Precision Spectroscopy to Enable Traceable Dynamic Measurements of Pressure

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Abstract: We present recent work aimed at creating a standard for the dynamic measurement of pressure. A near-IR laser spectroscopy system is demonstrated for measuring 8 cm^{-1} in 50 μs with a 4 kHz repetition rate.
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1. Introduction

Dynamic measurements of pressure are ubiquitous to modern life for example they are used for refining the efficiency internal combustion engines where the pressure cycles can reach 10 MPa at rates of tens of kilohertz.[1] High speed dynamic pressure sensors are used in automobiles to detect impacts in order to determine if the airbags should be deployed. Dynamic pressure mapping is used to understand the forces exerted on a dummy during crash test for automotive safety.[2] Another area of critical safety importance is characterizing the concussion inducing blast waves encountered on a battlefield which typically have a peak pressure near 1 MPa with duration of tens microseconds. However, even with the vast importance of dynamic measurements of pressure on a diverse cross-section of industry there lacks a traceable calibration to nationally (or internationally) recognized standard. Currently no National Metrology Institute (NMI) offers calibration services for these dynamic measurements at the needed measurement rates which is on the order of tens of kilohertz. Our goal is to develop traceability using high speed precision spectroscopy to measure the pressure broadened linewidth and temperature induced intensity changes at a measurement rate near one hundred kilohertz with uncertainties of 5 % or less.

Whenever there is an adiabatic change in pressure there is a corresponding change in temperature and so any dynamic measurement of pressure must also include a dynamic measurement of temperature because of the temperature dependence of the molecular lineshape. Typically, spectroscopic measurements of temperature use the ratio of the intensities of two ro-vibrational transitions from the same vibrational band but with different ground state energies and or temperature sensitivities. As an alternative to this two-line approach we propose scanning over many transitions and then perform a multi-spectrum fit for pressure, temperature, intensity with fixed mole fraction. To achieve rapid and broad wavelength tuning we are leveraging the well-known temperature dependence of the lasing frequency in common distributed feedback (DFB) lasers. Sanders et al. have demonstrated nearly 20 cm^{-1} scanning at a one kilohertz rate by using a chopped external laser to heat the laser substrate.[3] By applying a 2 ampere 250 ns duration current pulse directly to the DFB Njegovec et al has demonstrated wavelength tuning on the order of 50 cm^{-1} in 250 ns with a 10 kHz repetition rate.[4] The wavelength tuning is driven by internal heating of the substrate due to Joule heating.

2. Experiment

In our work we built upon Njegovec et al.'s approach. A 50 μs 8 Volt pulse generated from an arbitrary function generator at a repetition rate of 4 kHz is applied as modulation to the input of a commercial diode laser controller. The peak current from the current controller is about 500 mA. The DFB is a TO-can style with internal TEC cooling unit and operates at 1571 nm (6366 cm^{-1}). The DFB is initially internally cooled to a temperature of 0 ºC. A portion of the beam is sent to a temperature controlled solid silicon etalon with an FSR of 0.017 cm^{-1} for wavelength is measurement. The etalon signal is digitized at 1 GS/s with 12-bit vertical resolution. The remaining portion of the laser beam is sent through a 1-meter-long absorption cell and the resulting signal is focused onto a 400 MHz detector low pass filtered below 100 MHz and digitized at 200 MS/s using a 16 bit DAQ. The absorption cell was filled with 46.4 kPa of CO_2. A total of 164 pulses were recorded at a rate of 4 kHz and averaged. The total acquisition time was 41 ms. The bandwidth covered in each pulse is greater than 8 cm^{-1} and bandwidths up to about 13 cm^{-1} have been measured. We demonstrate scanning from R(26e) to R(R40e) of the (30012)←(00001) vibrational band of CO_2

centered at 6348 cm^{-1}. The resulting spectrum is shown in Fig 1 overlaid with a simulation created using HITRAN 2012. [5]

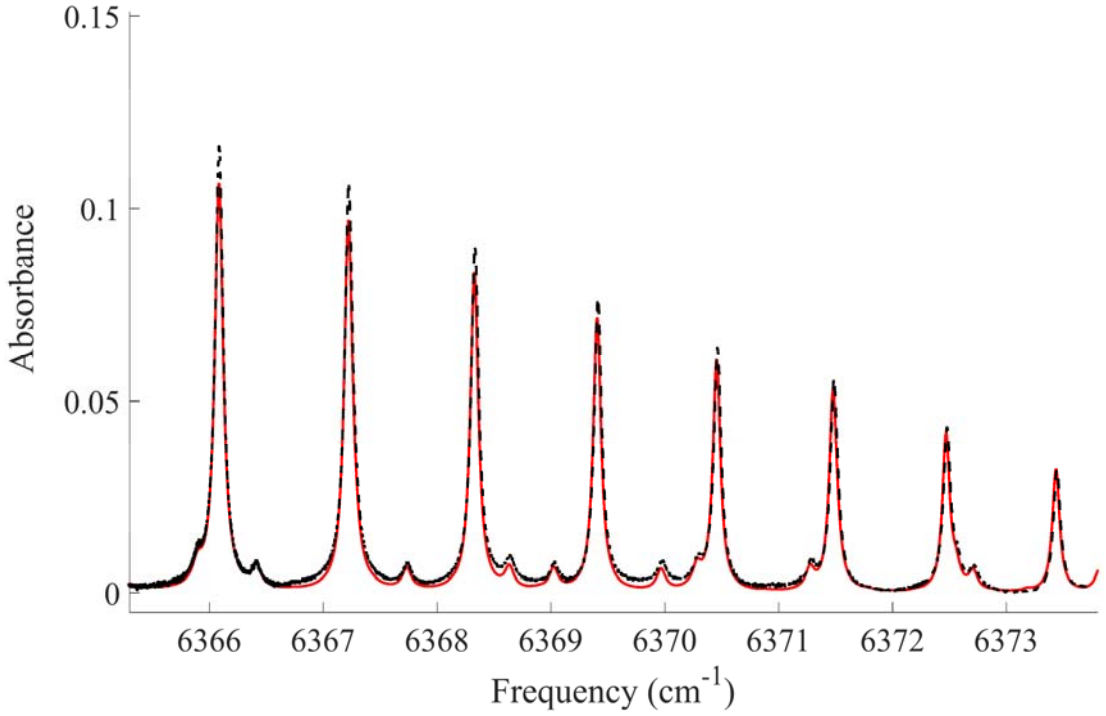

Figure 1. Absorption spectrum of CO_2 in a 1 meter path length at 46.4 kPa (black) overlaid with the simulation (red). The 8 cm^{-1} slice of the spectrum was acquired in 50 µs at rate of 4 kHz.

3. Summary

We have presented a method for using Joule heating via current pulsing to achieve rapid wavelength scanning of a DFB laser to record an 8 cm^{-1} section of the CO_2 spectrum in 50 µs with repetition rate of 4 kHz. An analysis of the spectrum of CO_2 using traditional methods compared to a multi-line fit to determine pressure and temperature is currently underway. The challenges, tradeoffs, and future directions of the rapid wavelength tuning method will be discussed. We will also present a rapid wavelength tuning in combination with wavelength modulation spectroscopy in order to achieve unprecedented speed and sensitivity.

[1] Hjelmgren, J. 2003 Dynamic Measurement of Pressure - A Literature Survey. *SP Swedish National Testing and Research Institute*. **SP Report 2002:34**.
[2] https://www.tekscan.com/.
[3] Sanders, S.T., et al. 2001 Rapid temperature tuning of a 1.4-mu m diode laser with application to high-pressure H2O absorption spectroscopy. *Optics Letters*. **26**(20): p. 1568-1570.
[4] Njegovec, M. and D. Donlagic 2013 Rapid and broad wavelength sweeping of standard telecommunication distributed feedback laser diode. *Optics Letters*. **38**(11): p. 1999-2001.
[5] Rothman, L.S., et al. 2013 The HITRAN2012 molecular spectroscopic database. *Journal of Quantitative Spectroscopy & Radiative Transfer*. **130**: p. 4-50.