Ultra-compact Multipass Laser Absorption Spectroscopy Platform for Distributed Sensor Networks

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Abstract: A prototype three-node wireless sensor network of portable, battery-powered spectroscopic trace-gas sensors equipped with custom 24-pass Herriott cells has been developed. Individual sensor performance and sensor network localization of a gas plume will be reported.

OCIS codes: (300.6360) Spectroscopy, laser; (280.3420) Laser sensors; (280.4788) Optical sensing and sensors

1. Introduction

We have developed a custom sensor platform for portable, battery-operated, low-cost, tunable diode laser absorption spectroscopy (TDLAS) sensors. Laser spectroscopic sensors have great potential for long-term, wide-area wireless deployments. TDLAS is ideally suited to wireless sensor network deployments due to its capabilities of: 1) high sensitivity and specificity, 2) low power consumption, 3) compact footprint, 4) low maintenance / no consumables, and 5) real-time data collection. To achieve higher sensitivities while maintaining constant low-power consumption, we developed a custom multipass cell (MPC) in a Herriott configuration [1] to increase the absorption pathlength. The MPC is low cost and compact to assure applicability of these sensors in distributed sensor networks with large node densities, while avoiding line-of-sight issues in open-path perimeter monitoring. We will describe development and deployment of a prototype three-node oxygen (O_2) sensor network for trace-gas localization applications.

2. Sensor Platform Configuration

We have implemented custom sensor electronics to perform TDLAS in a standalone, handheld package for sensor networks [2]. The current version is designed to accommodate most telecom distributed feedback (DFB) lasers and vertical cavity surface emitting lasers (VCSELs) with Peltier thermoelectric cooler (TEC) for temperature control. The system is capable of laser wavelength tuning through active temperature control. Additionally, the circuitry can acquire data using any combination of 1) slow temperature scanning, 2) sawtooth current ramping, 3) laser current sinusoidal modulation for wavelength modulation based techniques, and 4) first, second, or third harmonic detection via lock-in amplifier (see Fig. 1). The platform provides fully digital-sampling-and-processing 2 channel lock-in amplifier implementation for efficient noise and drift reduction.

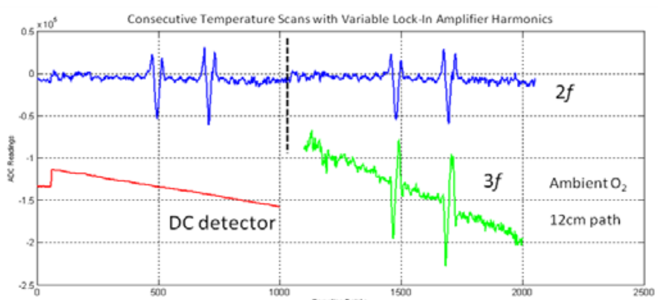


Fig. 1: Consecutive 2*f*, direct LAS (DC), and 3*f* scans (offset and scaled).

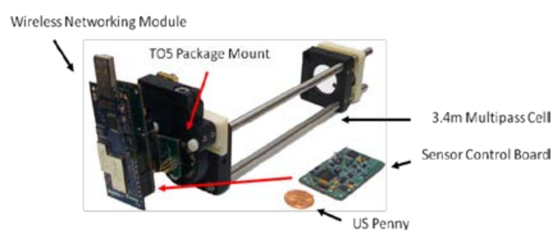
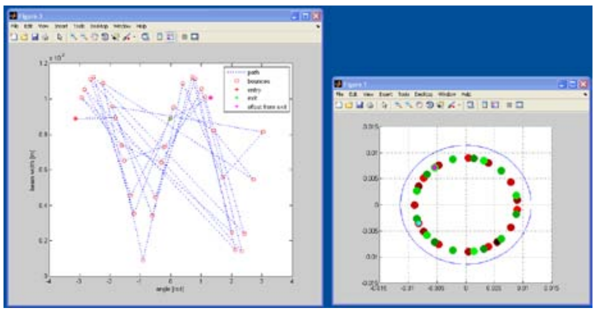


Fig. 2: Photograph of sensor platform with US Penny for scale.

Our multipass cells are based on a standard off-the-shelf optical cage mount system (Fig. 2) for cost-efficient implementation. A spherical Herriott multipass cell was designed using our custom MATLAB simulator based on ABCD ray tracing with complex beam parameter (Fig. 3). The simulation results were used as parameters to machine an input port in commercially available metallic spherical mirrors. This launched the beam into the correct spot pattern in a minimum volume. Our approach allows rapid simulation and construction of multipass cells with pathlengths tailored to a specific trace-gas and/or applications. The total bill-of-materials cost was USD$760 for one complete multipass cell, and each complete sensor takes a footprint of ~ 20cm x 7cm x 7cm.

3. Results

We deployed three prototype instruments using VCSELs with ~0.25 mW output power targeting O_2 absorption lines near λ=766 nm (13050 cm^{-1}). The sensors were configured in a wireless sensor network. A total power consumption of 0.5 W (including the TEC and the laser driver) was required by each individual sensor to detect ambient O_2 (21%) with 0.05% detection limit in 3.4m optical path. This corresponds to a minimum detection limit of $4x10^{-5}$ absorbance units obtained with 1 sec. lock-in time constant. During an initial calibration phase each sensor is scanned over the absorption line to provide a calibration between direct absorption and the peak 2*f* lock-in signal. Then, the system switches to a 2*f* / 3*f* lock-in detection mode, and automatically locks the laser emission wavelength to the target absorption line via current control. This method provides minimal signal processing power requirements, and runs in a standalone fashion on an 8MHz ultra-low-power digital signal processor.



Beam spot size evolution   Spot positioning on mirrors

Fig. 3: MATLAB multipass cell simulator output for 24 passes.

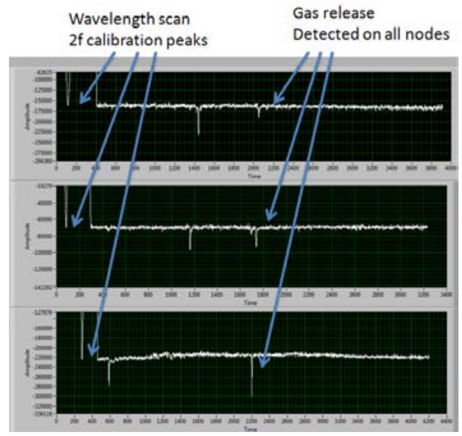


Fig. 4: Real-time data from 3 sensor nodes measuring O_2 for 3 plume releases. The direction of the release affected which nodes could detect the release. The final release was orthogonal to the plane of the sensors.

A preliminary test of a network deployment was carried out using three sensors deployed approximately three meters apart in a triangular configuration. These three sensors relayed their measurement data in real-time to a wireless base station connected to LabVIEW. In a closed room (minimum convection currents) an O_2 plume was released from an oxygen tank. Assuming a uniform diffusion of the gas the networked sensors were able to detect the concentration of the gas in real-time (Fig. 4) and the location of the release was calculated via time-of-flight.

4. Conclusion

Distributed trace-gas sensor networks have great potential to make a significant impact on the applications that require large area trace-gas monitoring (including environmental and industrial sensing or security applications). Laser spectroscopic sensors offer unique capabilities of high sensitivity and specificity for target analytes, in contrast to other methods (e.g. chemical or electrochemical methods). The reported system is cost-effective and offers flexible configuration. The developed system can accommodate a variety of laser sources such as TO packaged lasers, fiber coupled collimators, or custom cylindrical mounts up to 25.4mm x 6mm. It does not restrict adaptation of other lasers to the sensor platform, such as DFB laser arrays or high efficiency quantum cascade lasers. Different lasers may be mounted onto the same broadband multipass cell with the same electronics to be deployed in a heterogeneous sensor network to detect various greenhouse/pollutant gas species. We are currently developing other detection modules such as photoacoustic and Faraday rotation spectroscopy systems to use interchangeably with the direct absorption multipass modules. Results obtained with these other sensing techniques will also be reported.

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