explained in Chapter 3.4.1) for integrated LIAs, used two sine LUTs, one for each quadrature frequency pair, and multiplied using an embedded hardware multiplier. This method combines the effectiveness of generating a precise reference frequency to match high Q resonances, while allowing a low frequency processor. Combined with a software DDS on the same processor (with high enough processing capability), the entire lock-in and frequency generation can be performed on chip.

The 16 bit multiplying DACs used for the PHOTONS platforms use the relationship:

\[ V_{out} = V_{ref} \left( \frac{x}{2^{16}} \right) \]

where \( x \) is the digital scalar value.

2. **Embedded Temperature Controller**

The optimal choice of laser for the PHOTONS platform is the temperature tunable DFB laser. Thus, a precision temperature controller which provides a wide tuning range is required. For the initial development of a pulsed TDLAS sensor (described in Chapter 4.B) a standalone commercial temperature controller was implemented. Cost and efficiency were not design optimized for use in a platform suitable for WSN and PMD.

The first custom embedded temperature control was implemented using an ASIC developed by NTT NEL for laser control. The onboard temperature controller was an analog control loop, with an assumed linear output, due to the lack of requirement for
output inductors. The temperature control could stabilize the temperature to within 0.01 K according to the data sheet.

However, this chip became obsolete and unsupported in 2006 so a second method based on switching electronics and digital control techniques was developed. The temperature control functionality was addressed by means of a high efficiency, miniature, low cost method based on an H-bridge configuration with a digital control loop.

This custom embedded temperature controller developed for PHOTONS was first used with a 2.0 micron CO₂ sensor based on QEPAS (Chapter 4.D). It was also used to control the temperature of a 2.7 micron TDLAS based CO₂ sensor (Chapter 4.E). It provides stabilization to within 0.005 K.

The initial custom method in PHOTONS v2.0 used the TI DRV592 H-bridge chip which was driven by the timer output of an MSP430. A floating point temperature control loop with basic PID control provided an output value to the timer compare registers, providing PFM mode modulation of the H-bridge (Figure 23). PFM provides higher efficiency for light load power. A dataset which shows light load when driving a 2.0 micron laser is shown in Figure 24. The power consumption becomes negligible after steady state is reached. This method provided satisfactory control of the temperature, but disturbance rejection could be improved due to slow updates of the digital control loop using floating point processing.
The second custom method used the same TI DRV592 H-bridge, but instead ported the control algorithm into a fixed point method. The algorithm state diagram is shown in Figure 25.
Figure 25: PID algorithm driven by ADC interrupts. Red states are performed in an interrupt service routine. The final algorithm required 581 processor cycles within the ISR, providing a maximum loop rate of 13.7kHz at 8MHz clock rate.

After reprogramming, the PID was then re-tuned, and time to reach steady state compared to the original algorithm (see Figure 26). The ported method doubled the speed of updates without any other optimizations. The results showed that it was possible to halve the time to reach steady state, and thus provided better disturbance rejection. The 0.005 K peak-to-peak noise was determined using this fixed point algorithm.
Figure 26: Temperature controller performance for digital PFM control loop. The blue points were acquired using a floating point control loop. The red points were a fixed point control loop.

This method allowed for larger PID gain parameters, and fast disturbance rejection. The only issue with the method was the PFM modes reduced maximum power output. The pulse width was fixed at 1 clock cycle, and the shortest full period of the PFM waveform was 8 cycles. A method to provide both PFM at light loads and PWM at heavy loads provides optimized power consumption.

The final method tested was a change to the TI DRV593 H-bridge to provide PWM controlled by a DAC. This method provided high pulse width resolution, and was capable of fast updates via the onboard MSP430 DAC. This provided the lowest latency between the output of the PID control algorithm, and the update of the value.

In the case of the DRV59x based TEC drivers, the heat dissipated in the chip was transferred to the PCB ground layer copper through the recommended thermal pad configuration. The thermal pad was soldered to the ground plane through thermal vias, and to copper pours connected to ground on the top and bottom layers to increase surface area exposed to the air. The part was also placed as far away from the analog section as
possible to prevent PWM switching noise coupling. Additionally, the grounding for the PWM section was isolated and routed to the power input area to prevent the noise from leaking to other sections of the board.

Temperature sensing was accomplished by using a custom negative temperature coefficient (NTC) thermistor sensing solution. The first method was to use the NEL ASIC which had thermistor sensing onboard. When this chip became obsolete, a custom solution based on the INA330 current conveyor chip provided a solution with few components (Figure 27).

![Diagram](image)

*Figure 27: A high dynamic range thermistor sensing solution with digital control compensation driving a TEC.*

The most standard method for thermistor sensing is a Wheatstone bridge and an instrumentation amplifier, but requires well matched resistors, and the prevention of uneven heating across the bridge which would cause temperature coefficient related issues. In addition, the non-linearity of the thermistor relation given by the Steinhart-Hart thermistor equation would require a separate optimized bridge for different regions of the
sensed temperature, causing precision to change across the operating temperature of the laser. The current conveyor chip alone also requires different resistors for different ranges of temperatures. To address this issue, a low drift digital potentiometer was used to provide real-time variable resistance to compare with the thermistor. Additionally, a method to calculate the optimum resistance for the highest precision around the temperature setpoint was created.

Using the onboard MSP430 temperature sensor and storing temperature adjusted potentiometer resistance in flash would allow for further digital compensation for temperature drift, if necessary. This method also allowed the use of non-standard thermistor values, with varying non-linear Steinhart-Hart $B$ coefficient.

This custom method required calculation of the temperature from the various settings of the circuit and an inverse method to compute the settings of the circuit to reach a certain temperature.

The Steinhart-Hart equation using the $B$ parameter was used for temperature sensing which is stated:

$$\frac{1}{T} = \frac{1}{T_0} + \frac{1}{B \ln \left( \frac{R}{R_0} \right)}$$

Where $R$ is the resistance at temperature $T$, $B$ is the thermistor parameter, $R_0$ is the known resistance at temperature $T_0$ at 25 °C.

This method required 0.630 sq. in (394 mm²), an ultra compact solution with adequate performance for laser spectroscopy (see Figure 28).
Figure 28: Ultra compact temperature controller solution. Total 2D footprint of the temperature sensing and PWM system required 0.630 in², or 394 mm². The size of an MPT-1000 2.5A controller is 11 in², or 7100 mm², not including heatsink to accommodate linear output loss.

By providing a separate regulated 5.5 V to the power supply of the PWM IC and larger inductors, the maximum current of 3A provides a maximum dissipation of 16.5 W with minimal waste heat if the circuit components are optimized for this configuration. The inductors designed into the last version were rated for 0.5A, and with the onboard regulator providing 3.3V power, allows for 1.65W of TEC dissipation. Assuming ~50% TEC efficiency, the laser can dissipate 0.825W, enough for the latest high wall plug efficiency QCLs.
3. Analog Front End

The analog sections of the various versions of the sensor platform were improved significantly during the work discussed in this thesis.

Faraday shielding provides high noise rejection. However, the reduction of system frequency and digital coupling provides lower noise without the need for expensive shields due to the dependence of the electric field magnitude estimation [105]:

\[ E = 1.32 \times \left( \frac{f^2 A l}{r} \right) \]

Where

\( E = \mu \text{V/meter, } f = \text{MHz, } A = \text{loop area (L \times W) [cm}^2], \) \( f = \text{loop current [A], } r = \text{antenna to loop distance [m].} \)

The noise in PHOTONS v1.0 described in Chapter 4.C was analog amplifier noise limited, and did not have an issue with digital clock coupling since all of the signals were low frequency and low amplitude. This was due to filtering the signal first before routing it to the mixer circuit, since the AD8343 provided an input stage which accepted small amplitude LO waveforms (Figure 29).
Figure 29: Clock generation and distribution for PHOTONS v1.0. The dashed modules were integrated in proximity, minimizing digital loop area. The resulting 1f and 2f sine signals could be routed closer to high gain amplifiers due to their lower amplitude and frequency content.

To minimize cost in PHOTONS v2.0, these high bandwidth switched mixers were replaced with analog switches. However, these analog switches required a full digital logic level to switch, so the LO could not be adequately filtered. The digital coupling effect was not realized until after the prototype was designed. Investigating the noise structure revealed that the noise was related to the digital current loops formed by the clocks.

Figure 30: Signal paths for digital LO clocks for two board layouts. Noise was limited by EMI emission from these current loops coupling to the high gain amplifiers (circled in black). The noise level on the second layout was 16 bit accurate, due to larger distance to the current loops and clock filtering to lower the harmonic content.
This was verified by measuring the noise amplitude at the clock frequencies via an external lock-in amplifier (Table 5). These clocks were close in spacing to the high gain amplifiers, causing large amounts of coupling and amplification of the noise (Figure 30).

Table 5: Measured noise using Lock-in amplifier, and estimation of electric field generated by digital clocks in proximity to analog amplifiers. The approximate $f^2 A/r$ was calculated using an approximate loop area determined by the layout, and distance to the amplifier.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>approx $f^2 A/r$</th>
<th>total $f^2 A/r$ (both phases)</th>
<th>Measured LIA R Voltage</th>
<th>Normalized Measured LIA R Voltage</th>
<th>Calculated relative E-field normalized to maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>f</td>
<td>2273</td>
<td>2273</td>
<td>0.0123 mV</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>2f</td>
<td>830</td>
<td>1238</td>
<td>0.0056 mV</td>
<td>0.46</td>
<td>0.54</td>
</tr>
<tr>
<td>2f-90</td>
<td>409</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3f</td>
<td>342</td>
<td>757</td>
<td>0.004 mV</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>3f-90</td>
<td>415</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

With a copper shield and providing some re-wiring of the signal paths using extra wires, the noise was reduced to the point where the signal was thermal noise limited for a QEPAS implementation. The next version (PHOTONS v3.0) of the design filtered the clocks by an RC circuit with cutoff frequency slightly below the default 32kHz and 49kHz clocks. This significantly reduced the harmonic content of the clocks. Additionally, the high gain amplifiers were placed further away from the clock paths. The result was a 16 bit accurate noise level without any shielding. However, a space for a shield was still implemented to shield from external sources of noise, especially from RF circuitry involved in communications.

The analog signal conditioning was provided by custom op-amp configurations, providing either transimpedance or voltage inverting negative feedback configurations for two transducer signals (one power monitor, one spectral signal). The GBW needed to
be enough for high gain to reduce ADC quantization errors, >64kHz bandwidth in QEPAS configurations, low bias current to reduce errors, low voltage and current noise, provide rail-to-rail input and output to maximize single supply voltage swings, and provide low power dissipation and small size.

![Diagram](image_url)

**Figure 31:** Transimpedance/Inverting voltage amplifier. The resistor may be changed to switch between the two configurations. The amplifier is single supply with voltage reference at midscale (1.5V).

Multiplying DACs also provide noise reduction to assure analog circuits can operate in close proximity to the digital circuits. Instead of a fast digital bus updating a DAC every sample, the scalar is set once, and automatically produces the waveform.

4. **Power Supplies and Laser Driver**

A prototype laser driver using a SEPIC (single ended primary inductance converter) converter (Figure 32) in controlled current mode was performed to assess whether the closed-loop control bandwidth was adequate to modulate the laser current directly via reference modulation, while still providing high rejection of the switching frequency. The rejection frequency is related to the size of the inductors and capacitors of the output
filter. A prototype implementation showed control of the biased AC current output until ~1% modulation depth, which may not be enough for some applications. This could be addressed with an even higher clock frequency for the converter, but the efficiency would drop due to the required gate charge on the output switch transistors.

![Diagram](image)

Figure 32: A high frequency SEPIC converter developed to provide both low and high compliance voltages to lasers. The ratio of R1/R2 controls the output voltage. Direct control of current using the Iadj pins did not provide adequate bandwidth of modulation with a large filter to suppress switching noise, so a linear transconductance amplifier or op-amp is placed directly afterwards.

A revision to controlling current using a transconductance amplifier circuit as in Figure 33 provides a linear output, but is poor for power consumption. Replacing the high end voltage rail supplying the current with a switching power supply with dynamic voltage level allows for a current control stage with minimal loss. The complexity to generate a dynamic SMPS voltage is fairly high, causing cost and size to increase, but may be necessary for lowest noise level with high efficiency.
Figure 33: A voltage controlled current source driving a diode simulated in PSPICE. The power rail V24 may be substituted with a switching power supply (at the laser compliance voltage) in order to minimize power loss when controlled current is necessary for laser excitation.

For the variable laser compliance voltage, the power supply is generated using a SEPIC configuration which can provide both higher and lower voltages compared to the input supply. In the classic transconductance amplifier which provides a voltage controlled current source, the voltage to the high side of the load provides the overall compliance potential, and the output transistor converts the excess energy to heat. Having a SEPIC configuration allows the maximum voltage to be set to roughly the same voltage as the maximum compliance voltage of the laser. This reduces unnecessary energy loss due to the output stage. With higher modulation depths, the loss increases. But this method is the best for DFB lasers, since linear current mode control is provided using this technique.

Therefore, the SEPIC + linear output transconductance amplifier was found to address all of the configurations required in a relatively high efficiency manner, with low complexity and low cost, and low noise. The SEPIC can provide a constant voltage output with a very large output filter, allowing for less stability issues.
A high side current monitor was amplified by a wide common mode amplifier, allowing the current monitor to work with voltages higher than the system voltage. Thus QCL applications with compliance voltages greater than 10V may still have the current monitored by the system.

Additionally, an LDO regulator provided low-noise power to the analog circuitry from the main power switching regulator. This assured a lower drop out voltage of 0.3V, necessary for low dissipation and high efficiency. There was also a 1.5V LDO, providing a mid-rail regulated voltage reference for the analog circuitry, although efficiency is not a big issue for the reference, since currents are so low.

Noise is a large issue in sensitive precision instrumentation, and having the requirement of high power laser drive circuitry and adequate TEC cooling causes component placement issues. The TEC drive circuitry was placed as far away as possible from the analog portions to minimize noise coupling. As such, the noisy TEC drive components are in the upper right of the PCB, while the analog portions are in the lower left. The laser drive circuitry was either in the lower right, or on a separate board. Figure 34 shows the various splits of analog, digital/noisy circuits on various versions of the board.
To provide variable modulation depth, a multiplying DAC creates high resolution linear attenuation. This method avoids the need to generate every point within the sinusoid digitally to provide scaled waveforms. This type of circuit is essentially a high resolution voltage divider. In the first versions of the sensor, the real-time DAC update method was used for modulation. If such an architecture were used with QEPAS to generate the laser modulation waveform, the required serial communications clock speed would be greater than 32768Hz * 16 bits = 524kbps at the minimum. This is only at 2 times the signal
frequency, and much faster sampling rate would be required to achieve good quality sinusoidal generation.

5. Software and Firmware

The software and firmware of the PHOTONS platform is one of the main components of the sensor. Unlike sensor architectures which use hardware to perform all aspects of the control, while simply using software to provide acquisition and processing, PHOTONS converts much of the hardware into software to save power, size, and cost.

![Diagram](image)

*Figure 35: Conversion of hardware systems to software modules. Individual module control and processing requirements are consolidated into the single processor.*
The firmware for PHOTONS was developed using C, nesC [106], and MSP430 assembly language, and a basic sensor user interface was developed using National Instruments LabVIEW [107] communicating over universal asynchronous receiver transmitter (UART) serial either through (dynamic-link library) DLL calls to a universal serial bus (USB) transceiver chip driver or standard UART control. Finally, interfaces were defined for sensor networking platforms to control the sensor by implementations of power-aware sensor networks.

In the final versions of the platform, the Moteiv Tmotesky / Crossbow Telos mote was used to provide networking and communication [108]. This mote was programmed using nesC and TinyOS 2.0. Interfaces were defined to allow the platform to work as an original equipment manufacturer (OEM) module. A UART interface was used for bi-directional communication with a Telos, and also provided an I²C interface to communicate with power supply gas gauges or power controllers. Two additional pins are reserved for bi-directional interrupts. Thus, the system can directly leverage much of the technology being developed by the sensor networking community working on the TinyOS platform since it is designed to be portable across different hardware platforms for sensor networking.

When implementing a new sensor, a user interface is necessary to optimize the control parameters and visualize the signals. This was accomplished by a program written in Labview 8.2, communicating over the USB to COM driver provided by the Telos’s USB IC. A similar IC (FTDI FT232) was used in PHOTONS v1.0, using the same USB to COM driver. The implementation at 2 microns of PHOTONS v2.0 (see section Chapter 4.D) of the sensor platform used a Microsoft Windows DLL driver produced by FTDI
and called application programming interface (API) functions using DLL access within LabVIEW. This driver was also available for Linux and Mac OS. The LabVIEW program parsed the serial information back into the data structure, and provided graphical displays.

The current interface has been designed for a single sensor, but can be expanded to multiple sensors by providing the sensor node ID and sorting the data within the user interface. This also provides a scalable method to add additional chemical sensing modules to the same sensor, and wireless networking can be replaced with bus communications for intra-sensor communication.

6. **Networking and Energy Storage**

In PHOTONS v2.0, the network and energy modules were implemented using a TI Chipcon CC2420 radio and FT232 USB transceiver with switching Li-Ion battery charging capability via USB.

In PHOTONS v3.0, these features were removed to either be integrated or replaced by a power aware sensor networking platform to deal with determining how much energy is available for sensing. Temporarily, the Telos mote has been implemented since it provided the radio and USB functionality. However, it is missing battery charging and monitoring circuitry necessary to keep these sensors alive long-term in the field via energy harvesting.
B. TDLAS Pulsed 4.6 μm QCL for CO

The first sensor was based on a 4.6 μm pulsed DFB QCL, a 100 meter optical path astigmatic Herriott cell, an MCT detector, wavelength electronics temperature controller, a Directed Energy Inc laser pulser, and a 150 MHz TMS320F2812 based embedded processing unit. The sensor is pictured in Figure 36. This sensor is an example of typical sensors currently developed for field use.

Figure 36: Pulsed TDLAS QCL sensor with 100m optical path. Laptop is optional for data visualization, and is shown for scale.

This system provided a detection limit of 6 ppb in 1 second. The system required a table top, and required liquid nitrogen for the cryogenically cooled MCT detector. The power supply for the electronics and TEC took a majority of the size of the sensor. A linear supply to control the maximum laser bias voltage is not pictured. A pump is also not pictured to lower pressure of the MPC and provide better performance in terms of sensitivity and specificity.

The electronics were the main focus of this sensor and designed to perform pulsed TDLAS for up to 2 lasers, with sub-threshold current modulation to provide DFB
sawtooth wavelength scanning. Generally, performance was limited by the electronic noise present on the integrated ADC from the DSP itself.

Further optimizations are possible by reducing emissions through PCB layout techniques and removal of high frequency content. First, reduction of a digital 150MHz clock to an 8MHz clock drops emissions by 350 times. Second, reducing the trace lengths provides a smaller loop area.

The sensor modulation and acquisition was based on a fast sawtooth scan with 12 bit ADC sampling rate of 12.5 MSPS. The DSP performed oversampling for each point to provide more spatial locality of the data. A high bandwidth sample and hold system provided pulse height sampling.

Some optimizations which would improve the sensor performance based on the other test sensors described in this thesis are: 1) Switching power supplies, 2) low noise PCB techniques and shielding, and 3) miniaturized laser mount.

The power supplies for this sensor were all linear in an attempt to minimize noise. However, the linear supplies were bulky and inefficient. In this instance, the supplies were open frame linear supplies, and the temperature controller had a linear output. The amount of current required to drive the TEC from a linear supply is very large due to inefficiencies. With a TEC efficiency of 50% and a linear supply efficiency of 50%, and another linear output from the temperature controller at 50% efficiency, the required power to pump out heat from the laser to run at room temperature is 8 times the laser bias power dissipation. Thus, stability, noise, and size were traded off for power consumption.

The electronics for the sensor control and acquisition were also powered by linear supplies.
Figure 37: Network analyzer noise spectrum revealing noise coupling on an ADC pin due to digital noise from the running 150 MHz DSP. An external ADC and more shielding techniques are required in this case. The integrated noise for each spectrum is listed as the A parameter.

The dominating sensor noise for this DSP based sensor was digital noise from the DSP itself. The idle noise compared to the noise when the DSP is running is shown in Figure 37. Since the noise was present on the ADC simply by running the processor, an external ADC with a high SNR would have improved performance dramatically at a cost of power consumption and complexity. However, good performance from the sensor was still possible as shown in Figure 38.
Figure 38: Example spectrum for pulsed TDLAS measuring CO.

To protect the amplifiers on the daughtercard without a continuous ground plane, a grounded metal shield between the layers provide higher attenuation of the high speed digital emissions emanating upwards from the DSP.

A miniaturized laser mount also allows the sensor to cut size by at least half. The vacuum sealing required to keep moisture out of the chamber required a large volume, and custom valves and feedthroughs cause a great deal of complexity. Thus a hermetic seal is required to minimize size and avoid environmental effects on the laser.

C. PHOTONS v1.0 - QEPAS at 1.5 µm for CO₂

The PHOTONS v1.0 platform was the first prototype specifically targeting sensor networks, and was developed using an NEL NLD0531BPQ telecom laser driver,
embedded lock-in amplifiers using high bandwidth mixers, software DDS clock
generation, a telecom laser at 1.57 microns targeting CO₂, and a QEPAS configuration.
The alignment was achieved using standard adjustment mounts. In addition, the
collimating lens connected to an optical fiber was mounted on a 3D translation stage. An
acoustic micro-resonator was mounted onto a tuning fork mount. Additionally, a fiber
coil was necessary to connect the laser to the lens, but the laser and heatsink could have
been mounted very close to the collimating alignment system, and fusion spliced nearby
to keep size low.

![Diagram](image)

**Figure 39:** Electronics for PHOTONS v1.0 based CO₂ sensor based on 1.57 micron
telecom laser. Networking was provided by a custom sensor networking platform –
GNOMES 3.0.

The electronics depicted in Figure 39 were the first architecture designed with low power
in mind. The design leveraged the GNOMES sensor networking platform [109]. A
custom version of GNOMES was designed in order to provide a dual MSP430 processor
based system to accommodate the increased processing requirements of laser
spectroscopy. This was a direct implementation of a double DDS system, with 1
processor generating f, 2f, and 2f+ 90, and the other generating 3f and 3f+90. The lock-in
amplifiers were based on AD8343 2.5 GHz Active Mixers. An example spectrum is
shown in Figure 40.
Using the lessons learned from the TDLAS pulsed sensor, the analog and digital sections were isolated, with large continuous ground planes providing reduced EM pickup.

Figure 40: Spectrum of CO$_2$ acquired using PHOTONS v1.0 at 1.57 microns.

This sensor had issues with complexity, as can be seen in the lock-in amplifier schematics of one phase in Figure 41. This complexity was solved in v2.0 by providing shared amplifier configurations between phases, and LO generation optimizations. The size was also large to accommodate a heat sink for the NEL telecom driver, and a mount for a butterfly socket with heat sink, but the hermetically sealed butterfly mount based platform is still orders of magnitude smaller than the sensor described in the previous section.
Figure 41: LIA configuration using a mixer, difference amplifiers, and a switched capacitor 8th order filter. This circuit was replicated for four separate channels, requiring 20 discrete parts each, at a total of 80 parts.

D. PHOTONS v2.0 - QEPAS at 2.0 μm for CO₂

The next version of the PHOTONS platform (v2.0) was implemented using QEPAS at 2.0 microns. The laser was packaged in a TO package, minimizing size further compared to the telecom butterfly package in the previous section. Instead of using collimating lenses and adjustment mounts, a different technique was used to minimize size. As a bare minimum, a QEPAS configuration requires the laser, and the tuning fork. By mounting the tuning fork directly after the output facet of the laser, the sensor size dramatically improves. The tuning fork can be mounted as close as possible to the output facet to minimize power loss and clipping due to the divergent beam and then fixed with epoxy. The system provided similar detection limit as previous literature using the same laser and a QEPAS configuration. The system block diagram is shown in Figure 42 and a photograph of the QEPAS module is in Figure 43. The detection sensitivity was
approximately 300ppm in 1 second. The majority of the cost was the laser and TEC mount.

![Diagram](image)

**Figure 42: The PHOTONS platform for A) 2.0 micron QEPAS configuration with version 2 of PHOTONS**

This v2.0 sensor replaced the NEL chip from v1.0 for laser current drive and temperature control with custom modules. This provided higher complexity since the previously integrated functionality had to be split into a custom IC configuration, but it improved efficiency dramatically from the use of switching power supplies.
A buck converter (providing voltages lower than the input voltage via switching) provides voltage mode control for the laser. This voltage mode control is adequate for situations where the voltage to current relationship is in a linear regime. In the cases operating in the area between threshold and the linear regime, this becomes undesirable due to the non-linear increase in current due to voltage. In the most current versions of the sensor, a current controller with high efficiency based on the SEPIC/transconductance amplifier has been implemented to make use of this region of laser operation. This section of the LIV curve is more desirable for portable instruments, to minimize dissipation.
The QEPAS method was optimized by removing all of the collimating optics and mounting a tuning fork directly after the output facet of the laser (Figure 43). The signal did not show fringing, but did have temperature disturbance issues due to the laser being exposed to ambient air. With appropriate isolation (i.e. enclosure to provide relatively constant pressure and temperature) this method is best for applications which stress the absolute lowest cost and smallest size, though the cost of the laser is typically high enough that the addition of focusing optics and mounting equipment to achieve better results with a sealed laser package would be similar to the laser cost.

The processing was provided by 2 TI MSP430F161x processors, with 1 processor performing DDS. The processors communicated via SPI bus. A DMA transfer provided results as soon as they were available to the FT232 USB transceiver via the UART port. A TI ADS1112 16 bit delta-sigma ADC acquired the analog lock-in signal, and provided results using an I²C bus. Noise without shielding and measuring no signal was ~200 LSB. With the shielding this noise dropped to ~10 LSB, mostly due to the digital LO feedthrough described in Chapter 4.A.3. A flash chip with 16Mbit size was also integrated for data storage.
Additionally, networking was provided by a Chipcon CC2420 radio, a single cell Li-Ion charger based on a TI BQ24105. An MPXM2102 absolute pressure sensor provided onboard pressure sensing. The USB port also provided 5V @ 0.5A output to charge the Li-Ion battery. The power draw capability of USB is normally 5V @ 0.1A, but can be modified to the maximum 0.5A using the FT232 driver.

The 2.0 micron laser required 80 mA @ 1.4 V. The output optical power was 4 mW. The laser was run at 29 °C. Total power consumption was ~1W.

The overall sensor size was limited by the Thorlabs LDM21 laser diode mount, which provided the TEC and thermistor as well as a mounting point for a lens. See Figure 44.

Cost was limited by the 2 micron laser cost of $5000. All other components were about $550.

This sensor technique resulted in a performance of $1.5 \times 10^{-7}$ cm$^{-1}$ W/$\sqrt{Hz}$ (Figure 45).
Figure 45: A wavelength modulation (2f) spectrum of ambient CO$_2$ using PHOTONS v2.0 and 2 micron laser

The temperature controller performance was able to stabilize the temperature to 0.005 K, over a period >5 minutes (Figure 46). The temperature could be tuned to the line center of the absorption by scanning over the line first and selecting the temperature of the absorption maximum. This method showed little drift. However, the open canister caused some issues with isolation from large disturbances. When the sensor was subjected to human breath (large heat shock), the aggressive compensation occasionally caused oscillation. When the compensation was reduced, the temperature drifted too much to stay on the absorption line. Thus, any application which is in a rapidly changing environment should always use hermetically sealed packages, even if a more complicated optical system is required.
Figure 46: Temperature controller performance using PWM driver and digital control loop, with corresponding Allan deviation. Setpoint was 28.3 °C. Allan deviation shows best stability for 3.6 minutes.

E. PHOTONS v3.0 - TDLAS at 2.7 μm for CO₂

PHOTONS v3.0 used direct absorption TDLAS with 9 cm path. The laser was a 2.7 micron diode DFB laser. This laser required 150 mA @ 0.780 V and produced 2 mW of output power. 2.7 microns was chosen to provide lower detection limit to perform
environmentally interesting levels of sensing in a compact package suitable for WSNs (see Figure 47).

![Image](image_url)

**Figure 47: Example implementation of the PHOTONS v3.0 platform using a 2.7 micron DFB diode laser.**

The v3.0 electronics implemented further size reduction via higher integration, made the laser current drive section modular to accommodate both low (VCSELS) and high (QCL) dissipation lasers, and provided more noise reduction techniques. This was used in a low cost single pass TDLAS configuration. A machined mount was designed to align the laser, collimating and focusing optics, and detector, while providing a mounting point for the electronics. This was developed to provide an ultra compact TDLAS optical system to match the size of the electronics for the minimal complete sensor size (Figure 48).

The DDS system using the AD9833 replaced the processor based version of PHOTONS v2.0. Filtering the generated LO clocks before routing to the mixing switch circuit allowed for reduced noise. Optimized layout and ground plane configuration provided \(-1-2\) LSB of peak-to-peak noise with an ungrounded input.
A separate power board using the SEPIC regulator + linear high power op amp was implemented in this version, providing slightly reduced efficiency to improve noise performance.

A PWM temperature controller based on the DRV593 was implemented in this version. The DRV593 can use a single inductor for bidirectional current output to the TEC, saving space for the filter compared to the DRV592. The analog input method also provided high resolution, since the use of the MSP430 integrated 12 bit DAC could control the PWM output linearly. However, PFM mode could not be implemented with this technique.

An integrated multiplying DAC with 4 channels in a single chip (Linear LTC2604) was implemented to provide higher integration compared to 2 TI DAC8831 chips.

Communications were changed to the Telos/Tmotesky in this version. A UART bus transmitted data, while the Telos forwarded packets over ZigBee radio or USB.

![Diagram](image)

**Figure 48:** Left) Block diagram of sensor core systems, Right) Photograph of complete 2.7micron TDLAS using PHOTONS v3.0 with US Quarter.

This configuration implements a single pass over ambient air. The laser was collimated by an aspheric lens using an uncoated ECO550 lens with \( f = 6.24 \text{mm} \) with diameter 9.2 mm. The TO packaged laser and lens were mounted into a custom flexure mount with a
hole for a threaded bushing guiding a ball-tipped screw, which provides x-plane adjustments. After the optical path, another uncoated ECO550 lens with f=11mm and diameter 9.2mm focuses the radiation onto an un-cooled detector in a TO package. The focusing lens and detector are mounted into a similar flexure mount as the laser/collimator, with the flexing in the y-plane. This provides some adjustment of the optics with low cost in the case of misaligned laser packaging.

![Ambient CO₂(400ppm) using 2.7 micron laser](chart)

**Figure 49:** Spectrum acquired by PHOTONS platform with 2.7 micron DFB laser. Noise was limited by fringing. This was acquired using laboratory air with wireless communication, and battery powered. The only data processing implemented on the ADC values was polynomial fitting (no averaging) and normalization off board in LabVIEW using a 7th order Givens polynomial fitting to remove baseline fluctuations.

The SNR of a single temperature scan (Figure 49) over the absorption line at 3703.25cm⁻¹ was ~78 from data directly sampled by the ADC (no averaging), using peak-to-peak noise determined by holding the temperature setpoint at a single value (Figure 50).
Figure 50: Noise when operating at a single temperature setpoint. The signal without normalization had amplitude of 3900. Thus, SNR using 3σ noise was ~78. The noise data was gathered over 140 seconds.

The temperature controller readout showed the process variable was stabilized to within ~0.005 K. However the absorption value drifted away from line center. In these cases, extra cost is required to isolate the laser, and to keep waste heat from affecting the laser wavelength, or providing a much larger sensor footprint to provide a reference cell for line locking. The best solution to keep size and cost down for this sensor was to not implement line locking and use temperature scanning. For the best performance, the thermistors integrated into lasers should be placed as close as possible to the actual laser bar, and if a small canister type package is used, insulation should coat the walls of the TO canister. This prevents the waste heat generated at the bottom of the canister from conducting up the walls and affecting the laser wavelength, as it did in this sensor.

At 400 ppm of CO₂, the average ambient atmospheric concentration of CO₂ in 2008, the absorption is 2% over 9cm, the approximate single pass path. The minimum detectable absorption for 3σ noise measured by setting a single temperature value and using the
peak-to-peak value is therefore $2.6 \times 10^4$, with 1 second time constant for the LIA. The minimum detectable concentration for this $3\sigma$ noise is 5 ppm. The fringes showed a spacing of $\sim 0.025 \, \text{cm}^{-1}$. Thus, the length of the effective cavity causing fringing was $\sim 20\, \text{cm}$, or twice the path. This scan was taken remotely in real time, with the battery powered sensor measuring and radio forwarding data packets to a base station.

Noise performance could be greatly improved by using optimum optics at 2.7 microns, since the ECO550 material which was used for the aspheric lenses were opaque, and not AR coated.

![Absorption Spectrum](image)

Figure 51: Absorption for 400ppm of CO$_2$ at 2.7 microns, 1 atm pressure, and 0.09m path.

F. Performance Comparisons

Throughout the development of various sensor configurations (Table 6), a trend towards continuous improvement in size, power consumption, and cost was the principal
objective. Measures of absolute size, power consumption, cost, and detection limit will be described, while normalized performance metrics are provided to compare overall sensor characteristics.

Table 6: Various features for the different versions of the sensor platform.

<table>
<thead>
<tr>
<th></th>
<th>TEC</th>
<th>Data Acquisition</th>
<th>Demod</th>
<th>Processor</th>
<th>Timing generation</th>
<th>Laser Driver</th>
<th>Networking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsed TDLAS</td>
<td>MPT-5000</td>
<td>12 bit embedded SAR</td>
<td>AD9101 Sample Hold</td>
<td>150MHz F2812 pipelined</td>
<td>Non-resonant, timer</td>
<td>DEI pulser, linear supply</td>
<td>Crystal LAN CS8900A</td>
</tr>
<tr>
<td>QEPAS 1.5 (v1.0)</td>
<td>NLD0531</td>
<td>12 bit embedded SAR</td>
<td>AD8343</td>
<td>8MHz MSP430 (dual)</td>
<td>Onboard dual DDS</td>
<td>NLD0531</td>
<td>CC2420, FT232</td>
</tr>
<tr>
<td>QEPAS 2.0 (v2.0)</td>
<td>INA330, DRV592</td>
<td>16 bit ADS1112 Delta-Sigma</td>
<td>AD8608, ADG734</td>
<td>8MHz MSP430 (dual)</td>
<td>Onboard single DDS</td>
<td>TPS62320, voltage mode</td>
<td>CC2420, FT232</td>
</tr>
<tr>
<td>TDLAS 2.7 (v3.0)</td>
<td>INA330, DRV593</td>
<td>16 bit ADS1112 Delta-Sigma</td>
<td>AD8608, ADG734</td>
<td>8MHz MSP430 (single)</td>
<td>Single DDS, AD9833</td>
<td>LT3477, TCA0372 voltage mode</td>
<td>Telos Tmotesky</td>
</tr>
</tbody>
</table>

1. System Metrics

Each of the previous systems improved in size, cost, and efficiency, but are not easily compared with other sensors, since laser spectroscopic sensors in the literature have not typically optimized for all parameters at once and do not achieve performance suitable for WSNs or PMDs. Thus, new system metrics are required in order to evaluate performance in terms of sensor ideality.

The absolute measure of how the size affects the sensor is a measure of minimum detectable absorption coefficient compared with total sensor size.
Figure 52: Absorption Coefficient multiplied by volume. This measure shows how much volume was required to get a certain detection limit. Lower values indicate smaller minimum detectable absorption coefficient and/or smaller volume.

As can be seen from the data in Figure 52, smaller absorption coefficients (better detection limits) have been enabled using a smaller volume throughout the different sensor versions. Providing better utilization of the sensor volume of the 2.7 micron sensor using a 1m path multipass cell provides improvement in this metric, since the detection limit improves with little increase in total volume.

The next metric is the detection limit relationship with energy usage. A useful measure would be the total energy required to acquire a certain absorption coefficient in 1 second.
Figure 53: Absorption coefficient multiplied by energy dissipated is a measure of how efficiently the energy used measures absorption data. Lower values indicate smaller minimum detectable absorption coefficient and/or less energy required for a measurement.

In terms of energy, it is shown in Figure 53 that TDLAS provides large gains in this parameter by using a multipass configuration to improve detection limit without increasing the energy required. If multipass enhancement of power was used with QEPAS, the effect would be similar.

Figure 54: Absorption coefficient multiplied by cost. With more expensive lasers, the detection method can use more cost in the sensor architecture to provide more efficient detection limits. Lower values indicate smaller minimum detectable absorption coefficient with lower cost.
Figure 54 shows how improving the detection limit with MPCs provides better cost performance. The 1.5 micron sensor based on QEPAS required the least cost to get the best absorption coefficient performance. However, absolute costs must also be considered.

![Absolute Cost Chart](chart.png)

**Figure 55: Absolute cost of the various sensors.**

Figure 55 reveals how the sensor cost is currently dominated by the laser cost. The absolute cost is important to determine the node density in a WSN.

The performance of the sensors in the literature which provide good performance will be compared to the implementations described in this work. The "*" beside each value means the value was estimated from the data available in the literature describing the sensor.

The standalone battery powered TDLAS sensor platform created by Frish et al. [71] described a sensor drawing 1.5W, 6 in x 6 in x 2 in* (15.24 cm x 15.24 cm x 5 cm) size, path length of 2 in (5 cm), and cost of a few hundred dollars without the laser.
In Le Barbu et al. [68], they described a TDLAS sensor 3 cm x 36 cm x 3 cm in size, path of 1.2m, drawing 4-6W peak, and detection limit of $10^{-5}$ absorption units.

In Silver et al. [73], they developed a TDLAS system for CO$_2$ to fly on atmospheric weather balloons, which drew 4W using a 2µm VCSEL in direct absorption, measured 12.7 cm x 16.5 cm x 2.54 cm*; and weighed 1 kg.

In Pilgrim et al. [110], they developed a PAS sensor platform for space station air quality monitoring measuring 14.6 cm x 7.8 cm x 2.54 cm*, drawing 5W, and measuring 2.6 x $10^{-9}$ cm$^{-1}$ W Hz$^{-1/2}$.

In Henning et al. [69] they developed a methane and ethane TDLAS analyzer measuring 15cm x 10cm x 2cm*, drawing 2W, 19.8cm path, and measures 10ppm of methane at 1.68 microns, providing about 2.6x10$^{-5}$ minimum detectable absorbance.

In Webster et al. [72] they developed the Mars laser hygrometer based on TDLAS measuring 10cm x 5cm x 5cm, drawing 5W peak, with a 55.27 cm path at 1.87 microns. For all of the TDLAS configurations listed in the literature above, the power consumption is not optimized, especially the methods which use VCSELs. Since a VCSEL only takes 5mW for bias, the total $P_{bias} + P_{bias-loss} + P_{actrl} + P_{actrl-loss}$ should only be a maximum of 40mW assuming linear supply and 50% efficient TEC. Thus, a majority of the power is used in processing and acquisition. TDLAS as the sole platform (i.e. a platform not capable of PAS/QEPAS) should also require significantly reduced processing resources if using a lock-in type demodulation, since there is no resonant frequency and no processing power is required to generate a high precision continuously tunable clock. An estimate for the PHOTONS platform performing TDLAS with the DDS placed into standby mode is about 0.10-0.15W.
For comparison with the PAS instrument above, it is assumed the bias power of a JDS Uniphase 1.5 micron DFB laser is max 2.5V @ 500 mA = 1.25W, producing a max of 85mW of output power. The listed maximum power used in the experiments was 40mW, which requires 250 mA. Assuming relatively similar voltage, the bias power is 0.6W, and the total laser power is assumed to be max ~2.5W out of the total sensor power dissipation of 5W. Thus, power consumption could be optimized further in that sensor.

The sensor costs are relatively similar between the instruments in both the literature (which list component costs) and the sensors described in this work. Laser costs dominate these sensors, since the typical single board computer/laptops and data acquisition boards were not used. However, comparing only the electronics, the PHOTONS platform has at least a 50% drop in cost, assuming single quantities.

Sensor sizes were similar among the compared sensors, and the v3.0 platform is about half the size compared to these, limited by the TDLAS path. If a minimal QEPAS technique or an optimized QEPAS mount configuration was used with the v3.0 platform, the total volume compared to the smallest sensor in the literature would be 5x smaller.

Sensor performance was typically slightly better for the sensors in the literature (approximately 2-5x); however the goal in this work is for all of size, cost, power consumption, and scalability to be achieved at once.
Table 7: Performance for various sensors in this work and literature in terms of size, power, and cost.

<table>
<thead>
<tr>
<th>Sensor Details</th>
<th>Size [cm³]</th>
<th>Power (peak) [W]</th>
<th>Cost [$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDLAS pulsed 100m</td>
<td>171000</td>
<td>170</td>
<td>23000</td>
</tr>
<tr>
<td>QEPAS 1.5 μm</td>
<td>7761</td>
<td>10</td>
<td>2300</td>
</tr>
<tr>
<td>QEPAS 2.0 μm</td>
<td>360</td>
<td>1</td>
<td>5550</td>
</tr>
<tr>
<td>TDLAS 2.7 μm 0.1m (est.)</td>
<td>157.5</td>
<td>0.75</td>
<td>11000</td>
</tr>
<tr>
<td>TDLAS 2.7 μm 1m (est.)</td>
<td>253.6</td>
<td>0.75</td>
<td>11000</td>
</tr>
<tr>
<td>QEPAS 2.0 μm w/ mini ADM (est.)</td>
<td>63.6</td>
<td>1</td>
<td>5550</td>
</tr>
<tr>
<td>Frish et al. [71]</td>
<td>1161</td>
<td>1.5</td>
<td>&lt;1000+laser?</td>
</tr>
<tr>
<td>Le Barbu et al. [68]</td>
<td>324</td>
<td>4</td>
<td>N/A</td>
</tr>
<tr>
<td>Silver et al. [73]</td>
<td>532</td>
<td>4</td>
<td>N/A</td>
</tr>
<tr>
<td>Pilgrim et al. [111]</td>
<td>289</td>
<td>5</td>
<td>N/A</td>
</tr>
<tr>
<td>Henning et al. [69]</td>
<td>300</td>
<td>2</td>
<td>N/A</td>
</tr>
<tr>
<td>Webster et al. [72]</td>
<td>250</td>
<td>5</td>
<td>N/A</td>
</tr>
</tbody>
</table>

2. **WSN and PMD Sensor Characteristics**

This section provides an analysis for how well these laser based sensors may be used in WSN and PMD applications.

**Power Consumption**

The power consumption of the full sensor was significantly improved over the various sensor architectures. This section analyzes the power consumption required for WSN and PMD applications using the various techniques.

For WSN applications, the power consumption is one of the most important attributes of the sensor, since maintenance of many sensors is difficult. Fortunately, gas concentration diffusion over wide areas is typically slow. Thus, time in sleep modes can be extended.

Assuming a sensor power consumption of 1W @ 3 V, and reasonable battery capacity of 3Ah, the sensor would last for 9 hours. This is not appropriate for a long term sensor network. However, standby mode at 1.1 μA (MSP430F16x standby mode power
consumption) for the duration of the entire battery life would last 300 years (no measurements). If the sensor were to be used for 1 year, the duty cycle would need to be

\[ T_{life} = \frac{B}{d \times I_{active} + (1-d) \times I_{standby}} \]

Where \( B \) is the battery capacity in amp-hours and \( T_{life} \) is the sensor battery lifetime in hours.

The duty cycle \( d \) needs to be 0.1% to last 1 year in this application. This is 60 ms out of every minute or 3.6 seconds of every hour. A duty cycle of 1 second measurement for every 5 minutes provides environmentally useful data since the analysis performed in [111] was averaged to 5 minute periods. This is equivalent to 0.3% duty cycle. To last 1 year at this increased duty cycle, the battery can be enlarged to 9Ah, which would take up the bulk of the sensor size and weight. If the sensor instead took 3W at 0.3% duty cycle, the battery pack would need to be 27Ah, a value too large for deployable sensors. A 27Ah lead-acid battery pack from Newark Electronics costs $256, would require a tabletop, and weighs 25 lbs. (11 kg). With the PHOTONS platform, it is possible to have a TDLAS sensor with a VCSEL which may provide 0.2-0.3W dissipation, allowing either 5 times increased duty cycle or 5 times longer life in the field.

A small solar panel should be implemented to allow higher duty cycles in long term deployments, and could measure continuously with appropriate energy storage and harvesting. A typical 1W solar panel is \( \sim 10 \text{ cm} \times 10 \text{ cm} \), and costs about $25.

Size

For PMD applications, the sensor size is one of the most important parameters. A sensor which can measure unobtrusively enables minimal bias in the measurement. For instance, if the sensor were backpack sized, the size and weight difference could force the patient
to expend more energy during the day skewing the results of metabolism and breathing patterns.

For WSN applications, size is also important to allow for infrastructure free deployment, especially in natural settings. Small sizes also provide some security, if the sensors can be well hidden.

Cost

Assuming the sensor costs can achieve ~$1k per sensor in the future through economies of scale for the lasers, A 50 node network can be deployed for the cost of a single high resolution laboratory instrument (not including cost of a technician to maintain the sensor). Compared to a deployment using a vehicle which must be operated every day for an entire year, or providing a salary to a technician, the sensor network excels in terms of data cost efficiency.

Chapter 5. Developing with the PHOTONS platform

This section will describe a framework which demonstrates how to develop a sensor with the PHOTONS platform. Issues which will be addressed are hardware and software setup and firmware updates. Additionally, deployment issues will be described.

A. Sensor Hardware Adjustments

In order to design a trace gas sensor using the sensor module, various parameters must be defined and optimized in order to extract the best performance from the sensor.
Amplifier

The configuration for QEPAS and TDLAS differs in the amplifier configuration which detects the absorption signal.

The modifications required to switch to QEPAS are minimal. The first is to determine the resistance of the tuning fork transducer, and adjust the feedback resistor to provide the necessary gain. The gain can be increased until the resulting bandwidth is lower than the target signal bandwidth, or the feedback resistor noise increases beyond the noise of the sensor. If the TF already has a preamplifier and provides a voltage out, a load resistor with leads can be added to the connection.

For TDLAS, the configuration depends on whether the detector provides a voltage or current output. Photodiodes provide a current output, which should be amplified with a transimpedance configuration, similar to QEPAS. However, the signals are usually in the nA range, and should be amplified accordingly based on the responsivity of the detector. The high frequencies should be filtered to improve transimpedance performance, matched to the feedback resistor to provide the correct cutoff frequency. Commercial detectors may have onboard amplifiers and require external power supplies, which must be taken into account with load resistors and supply connections.

The second amplifier may be used with a reference cell to lock the laser wavelength to an absorption line. It may also be used with an etalon to lock to a certain value. To implement these techniques, the locking PID algorithm requires an error signal which is monotonic through the setpoint. With the etalon, it must have some mechanism for tuning which can be either temperature or mechanical. Lasers from NTT NEL with an integrated etalon provide separate TEC and thermistor modules on the same package. In a 3f line
locking method, the reference cell should contain a gas mixture with high concentration of the target analyte to always provide a sufficient SNR in the 3f signal used for error signal generation.

Temperature Controller

The temperature controller must be adapted to the TEC and thermistor value, and the PID compensation loop must be tuned for optimal performance.

First, the maximum voltage output to the TEC must be set, as high voltages may damage the TEC. The correct value for the maximum safe DAC value can be calculated using the following formula:

$$\text{TECDAC}_{\text{max}} = \text{round}\left(\frac{V_{\text{TECmax}}}{V_{\text{CCPWM}}} \times \text{DAC}_{\text{max}}\right)$$

Where $V_{\text{TECmax}}$ is the maximum voltage the TEC can handle, $V_{\text{CCPWM}}$ is the voltage of the PWM driver, and $\text{DAC}_{\text{max}}$ is the maximum DAC output. In the default case, the DAC output is set to bipolar mode (0 is midscale), and $\text{DAC}\_\text{max} = 2^{11}$. Therefore, to max the TEC at 0.8V, with a PWM voltage of 3.3V, the value to provide is 496 DAC units. This will limit the output voltage to both positive and negative 0.8V across the PWM.

Similarly, a current maximum can be implemented within the ADC interrupt. When the ADC interrupt service routine fires, the current monitor value should be compared to the maximum ADC value allowable.

Slow-start for both of these methods is implemented as a counter which increments until a maximum limiting value. The counter sets the limiting output value, and linearly increases the value, which provides safety from large current spikes at startup.

Second, the thermistor value and Steinhart-Hart B parameter must be set correctly within the firmware functions. The thermistor value at room temperature is $R_0$, and the B
parameter is either provided in the thermistor characteristics of the laser diode/thermistor datasheet, or can be calculated from the Steinhart-Hart a,b,c coefficients. For example, the values $a=1.129148\times10^{-3}$; $b=2.341250\times10^{-4}$; and $c=8.76741\times10^{-8}$ taken from a Vertilas VCSEL data sheet [112] provide a B parameter of 3854.7.

Finally, the digital control loop must be tuned in order to provide the best disturbance rejection and settling time. The standard method is tuning via the Ziegler–Nichols method [113]. This involves determining the critical gain for oscillation, and using these parameters to provide optimized control loop performance. However, hand tuning can also be an effective control loop tuning method with good results.

*Lock-in amplifier*

For the lock-in amplifier and laser drive systems, the modulation frequency must be determined. The circuitry has been designed to modulate from 0-17kHz, and perform demodulation at various harmonics. Modulation depth must also be optimized, and reports in the literature report 2 to 3 times the full width at half maximum (FWHM) of the absorption peak are optimum [114,86].

*Pressure system*

To create a pressure controlled system, the simplest method is to simply attach another sensor core module and replace the TEC with a pneumatic valve, as the PWM drivers are also designed for motor drive and valve applications. Lowering the pressure of the target sample can improve performance by reducing pressure broadening effects on the absorption spectrum.

Implementing a pressure system may be necessary when the gas species adsorbs onto surfaces, lowering the detected concentration. In this case, a heater may also be
necessary, which may be implemented with another PHOTONS board, and the PWM output should be connected to a heating element. Any power drive or motor movement capability can be implemented with the PWM driver with the appropriate programming and resistive sensors can be interrogated with the thermistor sensor, providing multiple uses for the PHOTONS circuits.

B. Sensor Deployment

The next issue is sensor deployment. The battery is the first issue with deployment. In a WSN application without energy harvesting, the sensor must be equipped with a fairly large battery. This battery must also survive field deployment subjected to the temperature extremes of the environment. The second issue is environmental ruggedization. If subjected to outdoor conditions, appropriate measures must be taken to shield from rain and moisture. The best route for such ruggedization is the use of epoxy potting material to coat the PCBs. This provides a relatively inexpensive and robust alternative to creating enclosures with o-rings and feedthroughs. However, epoxy potting lowers the heat removal from the board via convection, unless a high thermal conductivity epoxy is used.
Chapter 6. Future implementations

This section will describe examples of future PHOTONS implementations into a selection of useful applications.

In a standalone laboratory sensor which requires multiple species detection, the PHOTONS platform excels due to its replicable modular architecture. The route to creating a multi laser sensor based on TDLAS with a single multipass cell and detector is the following:

- Use wavelength division multiplexing (WDM) or pellicle to combine multiple laser beams
- Wire boards together on \( \text{i}^2\text{C} \) bus
- Wire each board to its own laser
- Implement appropriate MPC
- Command each board to use different modulation frequency
- From single detector signal, use external amplifier and high speed ADC
- Communicate ADC values by broadcasting (general call) over \( \text{i}^2\text{C} \)
- Perform lock-in on \( \text{i}^2\text{C} \) values instead of onboard ADC

Such a system provides a compact, scalable sensor with simultaneous detection of multiple target species (Figure 56).
Figure 56: Implementation of a multi-species, single MPC/detector sensor. The lasers are modulated at separate frequencies as in [24].

This method is different from multi-species sensors which implement tunable laser arrays or widely tunable lasers since the channels are ideally independent due to their spaced modulation frequencies. This provides real-time measurements for all species at once.

For a wide area monitoring application (such as a carbon sequestration monitor over a large area), the following method may be used to implement this type of network:

- Replicate complete sensors with size, cost, and power consumption optimization methods
- Provide WSN module for each sensor
- If very large inter-node distances are required, use node radios with power amplifiers, or place communications relay nodes
- Provide energy harvesting module to provide autonomous battery charging
- Implement relay mesh network, and provide network synchronization to have the network wake up after a measurement is made by all nodes
- Transmit to base station node, and display/record data
Figure 57: Wide area monitoring deployment of complete sensors. A wireless network is formed, and data is relayed to a base station for processing and visualization of the spatio-temporal measurements in real-time.

For a portable medical device application targeting long-term patient dose exposure to a certain molecule over time, the following methodology should be implemented:

- Create sensor with minimum size, relatively low power consumption to measure over at least a full day
- Provide charging module to charge device overnight in the vicinity of patient, or provide vibration based energy harvesting
- Provide flash memory large enough to hold data from at least a full day
- Provide data transfer to PC for storage or transfer to database or physician

A second version of this type of application where the exposure locations are known would be (see Figure 58)

- Create sensor network of gas sensing nodes
- Deploy to create real-time maps of chemical in high risk areas
- Provide patients with a communications node which communicates with gas sensor network and determines proximity to determine local exposure
- Provide data transfer to PC for storage or transfer to database or physician
Furthermore, the sensor must not have any issues with safety, excluding non-eye-safe techniques, cryogens, high heat production, and non-ruggedized gas reference cells if the gas is toxic.

Fast prototyping and deployment of a wide variety of configurations will be possible by designing the optical system for manufacture using rapid prototyping techniques. As a test of this method, a prototype TDLAS optical multipass module was consolidated into a single part using fused deposition modeling (FDM) prototyping techniques. The entire part was printed using ABS-polycarbonate plastic materials, and mirrors and adjustment screws were attached to provide 15 passes over 5 cm (Figure 59). The initial module used flat mirrors to determine if the beam could be steered accurately and whether the material provided adequate rigidity. A future module will use concave mirrors, to provide periodic refocusing of the beam. By machining a single basic part that acts as the laser mount,
multipass cell support structure, beamsteering optical holder, and detector mount all in one, cost and size are reduced.

![Image](image_url)

Figure 59: Custom optical MPC unit designed and constructed using rapid prototyping FDM in ABS-PC plastic and components of the shelf, left) pictured with networking module, right) shows spot pattern for 15 passes for ~75cm path. The detector mount is behind the mirror, and the hole for the detector is illuminated with the final beam spot.

Automatic synthesis of an optimized optical system for multipass cells would also provide powerful new tools for deployment of WSNs or PMD implementations. For instance, a Herriott cell could be generated with proper mirror spacing, beam injection angle, and mirror focal length for immediate construction using rapid prototyping. A simulation of a spherical mirror Herriott cell is shown in Figure 60.
Figure 60: Simulation of a spherical mirror Herriott cell spot pattern. Synthesis using off-the-shelf optical components targeting a certain path would provide rapid generation of optimized size and cost sensors.

With quickly scalable new designs and built in self-organizing networking capability, new applications can be generated and deployed in less time.

Chapter 7. Future Prospects and Conclusions

With the optimizations for laser spectroscopy presented in this thesis, the application space for these sensors can greatly improve, but some future technologies may allow these sensors to be improved much further. These technologies are 1) future QCL technology, 2) improving digital technology, 3) Lab-on-chip and micro-fluidic technology, 4) advanced energy storage and harvesting, and 5) micro-electromechanical
systems (MEMS). These sensors will eventually reach <0.1W power consumption, <$500, and system-on-chip size with appropriate configurations.

*Future QCL technology*

With QCL technology maturing, costs will eventually come down to meet the price of current telecom lasers. As wall plug efficiency improves, the sensor power consumption will continue to reduce. Packaging will also improve, integrating features currently available in telecom lasers such as integrated power monitors, integrated thermistors, optical isolators, and integrated etalons.

*Digital technology*

Digital technologies are evolving at a rapid pace. The newest microcontrollers have ultra low power and provide peripherals such as low power vector floating point units, built-in radios, and precision PWM drivers. These technologies will improve processing performance at lower cost, and provide low power and higher integration.

*MEMS technology*

MEMS technology will also provide new types of sensors, and allow novel methods for laser spectroscopy. MEMS micro mirror arrays (such as DLP from Texas Instruments) show that MEMS optical components can be mass produced. For instance, a mirror on a worm drive linear actuator can replace lead-zirconium-titanate (PZT) piezos in cavity enhanced methods. Clock resonators made in MEMS have been of interest to generate oscillators for system-on-chip applications, but can eventually be used in photoacoustic type applications. MEMS can also provide external cavity gratings with no macro-moving parts, increasing robustness and greatly miniaturizing the optical configuration for wide tuning ranges [115].
Platform Development

Further platform development will greatly benefit by improving the software to quickly configure new sensors and networks, and providing complete sensor modeling and simulation to determine performance before a sensor is built. Additionally a software toolbox with open-access will be implemented to quickly find the best algorithms for each sensing application. Further software optimization to provide more optimized processing can improve efficiency to drive power consumption down further.

Novel Contributions

This thesis has provided a novel sensor platform suitable for many different implementations where chemical sensors are necessary. Sensor characteristics which have been overlooked previously were analyzed, and guidelines have been provided for constructing a sensor optimizing for one or more of these characteristics.

This sensor platform is the first laser spectroscopy platform to achieve size, cost, sensitivity, specificity, scalability, and power consumption suitable for potentially important applications of wireless sensor networks and portable medical devices.

A sensor platform has been designed, constructed, and analyzed, with simultaneously at least an order of magnitude better compared to typical sensors in this work for optimization of power consumption, size, and cost.

A comparison of sensors implemented along the development path was performed, and the reasoning behind various optimizations has been provided.

Important issues addressed were 1) the relationship between the three parameters of cost, size and power consumption, and the tradeoffs inherent to their simultaneous optimization, 2) development path of suitable sensor components to meet the target levels
of optimization, and 3) a comparison to between the sensors in terms of optimization level for each characteristic.

Although it required a significant change in developmental direction, laser spectroscopy now has sensor characteristics to enable applications which are crucial, yet would be impractical to implement with other detection techniques.

References

33 ZigBee Specification 2B Alliance - Zigbee Alliance Board of Directors, December, 2004
34 IEEE 802.15.4 standard, http://www.ieee802.org/15/pub/TG4.html
35 J. Alguacil; M. Porta; N. Malats; T. Kauppinen; M. Kogevinas; F.G. Benavides; T. Partanen; A. Carrato Carcinogenesis, 23: 1, pp. 101-106 2002
41 P. Silko, M. Carlson, T. Bourke, R. Kativa, E. Ögren, S. Szefler The Aerocrine exhaled nitric oxide monitoring system NIOX is cleared by the US Food and Drug Administration for monitoring therapy in asthma. Journal of Allergy and Clinical Immunology, Volume 114, Issue 5, Pages 1241-1256
42 US Department of Labor, Occupational safety and health administration http://www.osha.gov/
49 Edward J. Wolfram, Robert M. Meglen, Darren Peterson and Justin Sluiter, Metal oxide sensor arrays for the detection, differentiation, and quantification of volatile organic compounds at sub-parts-per-million concentration levels, Sensors and Actuators B: Chemical, Volume 115, Issue 1, , 23 May 2006, Pages 322-329.
50 http://www.thermo.com/


74 http://www.actel.com/documents/IGLOO_DCSpecs_DS.pdf

75 TI C6455 DSP, http://focus.ti.com/docs/prod/folders/print/tms320c6455.html


77 http://www.analog.com/en/ prod/0.,773_862_AD835%2C00.html

78 http://focus.ti.com/docs/prod/folders/print/ mpy634.html
99 www.dell.com
100 National Instruments PCI data acquisition cards: www.ni.com
101 Microsoft www.microsoft.com
103 Wavelength electronics www.teamwavelength.com
104 MKS instruments www.mksinst.com


112 http://www.vertilas.de/


### Appendix A: Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC</td>
<td>Analog to Digital Converter</td>
</tr>
<tr>
<td>ADM</td>
<td>Absorbance Detection Module</td>
</tr>
<tr>
<td>ALU</td>
<td>Arithmetic Logic Unit</td>
</tr>
<tr>
<td>AR</td>
<td>Anti-Reflection</td>
</tr>
<tr>
<td>ASIC</td>
<td>Application Specific Integrated Circuit</td>
</tr>
<tr>
<td>BW</td>
<td>Bandwidth</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary Metal-Oxide Semiconductor</td>
</tr>
<tr>
<td>CRDS</td>
<td>Cavity Ringdown Spectroscopy</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>DAC</td>
<td>Digital to Analog Converter</td>
</tr>
<tr>
<td>DCR</td>
<td>Direct Current Resistance</td>
</tr>
<tr>
<td>DDS</td>
<td>Direct Digital Synthesis</td>
</tr>
<tr>
<td>DFB</td>
<td>Distributed Feedback</td>
</tr>
<tr>
<td>DFG</td>
<td>Difference Frequency Generation</td>
</tr>
<tr>
<td>DMA</td>
<td>Direct Memory Access</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processing</td>
</tr>
<tr>
<td>EC</td>
<td>External Cavity</td>
</tr>
<tr>
<td>EM</td>
<td>Electromagnetic</td>
</tr>
<tr>
<td>EMI</td>
<td>Electromagnetic Interference</td>
</tr>
<tr>
<td>ENBW</td>
<td>Effective Noise Bandwidth</td>
</tr>
<tr>
<td>ESR</td>
<td>Effective Series Resistance</td>
</tr>
<tr>
<td>FDM</td>
<td>Fused Deposition Modeling</td>
</tr>
<tr>
<td>FIR</td>
<td>Finite Impulse Response</td>
</tr>
<tr>
<td>FPGA</td>
<td>Field Programmable Gate Array</td>
</tr>
<tr>
<td>FTIR</td>
<td>Fourier Transform Interferometer</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width at Half Maximum</td>
</tr>
<tr>
<td>GBW</td>
<td>Gain Bandwidth</td>
</tr>
<tr>
<td>GC</td>
<td>Gas Chromatography</td>
</tr>
<tr>
<td>GRIN</td>
<td>Gradient Index</td>
</tr>
<tr>
<td>HDL</td>
<td>Hardware Description Language</td>
</tr>
<tr>
<td>HR</td>
<td>High-Reflection</td>
</tr>
<tr>
<td>IC</td>
<td>Integrated Circuit</td>
</tr>
<tr>
<td>ICOS</td>
<td>Integrated Cavity Output Spectroscopy</td>
</tr>
<tr>
<td>IIR</td>
<td>Infinite Impulse Response</td>
</tr>
<tr>
<td>IMS</td>
<td>Ion Mobility Spectroscopy</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>LAS</td>
<td>Laser Absorption Spectroscopy</td>
</tr>
<tr>
<td>LDO</td>
<td>Low Drop Out</td>
</tr>
<tr>
<td>LIA</td>
<td>Lock-In Amplifier</td>
</tr>
<tr>
<td>LO</td>
<td>Local Oscillator</td>
</tr>
<tr>
<td>MAC</td>
<td>Multiply Accumulate</td>
</tr>
<tr>
<td>MCT</td>
<td>Mercury Cadmium Telluride</td>
</tr>
<tr>
<td>MEMS</td>
<td>Micro Electro Mechanical System</td>
</tr>
<tr>
<td>MIPS</td>
<td>Millions of Instructions per Second</td>
</tr>
<tr>
<td>MOSFET</td>
<td>Metal Oxide Semiconductor Field Effect Transistor</td>
</tr>
<tr>
<td>MPC</td>
<td>Multipass Cell</td>
</tr>
<tr>
<td>MS</td>
<td>Mass Spectroscopy</td>
</tr>
<tr>
<td>NDIR</td>
<td>Non-Dispersive Infrared</td>
</tr>
<tr>
<td>NICE-OHMS</td>
<td>Noise-Immune Cavity-Enhanced Optical-Heterodyne Molecular Spectroscopy</td>
</tr>
<tr>
<td>NTC</td>
<td>Negative Temperature Coefficient</td>
</tr>
<tr>
<td>PAS</td>
<td>Photoacoustic Spectroscopy</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>---------------------------------------</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>PFM</td>
<td>Pulse Frequency Modulation</td>
</tr>
<tr>
<td>PHOTONS</td>
<td>Photonic Networked Sensors</td>
</tr>
<tr>
<td>PID</td>
<td>Proportional Integral Derivative</td>
</tr>
<tr>
<td>PLL</td>
<td>Phase Locked Loop</td>
</tr>
<tr>
<td>PMD</td>
<td>Portable Medical Device</td>
</tr>
<tr>
<td>ppb</td>
<td>parts per billion</td>
</tr>
<tr>
<td>ppm</td>
<td>parts per million</td>
</tr>
<tr>
<td>ppt</td>
<td>parts per trillion</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse Width Modulation</td>
</tr>
<tr>
<td>PZT</td>
<td>Lead Zirconium Titanate</td>
</tr>
<tr>
<td>QCL</td>
<td>Quantum Cascade Laser</td>
</tr>
<tr>
<td>QEPAS</td>
<td>Quartz Enhanced Photoacoustic Spectroscopy</td>
</tr>
<tr>
<td>RAM</td>
<td>Random Access Memory</td>
</tr>
<tr>
<td>RMS</td>
<td>Root mean square</td>
</tr>
<tr>
<td>SEPIC</td>
<td>Single ended Primary Inductance Converter</td>
</tr>
<tr>
<td>SERS</td>
<td>Surface Enhanced Raman Spectroscopy</td>
</tr>
<tr>
<td>SMPS</td>
<td>Switch Mode Power Supply</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>SOC</td>
<td>System on Chip</td>
</tr>
<tr>
<td>TDLAS</td>
<td>Tunable Diode Laser Spectroscopy</td>
</tr>
<tr>
<td>TEC</td>
<td>Thermoelectric Cooler</td>
</tr>
<tr>
<td>TF</td>
<td>Tuning Fork</td>
</tr>
<tr>
<td>VCSEL</td>
<td>Vertical Cavity Surface Emitting Laser</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength Division Multiplexer</td>
</tr>
<tr>
<td>WM</td>
<td>Wavelength Modulation</td>
</tr>
<tr>
<td>WSN</td>
<td>Wireless Sensor Network</td>
</tr>
</tbody>
</table>