Fully automated, real-time monitoring of ambient water vapour using a compact 1392 nm tunable diode laser-based system

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***Abstract*—This paper describes the development and deployment of an ambient water vapour measurement system based on tunable diode laser absorption spectroscopy (TDLAS). The system was designed with a near-infrared 1392 nm distributed feedback (DFB) tunable semiconductor laser that targeted the 1391.672 nm absorption line of water vapour. A compact and field-deployable system used made using a combination of a Raspberry Pi unit and Picoscope 2406B for data acquisition, signal processing and estimation of mole fraction using $R_{1f}/\Delta I_1$ wavelength modulation spectroscopy (WMS) technique implemented in Python. The battery-powered setup was fully automated and remotely accessible over a wifi connection. The system was mounted on a vehicle and in-field measurements were carried out at fixed locations and with the vehicle moving in Gandhinagar.**

Keywords*— Water vapour measurement, wavelength modulation spectroscopy, remote pollution monitoring, Raspberry Pi

I. Introduction

Accurate monitoring of trace gases in the urban locations in India is important to understand the extent and severity of global warming and air pollution levels due to industrial emissions. Gases such as carbon dioxide (CO_2), methane (CH_4) and water vapour contribute heavily to the greenhouse effect. Currently, almost all of the greenhouse gas monitoring and urban pollution monitoring in India is carried out at fixed locations with bulky sensors systems. It is necessary to develop compact, light-weight and battery-powered sensor units that can be mounted on vehicles and deployed in various locations to obtain real-time spatial mapping of emissions. This paper describes the development and field deployment of a tunable diode laser-based water vapour measurement system, the details of which are described later. Such systems can be mounted on existing urban transport networks to continuously monitor emission levels over large areas and thereby contribute to effective monitoring and management of emissions. They can also be mounted on unmanned aerial vehicles (UAV) to obtain vertically resolved measurements of greenhouse gases and other hazardous gases. This work focuses on the measurement of water vapour partly because it is the dominant greenhouse gas that creates positive feedback for global warming [1] and plays a vital role in monitoring the temperature of the earth.

II. Measurement Technique

TDLAS-based trace gas measurement systems are widely used for accurate estimation of gas parameters [2]. The simplest form of TDLAS is known as direct detection technique. A schematic of the experimental arrangement is shown in Fig 1. In TDLAS, the emission wavelength of a narrow linewidth tunable semiconductor laser is precisely tuned across a single near-infrared or mid-infrared absorption line of a gas, and the variation of the relative transmission with wavelength is measured. The relative transmission has the same form as the absorption line shape, and this makes it possible to extract the mole fraction of the gas from it by fitting an appropriate line shape function. This technique is straightforward but has limited sensitivity. High-sensitivity applications require that one uses WMS, which is somewhat more involved. A recent WMS technique, known as the $R_{1f}/\Delta I_1$ WMS technique [3], has proven to be very effective in high-sensitivity detection in outdoor scenarios [3]. This prototype used the $R_{1f}/\Delta I_1$ WMS technique to estimate the mole fraction of the water vapour.

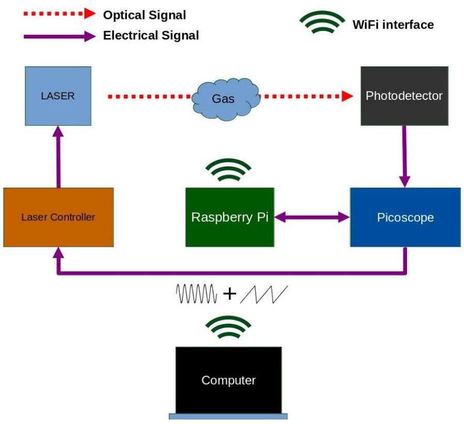

Fig. 1: Schematic of the prototype

III. Description of the Prototype

The prototype shown in Fig 1 is designed using a fiber-coupled DFB edge-emitting laser (Eblana Photonics, EP-1392-5-DM-B01-FM), photodetector (Thorlabs, PDA10DT-EC), a custom laser diode controller, data acquisition device (Picoscope 2406B), Raspberry Pi (Raspberry Pi 4 Model B), power bank (Anker, A1271012) and 12 V lithium ion batteries. The collimator and the photodetector were placed in a 3-D printed stage with two degrees of freedom for alignment. The other components were fixed inside a 25.5 x 20.5 x 12.8 cm acrylate box. The compact and portable prototype shown in Fig 2 weighs only 3.86 kg and is therefore easy to mount on any vehicle.

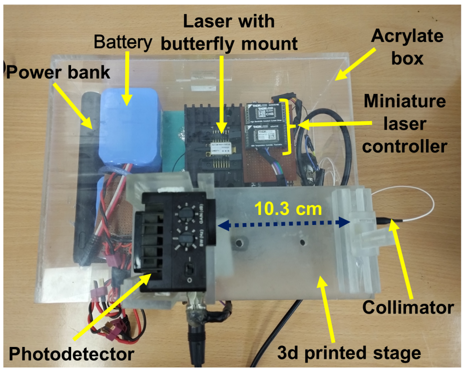

Fig. 2: Photograph of the compact water vapour measurement system.

The 1391.672 nm absorption line of water vapour that has a line strength of 5.984 x 10^{-22} cm^{-1}/ (mol cm^2) shown in the black box in Fig 3 was chosen because it is free from interference from adjacent lines.

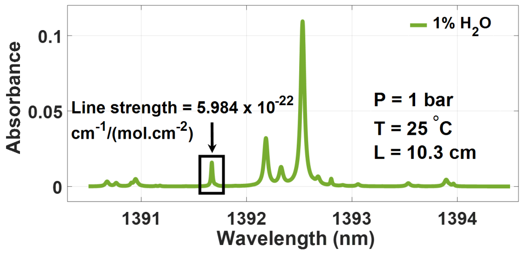

Fig. 3: Simulation of absorption spectrum of 1% water vapour at 1 bar and 25 ℃ for the temperature tuning range of the 1392 nm laser.

A. Adjustable Collimator-Photodetector 3-D printed Stage

The photodetector and collimator stage was 3-D printed with a fixed cavity for the relatively heavy photodetector at one end and a movable mount for the collimator at the other end separated by 10.3 cm. The collimator can be adjusted sideways and vertically with respect to the photodetector. This provides sufficient room for alignment. This stage being lighter provides more stability.

B. Miniaturized Laser Diode Controller

The miniature laser diode controller consists of a laser diode driver and temperature stabilization unit. This is implemented using a laser driver IC (Thorlabs MLD203CHBE) and a temperature controller IC (Thorlabs MTD415TE). Various parameters such as laser temperature, maximum TEC (thermoelectric cooler) current and PID (proportional integral differential) values for the target laser are programmed into the controller module. This ensures precise tuning of the laser.

C. Data Acquisition and Processing

The photodetector signal is acquired at 1 MSPS and digitized with a vertical resolution of 8 bit using the Picoscope and sent to the Raspberry Pi, which is connected to it using a USB interface. The Raspberry Pi calculates the signal range, offset voltage and trigger threshold voltage and ensures that the acquired signal is properly triggered. For WMS, a lock-in amplifier Python program is used to obtain harmonic signals for post-processing. The $R_{1f}/\Delta I_1$ WMS method is then used to estimate the mole fraction in the on-board Raspberry Pi using an algorithm that was previously developed in our lab [3]. The extracted mole fraction is then obtained remotely from the Raspberry Pi along with the timestamp of the recorded data. The minimum time resolution of measurement is 1.5 min.

D. Remote Access

The prototype is configured to automatically connect to known WiFi hotspots. The remote connection is established and managed using the RealVNC service. With an active internet connection, the setup is accessible over the RealVNC cloud service from any RealVNC Viewer client. The remote access enables an user to control the sensor system, view or obtain the output.

E. Power Supply

The prototype is fully battery powered. The Raspberry Pi and laser diode controller are powered by the 5V power bank. The Picoscope is powered by the Raspberry Pi's USB port. The photodetector requires three voltage levels i.e. +5V, +12V and -12V. The +5V supply is provided by the power bank and rest by two 12 V lithium ion batteries. The system operated continuously for 6 h during the tests.

IV. Experimental Results

Three in-field measurement trials were carried out using this prototype at a snack store in IITGN campus and at Shree Umiya Book Store in Motera, Ahmedabad in the rainy season (August 2022). The variation of the mole fraction of water vapour is shown in Fig 4a and Fig 5a respectively. Figure 4b and Fig 5b show the simulated and experimentally obtained $R_{1f}/\Delta I_1$ terms at a particular point of time denoted by the point A in Fig 4a and Fig 5a. The quality of fit demonstrates that the extraction of gas parameters is reliable.

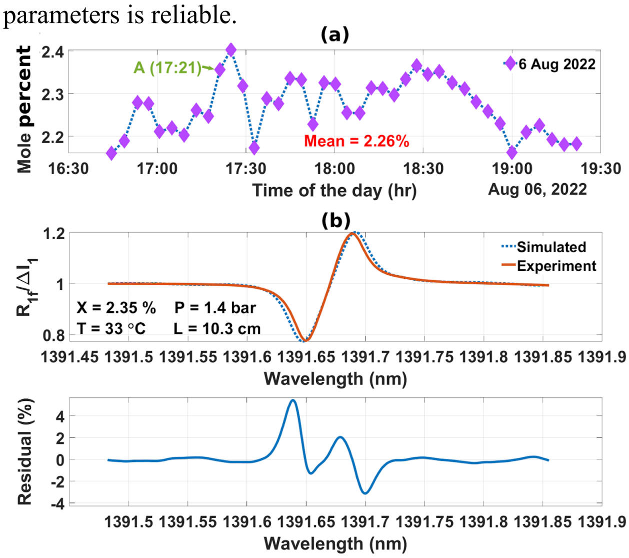

Fig. 4: (a) Variation of mole percent of ambient water vapour on 6 Aug 2022 over 2 h 37 min at 5 min intervals at Tea Post at IITGN with point A indicated in green and (b) Simulated and experimental $R_{1f}/\Delta I_1$ terms fit at that point.

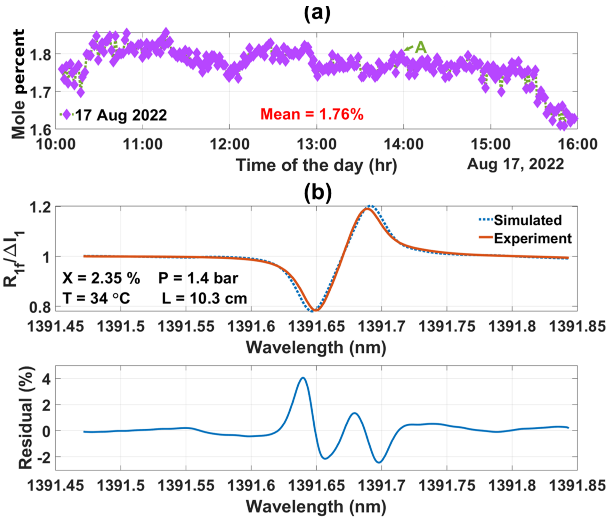

Fig. 5: (a) Variation of mole percent of water vapour on 17 Aug 2022 over 6 h at 1.5 min intervals at Shree Umiya Book Store at Chandkheda, Gandhinagar with point A indicated in green and (b) Simulated and experimental $R_{1f}/\Delta I_1$ terms fit at that point.

Mobile measurements were carried out next by mounting the prototype inside a vehicle. The vehicle was driven across the city of Gandhinagar at five places. A few breaks in the journey were deliberately introduced, and the vehicle's windows were rolled down and the air conditioner (AC) was turned off. There was also intermittent rainfall along the way. The prototype successfully recorded the variation of the ambient water vapour during the entire trip as shown in Fig 6a that shows the variation of mole fraction during the journey. The simulated and experimentally obtained $R_{1f}/\Delta I_1$ terms at 14:35 h are shown in Fig 6b denoted by the point C in Fig 6a to demonstrate the quality of curve fitting.

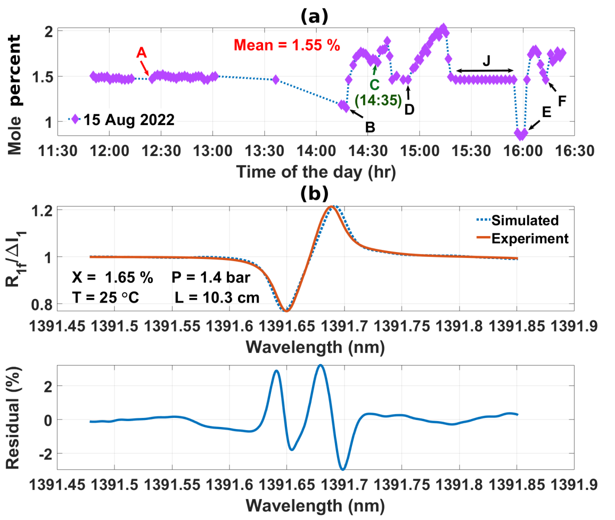

Fig. 6: (a) Variation of mole percent of ambient water vapour along the journey of various places at Gandhinagar on 15 Aug 2022 over 4 h and 28 min at 1.5 min intervals with point C indicated in green and (b) Simulated and experimental $R_{1f}/\Delta I_1$ terms fit at that point.

A few important aspects of Fig 6a are explained next. The points A, B, C, D, F are the time when the vehicle was parked and windows were opened and hence the water vapour measurement after these points show a gradual increase. The sharp drops in mole fraction that appear after each of these points correspond to the time instant when the AC was turned on and the windows were rolled up. A large spike appears after point E because the AC was turned off and the windows were rolled down at that instant while the vehicle was moving. The system was therefore measuring the high mole fraction of water vapour in the incoming air. The flat region marked J corresponds to a period in the journey when the sensor system encountered a technical problem, which caused it to report the same mole fraction.

The Allan deviation plot for the prototype shown in Fig 7 shows that the minimum detection limit is 32.2 ppm for an optimum integration time of 59 sec and a path length of 10.3 cm. This corresponds to a sensitivity of 3.31 ppm-m.

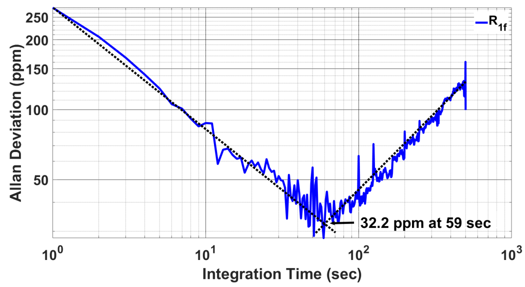

Fig. 7: Allan deviation plot to determine the minimum detection limit

V. Conclusions

A TDLAS-based water vapour measurement system has been implemented and tested for field measurements. The system is highly sensitive and has excellent time resolution. The most important feature of the $R_{1f}/\Delta I_1$ WMS measurement technique is that it is calibration-free. This is of great significance as regards in-field automated measurements. The system described here is the first step in the development of a network of compact TDLAS sensor units to carry out continuous real-time monitoring of trace pollutants. We aim to reduce the size and weight of the system further to make it suitable for UAV-mounted vertically resolved measurements of other trace gases.

Acknowledgement

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