Measurement of Carbon Dioxide Using Low-Cost & Compact Spectroscopy Based Gas Sensor

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***Abstract*—A compact and low-cost gas sensor using absorption spectroscopy for Carbon Dioxide (CO_2) measurement is presented. The sensing principle is based on open-path direct absorption spectroscopy in the mid-infrared range. The improved reflective structure of optical gas sensor consists of low cost and compact components, such as filament emitter, multispectral pyroelectric detector, Calcium Fluoride (CaF_2) window and aluminium curve reflective surface. In the previous investigation, the optimized gas cell structure was simulated using ZEMAX®12 software prior to fabrication for measuring CO_2 gas concentration. The developed gas sensing system using the optimized gas cell structure has shown the capability of accurately detecting CO_2 concentration. The sensor utilizes a CaF_2 narrow bandpass (NBP) filter for detection of CO_2 gas with no cross-sensitivity with other gases present in the gas cell. The repeatability of sensor's response of detecting CO_2 was tested with response times were calculated as being less than 1 second.**

***Index Terms*—Carbon Dioxide; Mid-Infrared Spectroscopy; Low Cost; Compact; Gas Monitoring.**

I. INTRODUCTION

The increasing of CO_2 levels in atmospheric can give rise to a process known as 'global warming' and can have detrimental effects on both human and animal life here on the Earth. The excessive of CO_2 gas emission may create a host of potential economic and environmental threats, including increased property damage from storms, human health risks, reduced agricultural productivity, and ecosystem deterioration [1]. One of the primary sources of CO_2 emission comes from the internal combustion engines and can lead to large-scale releases of CO_2 into the Earth's atmosphere on a daily basis [2]. In particular, the CO_2 emission amount from the transport sector (including cars) takes up 20% of total CO_2 emissions. Being a part of the energy sector, car manufacturers are facing significant challenges in developing technologies for reducing this portion of total CO_2 emissions [3].

Undoubtedly, uncontrollable exposure of CO_2 to human will definitely lead to harm and could be hazardous. Analysing and designing the highly sensitive and efficient CO_2 gas sensors have become subject of interest among scholars and industry people for more than two centuries in order to fulfill human needs. Numerous conventional gas sensing designs have been reported in the literature as potential optical Carbon Dioxide (CO_2) gas sensors in various applications which include catalytic combustion sensor, semiconductor sensor and electrochemical sensors [4-7]. Catalytic combustion sensors can perform well in detecting flammable gases close to the lower explosive limit but suffer from zero drift at ppm levels [8]. Semiconductor sensors can be very highly sensitive at the low ppm levels but it also suffers from drift and cross-sensitivity issues to other gases [9]. On the other hand, electrochemical sensors can be very relatively specific to individual gases and very sensitive at ppm or ppb levels, but they have limited and short lifetimes and also suffers from cross sensitivity issues [10]. In contrast, an optical absorption based gas sensor offers fast response, very minimal drift and high gas specificity with zero cross sensitivity to others gases [11-12]. In terms of detection limit, lifespan, susceptibility to cross-sensitivity and ability to withstand a harsh environment, an open path absorption sensor has been proven to be the most suitable of these technologies. Sensors based on open path configuration can provide the capability of lower detection limit. An open path gas sensor is where the light is coupled into the gas cell and propagates into the free space through the measured [12].

The existing CO_2 sensors with high level of accuracy and/or sensitivity are commonly designed and applied to wide range of applications such as monitoring indoor air quality [13] reducing energy usage in heating, ventilating and air conditioning (HVAC) systems [14], automotive for anti-drowsiness monitoring and air-management systems [15], intensive spatial field monitoring of CO_2 concentrations in a naturally ventilated dairy cow house [16], prime indicator of food spoilage in packed foods [17], monitoring CO_2 using mobile sensor system in permafrost areas [18] and horticulture to accelerate plant growth and eliminate pests such as whiteflies and spider mites [19]. Those gas sensors are typically designed to be an optimized and compact structure, which enables to be independently applied as potential absorption based CO_2 gas sensor for a variety of the aforementioned applications. However, the CO_2 sensors with such capabilities and characteristics normally require a high level of cost fabrication due to the uses of expensive material or components and also due to the sophisticated structure design. Hence, designing an economical, optimized and compact structure of absorption spectroscopy based CO_2 gas sensor to effectively monitor and control the level of CO_2 in the environment is essential indeed.

II. THEORETICAL BACKGROUND

Absorption spectroscopy techniques offer direct, rapid, and often highly selective means of accurately measuring gas concentration [20]. However, to use absorption spectroscopy technique, the gas detected must have significant distinct absorption, emission or scattering in a convenient region of

the optical spectrum. Different gas molecules will absorb radiation at different wavelengths, as each gas species has their own individual absorption spectrum. CO_2 has a characteristically strong absorption band in the mid-infrared region, extending from 4.2 μm to 4.5 μm, with its high peaks at 4.23 μm and 4.28 μm wavelengths as shown in Figure 1. Apart from that, CO_2 also shows a weaker corresponding near-infrared overtones absorption band around 2.7 μm, two orders of magnitude lower than that at 4.28 μm. The fundamental absorption lines of the majority of the atmospheric gases are located in the mid-infrared region with weaker overtones in the near infrared region [21]. Figure 1 illustrates the intensity of absorption by carbon dioxide in the mid-infrared region with the maximum carbon dioxide intensity of 3.543×10^{-18} cm^{-1} mol^{-1} cm^2.

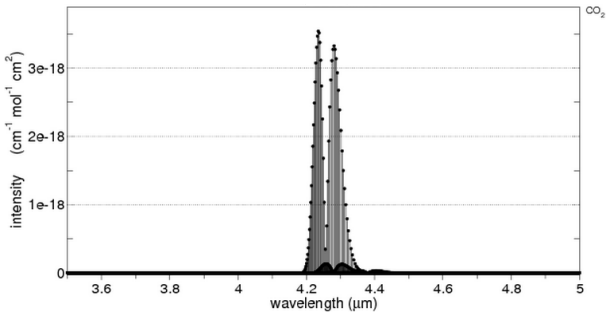

Figure 1: The absorption spectrum of CO_2 in the mid-infrared region showing its fundamental line strength at 4.23 μm and 4.28 μm

The linear relationship between absorption and concentration of an absorbing species can easily be calculated by using the Beer-Lambert law, which is shown in Equation (1). It is most commonly used to calculate how much incident radiation is absorbed by a sample. This is described in detail by many chemistry textbooks and journal [22]:

$$\ln\left(\frac{I}{I_o}\right) = -\varepsilon \times c \times l \tag{1}$$

where I is the transmitted intensity or the radiation after absorption, Io is the incident intensity or the radiation before absorption, ε (cm^2/mol) is the wavelength dependent molar absorptivity of the species, l (cm) is the optical path length and c (mol/cm^3) is the concentration of the absorbing species.

A variation of the Beer-Lambert Law was utilized by a specifically designed LabVIEW program to calculate the concentration of the gases present. The concentration of the species and a molar absorptivity of the species can also be expressed in different terms as shown as follows [12]:

$$c = \frac{c_{ppm} \times d}{w \times 10^{6}} \tag{2}$$

$$\varepsilon = \sigma \times N_A \tag{3}$$

where σ (cm^2/Molecule) is the wavelength dependent absorption cross-section of the species, w (kg/mol) is the molecular weight of the species, d (kg/cm^3) is of the density of the species in air by volume, N_A (Molecule/mol) is Avogadro's constant and c_{ppm} is CO_2 concentration in parts-per-million, or ratio of CO_2 molecules to total molecules, in the atmosphere. Hence, substituting Equations (2) and (3) into Equation (1) will give:

$$\frac{I}{I_o} = e^{-(\sigma \times N_A) \times \left[\frac{c_{ppm} \times d}{w \times 10^6}\right] \times l} \tag{4}$$

Therefore,

$$c_{ppm} = \frac{-\left[\ln \frac{I}{I_o}\right] \times w \times 10^6}{\sigma \times N_A \times d \times l} \tag{5}$$

or,

$$\sigma = \frac{-\left[\ln \frac{I}{I_o}\right] \times w \times 10^6}{c_{ppm} \times N_A \times d \times l} \tag{6}$$

A variation of Equation (5) shown in Equation (6) is utilized to calculate the measured absorption cross section for CO_2. This measured absorption cross section represents the average of the absorption present across the full spectrum of the filter range. This value will be used during further tests to calculate the concentrations of the CO_2 present in the gas cell (will be discussed further under Experimental Set-up section).

III. Proposed Technique

Instead of using transmissive type for the gas chamber, we chose to use reflective type. A reflective type of gas cell offers long path length incorporating more compact gas cell design than that of the transmissive type. It is proven from Beer-Lambert law in which absorption is directly dependent on path length of the gas cell [22]. As shown in Figure 2, longer optical path length offered by the reflective gas cell than transmissive type by which indirectly raising the level of absorption by the gas species, subsequently improve the sensitivity of the system [23-24]. In the optical carbon dioxide gas sensor, the infrared radiation from optical source transmitted through the detected gas twice and doubled the optical path length, thus improve the detection accuracy [25]. In comparison, a reflective gas cell is not only compact in size but also offers better sensitivity due to its longer optical light path. The sensitivity of an open path absorption based sensor can simply be improved by increasing the path length of the gas cell. However, this will decrease the signal detected at the detector circuitry subsequently reducing the signal-to-noise ratio (SNR) of the sensor system which may affect the minimum detection limit of the sensing system. Hence, the optical path length of the gas cell should not be increased to a point where it may decrease the overall minimum detection limit of the sensing system [12].

The reflective gas cell used to house the sample of gas in the optical gas sensor must be constructed from either stainless steel or aluminium due to ruggedness and relatively low cost of these metals. In the previous investigation, the CO_2 sensor was designed and simulated using ZEMAX®12 software to get the optimized structure of reflective curve

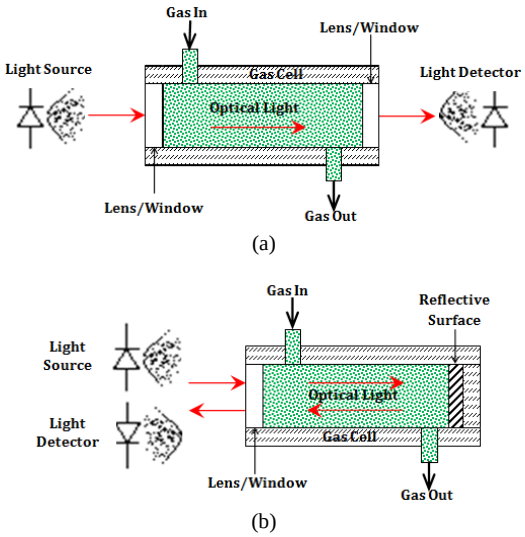

Figure 2: Open path absorption based gas cell (a) Transmissive type (b) Reflective type

surface using Non-sequential ray tracing technique [26]. The proposed gas cell is compact as it is based on reflective type which consists of few optical components, tubes and reflective surface. Figure 3 illustrates the detailed cross-section view of the proposed reflective CO_2 gas sensor showing the light propagation and gas circulation inside the gas cell. The infrared emitters are attached on top of the gas sensor's surface subsequently reducing the transmission losses. Instead of using the highly expensive CaF_2 lens for collimating the infrared radiation as used in previous works [27-30], it is replaced with a CaF_2 window. To have better light coupling to the detector at which centered in the middle of the gas cell, the rectangular tube is attached between the CaF_2 window and the detector position. Curved surface as a reflective mirror which also made of aluminium is attached at the end of the gas cell replacing the previous flat reflective mirror used.

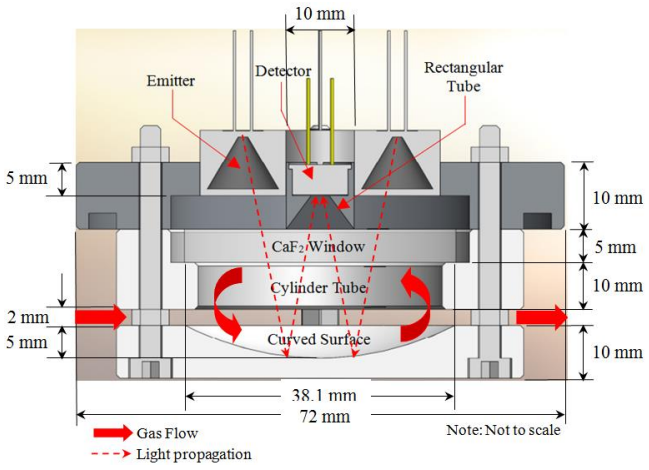

Figure 3: Detailed cross-section view of the optimized reflective based CO_2 gas sensor

As depicted in Figure 3, the pulsed infrared radiation from filament emitter will be launched into the gas cell through the CaF_2 window. Following transmission into the gas chamber, the infrared radiation traveled across 10 mm of cylinder tube where it will interact with the measured gas before coming in contact with a curved aluminium end surface. Upon contact with the curved aluminium surface, parts of the infrared radiation will be transmitted back to the same CaF_2 window where it will be confined to the rectangular tube attached to the centered pyroelectric detector.

IV. Experimental Setup

The schematic diagram of experimental set-up of the proposed reflective mid-infrared sensing system as assembled in the laboratory is shown in Figure 4. The optimized gas sensor using low cost and compact mid-infrared region component, consists of a broadband infrared radiation light source (2–20 μm); filament emitter reflectIR-P1C (1-10 Hz) and infrared light source evaluation kit from ion optics, LIM-262 multispectral pyroelectric detector circuitry, and also a compact reflective gas cell where curved aluminium reflective surface was used at the end of one side of the gas cell while CaF_2 window located at the other side. The window acts as a transparent barrier between the outside environment and the interior of the gas chamber. The pyroelectric detectors are fitted with two different filters, one with Narrow Bandpass filter at a centre wavelength of 4.26 μm for CO_2 detection and the other with a reference filter at a centre wavelength of 3.95 μm with a bandwidth of 180 nm and 90 nm respectively. The voltage response of the sensor was detected by a computer by using a National Instruments BNC 2110 Data Acquisition (DAQ) card and LabVIEW software. Both gases CO_2 and N_2 were mixed using Mass Flow Controller (MFC) to control the gas flow before purging into gas cell. The flow in and flow out of the gas before and after entering the gas cell as shown in Figure 4. A specifically designed LabVIEW program has been developed for use in the sensing system as a means of controlling data acquisition from the receiver circuitry.

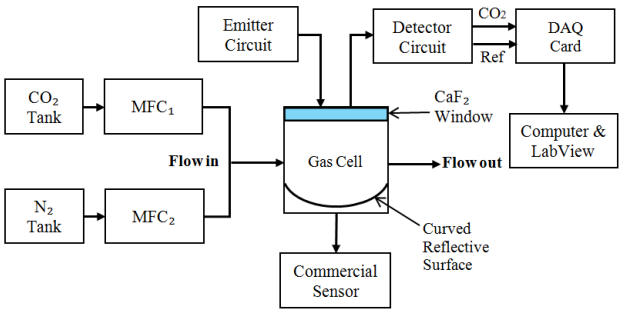

Figure 4: Schematic diagram of experimental setup

Reduction of transmission of the infrared beam due to the presence of the CO_2 can be verified by the unchanging output from the reference detector while the output from the detector fitted with the CO_2 selective filter drop noticeably. Besides that, selective detection scheme which is free from the cross-sensitivity issue with other gases can be realized by the use of these NBP filters. Water vapour (H_2O) has relatively significant absorption within the mid-infrared region and has been the main concern in designing a highly sensitive spectroscopic based gas sensor. The transmission of NBP filters which fitted on CO_2 and reference detector mentioned and the H_2O absorption is shown in Figure 5. It is clearly shown that the water vapour has no significant absorption within the wavelength range covered by the NBP filters on detector's channel.

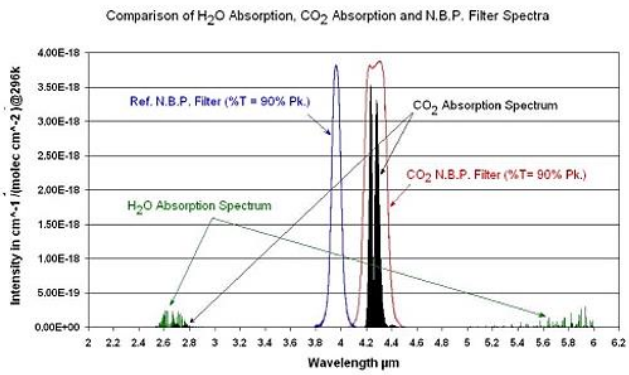

Figure 5: Pyroelectric detectors fitted with NBP filters provide immunity to H_2O [28]

Figure 6 illustrates the photographic experimental set-up of the optimized CO_2 gas sensing system. The gas flow from CO_2 and N_2 tanks were transported through the Mass Flow Controllers (MFC) to ensure more stable gas flow channeled to the optimized gas cell. The MFC used in the proposed optical sensing system is a trustworthy and well calibrated commercial gas mixer. The use of MFC has significantly affected the quality or the stability of sensor's response which described earlier. Voltage response from the sensor has shown less drift effect as reported by the previous gas sensor during initial test [30]. Besides that, the cost-effective of the proposed gas sensor has been improved as compared to the previously developed gas sensor. The proposed gas sensing system has eliminated the use of the aforementioned component, thus the replacement and modification are made on the structure of the gas cell to comply with the changes made.

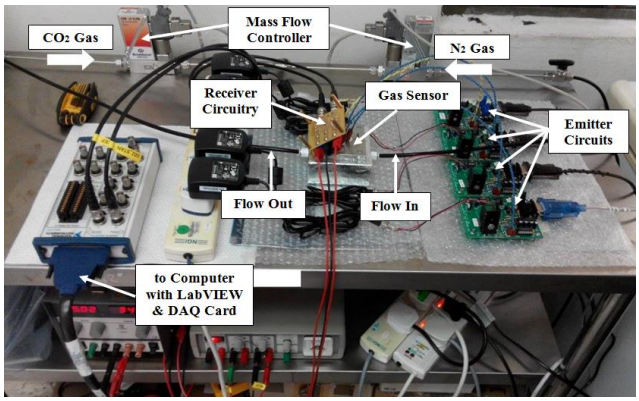

Figure 6: Photographic experimental set-up of CO_2 sensing system

V. Results and Discussion

The initial measurement was carried out to determine the background intensity (due to dark current) of the multispectral pyroelectric detector, LIM-262 that used in this experiment. Background intensity, I_b is a phenomenon caused by dark spectrum and stray light. Dark spectrum is described as the intensity captured in the absence of any incident light. The measurement was completed by switching off the light source and voltage drop was recorded for 15 minutes as shown in Figure 7. An averaged background voltage for CO_2 channel was computed to be 4.508 mV approximately. This value has to be subtracted from the recorded initial and transmitted voltage for each second to get an accurate voltage reading.

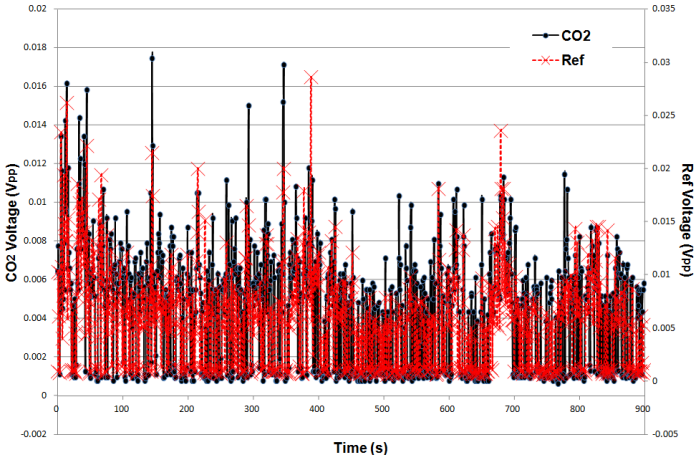

Figure 7: Background voltage, V_b response

Initial calibration was performed to estimate the measured average absorption cross section for this work. The flow rate of CO_2 and N_2 from the MFC were set to be 0.02648 ln/min and 1 ln/min respectively. As discussed in the previous paragraph, the CO_2 gas concentration of 2% would be supplied provided both of the flow rates of CO_2 and N_2 were set as calculated. As shown in Figure 8, N_2 gas was released at 1 ln/min to remove all the atmospheric gases which may present in the gas cell for 450 seconds. Following this, CO_2 gas was released into the gas cell at a flow rate of 0.02648 ln/min (2.648% of full scale) for another 450 seconds. Notice that, constant output voltages were recorded with and without the presence of CO_2. Also, very minimal fluctuation could be observed for both reference and CO_2 output signals indicates that the advantage of MFC used in this experimental works. For validation purpose, a commercial sensor used to validate the corresponding CO_2 concentration which presents inside the gas cell before and after CO_2 gases were released. The output voltages were constantly maintained for more than 7 minutes to ensure the stability of average voltages responses from the developed sensor. Average voltage for both steps was recorded and used in Equation (6) to estimate the averaged measured absorption cross-section.

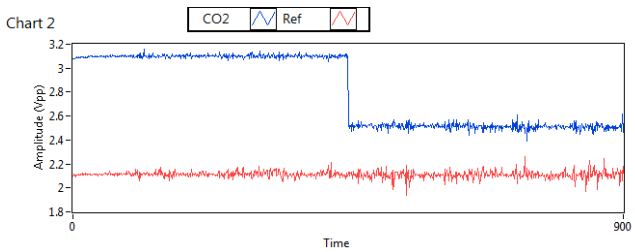

Figure 8: Measurement of averaged absorption cross section at CO_2 concentration of 2%

The same method was applied to calculate the respective CO_2 concentration supplied into the gas cell at various flow rates of CO_2 and N_2 gases. Figure 9 depicts the response of the sensor by varying the flow rate of N_2 at 1, 0.75, 0.5 and 0.25 ln/min while maintaining the CO_2 flow rate at 0.02648 ln/min which produced a CO_2 concentration of 1.52%, 2.01%, 2.99% and 5.81% respectively. CO_2 gas is fairly heavy gas, therefore proper and suitable flow of gas must be properly designed so that it would not take too much delay to remove the remaining CO_2 gas inside the gas cell between the concentration step transition. As discussed in earlier, the averaged absorption cross section value will be used in

Equation (5) to calculate the CO_2 concentration for each step response measured by the developed CO_2 sensor throughout the measurement process. The accuracy of CO_2 gas concentration reading from the developed CO_2 sensor is then compared to the reading by the commercial sensor, eSENSE®-D for verification.

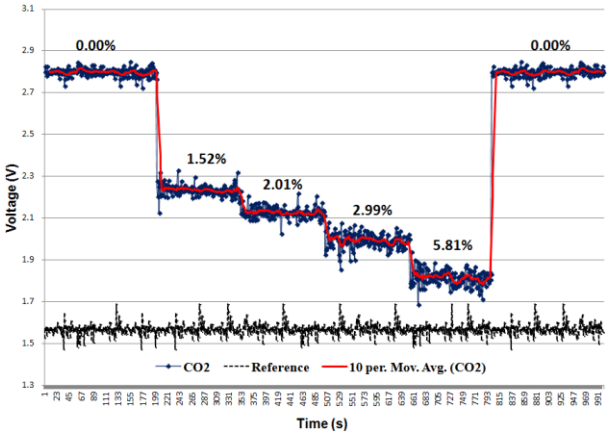

Figure 9: Graph voltage (V) vs time (s)

Figure 9 above illustrates both reference and CO_2 responses for 1000 seconds. Notice that, the reference output voltage remains constant throughout the measurement, indicating that there is no cross-sensitivity of the sensor to other gases present in the gas cell. Initially, the N_2 gas was purged at 1 ln/min for 200 seconds before purging CO_2 at 0.02648 ln/min and was fixed at all times. The gases were mixed for the next 200 seconds before lowering the flow rate of N_2 at 0.75 ln/min. The same process was repeated for a different flow rate of N_2 at 0.5 ln/min and 0.25 ln/min. The voltage response shows that the sensor is very responsive and has the capability of detecting the CO_2 concentration.

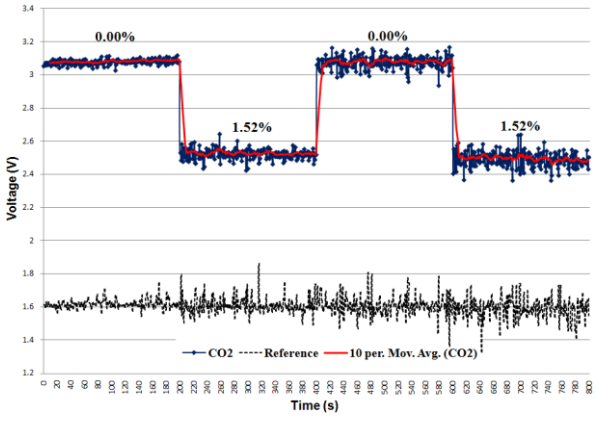

Figure 10: Voltage responses at 1.52% CO_2 concentration for 2 consecutive cycles

The repeatability of sensor's response of detecting CO_2 at 1.52% for two cycles is depicted in Figure 10. It proves that the sensor has a constant response and able to detect CO_2 concentration changes immediately. Again, voltage response for reference channel is constant for all times indicating that the sensor is not cross-sensitive to any other gas presents in the gas cell. Response times were calculated as being less than 1 second. Although recovery times appear relatively slow, this is due to the small flow rates used, resulting in the slow purging of the gas cell and CO_2 gas molecules remaining in the gas cell for a slightly extended period of time.

VI. CONCLUSION

The performance of the developed sensor is competitive and having the advantage of the low-cost structure. The developed sensor is compact in size, robust and constructed from inexpensive components and material. Although the response time is relatively slow as compared to that of others reported previous works (in order of milliseconds), the times are sufficient for monitoring purposes and comparable to many commercial sensors. The use of the expensive lens in various sensor designs previously reported [27-30] was replaced by the optical window. The optical window which applied in reflective type for this work will absolutely need the use of curved reflective surface instead of the flat reflective surface to ensure better light coupling subsequently, reducing the transmission loss.

The developed CO_2 gas sensor has shown its capability of accurately detecting CO_2 concentration ranging from 1% to 6%. The initial measurement was conducted to obtain the measured absorption cross-section which will be used to calculate the average CO_2 concentration from the CO_2 sensor. The optimized sensor's reading was verified with the reading from the SenseAir commercial sensor and the measured CO_2 concentrations reading have a close agreement to that of the commercial sensor.

It is proven that the prototype of the optimized gas sensor has been successfully developed and tested in the laboratory for measuring CO_2 concentration. Hence, the practicality and effectiveness of the optimized gas cell in this work is then examined and evaluated in various potential applications such as monitoring indoor quality, automotive, horticulture as well as heating, ventilating and air conditioning (HVAC) systems.

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