REFLECTIVE GAS CELL STRUCTURE FOR SPECTROSCOPIC CARBON DIOXIDE SENSOR

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requirements for the award of the degree of
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To my family for their constant support and encouragement throughout my postgraduate studies.

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ABSTRACT

This thesis describes an optical gas sensing system suitable for monitoring the presence of carbon dioxide (CO_2). An optical gas sensor using low cost and compact mid-infrared components has been developed and tested. The emitter and detector are compact, inexpensive and have low power consumption when compared with devices typically used in gas spectroscopy. Simulators such as ZEMAX®12 and SpectralCalc.com are primarily used in this work. Firstly, the research focuses on the simulation of the optimized and low cost gas cell for improvement using ZEMAX®12. Few gas cell structures have been designed and analyzed, which include Single-Input-Single-Output (SISO), 2-Multi-Input-Single-Output, 4-Multi-Input-Single-Output (4-MISO) and 8-Multi-Input-Single-Output. Of all these structures, SISO achieves the highest power efficiency of 28.028%. However, sensitivity analysis has shown that 4-MISO yields the highest sensitivity of -0.2879%$^{-1}$ and -0.2895%$^{-1}$ for concentration range from 1.5% to 1.8% and from 1.1% to 2.0% respectively. Secondly, the optomechanical design of optimized 4-MISO was analyzed and fabricated using low cost and robust material. Experimental works were then carried out and the sensor's output was acquired and recorded using Data Acquisition card and LabVIEW programme. Experimental results show that the new developed 4-MISO sensor has similar sensitivity to simulated gas sensor for detecting carbon dioxide gas concentration range from 1.5% to 1.8% with overall sensitivity of -0.2916%$^{-1}$. However, the deviation of sensitivity between the measured and simulated range of concentration was calculated at 0.0037%$^{-1}$. Finally, the developed low cost sensor has shown the capability of detecting CO_2 gas concentration with high accuracy of 0.6357% and response time of less than 1 second. The optimized gas sensor can be applied in various potential applications such as in monitoring indoor air quality, automotive, horticulture and heating, ventilating and air conditioning systems.

ABSTRAK

Tesis ini menerangkan sistem penderia gas optik yang sesuai untuk memantau kehadiran karbon dioksida (CO_2). Penderia gas optik yang terdiri daripada komponen kos rendah dan inframerah pertengahan yang padat telah dibangunkan dan diuji. Pemancar dan pengesan adalah padat, murah dan mempunyai penggunaan kuasa yang rendah jika dibandingkan dengan peranti yang biasanya digunakan dalam spektroskopi gas. Simulator seperti ZEMAX$^{®}$12 dan laman SpectralCalc.com digunakan terutamanya dalam kerja ini. Pertama, kajian ini memberi tumpuan kepada simulasi pada struktur sel gas yang optimum dan berkos rendah untuk penambahbaikan menggunakan ZEMAX$^{®}$12. Beberapa struktur sel gas telah direka bentuk dan dianalisis yang terdiri daripada Satu-Input-Satu-Output (SISO), 2-Multi-Input-Satu-Output, 4-Multi-Input-Satu-Output (4-MISO) dan 8-Multi-Input-Satu-Output. Daripada ini, SISO mencapai kecekapan kuasa tertinggi sebanyak 28.028%. Walau bagaimanapun, analisis kepekaan telah menunjukkan bahawa 4-MISO menghasilkan kepekaan tertinggi iaitu $-0.2879\%^{-1}$ dan $-0.2895\%^{-1}$ masing-masing, untuk julat kepekatan gas dari 1.5% sehingga 1.8% dan daripada 1.1% sehingga 2.0%. Keduanya, reka bentuk optomekanikal 4-MISO yang optimum dianalisis dan dibikin menggunakan bahan yang murah dan teguh. Kerja-kerja eksperimen kemudiannya dijalankan dan keluaran penderia diperolehi dan direkod menggunakan Kad Perolehan Data dan program LabVIEW. Keputusan eksperimen menunjukkan bahawa penderia baru 4-MISO mempunyai kepekaan yang serupa dengan penderia gas simulasi yang dapat mengesan julat kepekatan gas karbon dioksida dari 1.5% sehingga 1.8% dengan kepekaan keseluruhan sebanyak $-0.2916\%^{-1}$. Walau bagaimanapun, sisihan kepekaan antara julat kepekatan yang diukur dengan yang disimulasi dikira sebanyak $0.0037\%^{-1}$. Akhir sekali, penderia kos rendah yang dibangunkan telah menunjukkan kebolehan mengesan kepekatan gas CO_2 dengan ketepatan sebanyak 0.6357% dan masa tindak balas kurang dari 1 saat. Penderia yang telah dioptimumkan boleh diguna dalam pelbagai aplikasi yang berpotensi seperti memantau kualiti udara dalaman, automotif, hortikultur serta sistem pemanasan, pengalihudaraan dan penyaman udara.

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2-MISO - 2-Multi-Input-Single-Output
3-D - 3-Dimension
4-MISO - 4- Multi-Input-Single-Output
8-MISO - 8- Multi-Input-Single-Output
ABB - ASEA Brown Boveri
AEG - Allgemeine Elektricitats-Gasellschaft AG (German Electrical Company)
AR - Anti-Reflective
ARC - Antireflective Coatings
ASE - Amplified Spontaneous Emisssion
BAW - Bulk Acoustic Waves
CIR - Chalcogenide Infrared
CRDS - Cavity Ring-Down Spectroscopy
CTE - Coefficient of Thermal Expansion
DAQ - Data Acquisition
DC - Direct Current
DDE - Dynamic Data Exchange
DLS - Damped Least Square
DSB - Distribution Feedback Laser
EMF - Electromotive Force
FTIR - Fourier Transform Infrared
HDMS - Hexamethyldisiloxane
HITRAN - High Resolution Transmission Molecular Absorption Database
HVAC - Heating, Ventilating and Air Conditioning
IR - Infrared

LabVIEW	-	Laboratory Virtual Instrument Engineering Workbench
LB-OSFET	-	Langmuir–Blodgett Oxide Semiconductor Field Effect Transistors
LED	-	Light Emitter Detector
LSFO	-	Layered Perovskite Oxide
MFC	-	Mass Flow Controller
MKS	-	Mortice Kern Systems (Multinational Independent Softwear Vendor)
NBP	-	Narrow Bandpass
NDIR	-	Non-Dispersive Infrared
NIR	-	Near Infrared
NIST	-	National Institute of Standards and Technology
OFSRC	-	Optical Fibre Sensor Research Center
OPD	-	Optical Path Difference
PAS	-	Photoacoustic Absorption Spectroscopy
PC	-	Photoconductive
PCB	-	Printed Circuit Board
PTFE	-	Polytetrafluoroethylene
PV	-	Photovoltaic
QCL	-	Quantum Cascade Laser
RMS	-	Root Mean Square
SAW	-	Surface Acoustic Waves
SCM	-	Single Chip Microcomputer
SISO	-	Single-Input-Single-Output
SMA	-	SubMiniature version A
SNR	-	Signal-to-Noise Ratio
STP	-	Standard Temperature and Pressure
TDLAS	-	Tuneable Diode Laser Absorption Spectroscopy
UV	-	Ultraviolet
VI	-	Virtual Instruments

LIST OF SYMBOLS

N_A - Avogadro’s Constant, 6.02214199 x 10^{23} Molecule mol^{-1}

ΔP - Pressure Differential

ΔP_W - Pressure Differential on Deflected Window

Δx - Deflection of Circular Plane-Parallel Plate Window

A - Absorbance

A_w - Unsupported Aperture

A_W - Window Aperture

c - Concentration in cm^{-3} × Mol

c - Speed of Light

CF_V - Conversion Factor

C_p - Specific Heat Capacity at Constant Pressure

c_{ppm} - Concentration in Parts-per-Million

C_v - Specific Heat Capacity at Constant Volume

d - Density of the Species in Air by Volume kg/cm^3

D - Diameter

D* - Specific Detectivities

D_G - Diameter CF_2 Window

D_n - Normal Density

E - Photon Energy

E_G - Young’s Modulus

F_1 - Instrument Flow using Fluid1 in Normal Volume Flow Units (f.i. ln/min)

F_2 - Calibration Flow using Fluid2 in Normal Volume Flow Units (f.i. ln/min)

f_s - Safety Factor

h - Planck's constant

i - Operand Number (row number in the spreadsheet)

I - Radiation Intensity

I_b - Background Intensity

I_o - Initial Intensity

K_W - Support Condition Constant

l - Optical Path Length in cm

M_F - Merit Function

n - Reflective Index

$P_{efficiency}$ - Power Efficiency

P_{in} - Total Input Power

P_{out} - Output Power

ppm - Parts-per-Million

$P_{reference}$ - Reference Power

P_{signal} - Signal Power

P_W - Total Force Applied to Window Area

R - Radius

R_1 - Optimum Radius of Curvature

S - Sensitivity

S_F - Material's Fracture Strength

S_g - Sagittal Depth

T - Target Value

t_A - Axial Thickness

t_E - Edge Thickness

t_e - Elastomer Thickness

T_r - Transmittance

t_W - Window Thickness

V - Current Value

v - Frequency of Electromagnetic Radiation

V - Variable

V_b - Background Voltage

V_o - Initial Voltage

$\mathrm{V}_{\mathrm{p-p}}$ - Original Voltage Response

V_t - Transmitted Voltage

W - Absolute Value of the Weight of the Operand Listed

w - Molecular Weight of the Species kg/mol

α_e - Coefficient of Thermal Expansion Elastomer

α_G - Coefficient of Thermal Expansion Window

α_M - Coefficient of Thermal Expansion Mount

ε - Wavelength Dependent Molar Absorptivity cm^2/Mol

λ - Radiation Wavelength

v - Poisson’s Ratio

σ - Wavelength Dependent Absorption Cross Section in cm^2/Molecule

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CHAPTER 1

INTRODUCTION

1.1 Introduction to Carbon Dioxide

Since the early 1800’s, various gases in atmosphere acting as glass in a greenhouse whereby they transmit incoming sunlight and absorb outgoing infrared radiation. This process can ultimately raise the average historical air temperature on the Earth’s surface. Carbon dioxide (CO_2) has been the predominant source of pollutant gases incurred by the combustion process of fossil fuel and recognized as being one of the most influential greenhouse gases. Over the 420,000 years ago, the Earth’s atmosphere which comprised of CO_2 that has periodically changed in the time frame of about 100,000 years (in conjunction with the movement of Earth’s axis) from 180 to 290 parts-per-million (ppm) by volume (Kutscher, 2006). However, the CO_2 concentration level has begun to reach the maximum value of about 280 ppm in 1850 (Hansen *et al.,* 1981). Surprisingly, the overall level of CO_2 concentration in the Earth’s atmosphere has significantly increased and reached the unprecedented level. The average annual concentrations of CO_2 in the atmosphere in 2013 and 2014 are 396.48 ppm and 398.55 ppm respectively. For the past decade between 2005 and 2014, the average annual increase is 2.1 ppm per year meanwhile the average for the prior decade between 1995 and 2004 is 1.9 ppm per year (NOAA-ESRL, 2015).

These increases in atmospheric CO_2 levels 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 (Marron *et al.*, 2015). 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 (Peirce *et al*., 1998). 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 energy sector, car manufacturers are facing significant challenges in developing technologies for reducing this portion of total CO_2 emissions (Ishii *et al*., 2015).

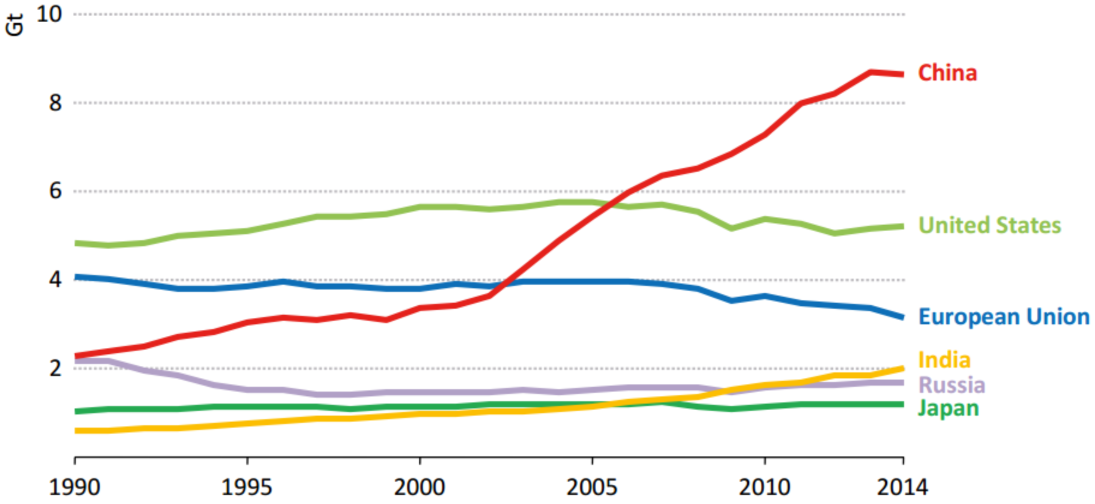

Figure 1.1 Energy-related CO_2 emissions by selected region (OECD/IEA, 2015)

As illustrated in Figure 1.1, a large share of energy-related CO_2 emissions comes from a small number of countries. In 2012, three countries (China, United States and India) gave rise to almost half of global CO_2 emissions from fossil-fuel combustion, while ten countries (China, United States, India, Russia, Japan, Germany, Korea, Canada, Iran and Saudi Arabia) accounted for around two-thirds (IEA, 2014a). Since 1990, total emissions in the United States and Japan have increased slightly, while they declined by about a fifth in the European Union. After a fall of almost 30% in emissions from Russia in the early 1990s, the emissions increase thereafter has remained limited. In 2006, China overtook the United States as the biggest CO_2 emitter, while India overtook Russia as the fourth-largest emitter in 2009 (OECD/IEA, 2015).

With thoughtful consideration to global warming issue, particularly from the standpoint of reducing CO_2 emissions, the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC) was held in Paris in December 2015 with the aim of adopting a new global agreement to limit greenhouse gas emissions. The ultimate objective already adopted by governments is to limit global warming to an average of no more than 2 °C, relative to pre-industrial levels. This must involve the transformation of the energy sector (eg. buildings, transport, industry, power generation and others), as it accounts for roughly two-thirds of all anthropogenic greenhouse gas emissions today (OECD/IEA, 2015).

1.1.1 Why Carbon Dioxide?

CO_2 gas comprised of two elements which are carbon and oxygen. It is slightly irritating odourless and colourless gas which composed of carbon atom covalently double bonded to two oxygen atoms. Sharp and acidic odour of the CO_2 gas will be significantly felt at higher concentration. The density of the CO_2 gas is higher than air. The standard density value of CO_2 is 1.98 kg/m^3 at standard temperature and pressure (STP), indicating that the CO_2 is 1.67 times denser than normal air in the Earth's atmosphere. CO_2 presents in the atmosphere as a trace gas in a small quantities which is at a concentration of about 370 ppm by volume. Being a part of the Earth's environment, CO_2 has absolutely played an essential role to preserve and retain the ecosystem of the life cycle between plants and animals (Freund *et al.*, 2013).

CO_2 is freed from various sources such as volcanoes, hot springs and geysers (Burton *et al*., 2013; Reigstad *et al*., 2010; Han *et al*., 2013) and also widely emitted from the chemical reaction of carbonate rocks through the process of dissolution in water or acidic solution (Shao *et al*., 2010). The presence of CO_2 is often found in water in which surrounded by land. The existence of commingled CO_2 with the oils and gases is significantly at depth under the ocean. Due to the unique characteristic of CO_2 which has high solubility in water, CO_2 naturally exists in seas, rivers and lakes. There are anthropogenic activities which will lead to the raise of CO_2 emission. It includes the burning process of fossil fuels and other carbon based materials (Bates *et al*., 2012), organic compound which prepared using fermentation process and also through the process of human breathing (Smallegange *et al*., 2010 and Blain *et al*., 2010).

1.1.2 Carbon Dioxide Properties

CO_2 naturally exists in gas state at normal temperature and pressure (STP). Figure 1.2 illustrates the variation of CO_2 phases which depending on changes of the temperature and pressure. By default, CO_2 exists in solid state at the extremely low temperature level. However, the solid state of CO_2 will gradually turn to the water vapour state as the pressure decreases down to 5.1 bar. As can be seen from the Figure 1.1, within the intermediate temperature extended from the triple point and critical point at -56.5 ^oC and 31.1 ^oC respectively, the original vapour state of CO_2 will directly turn to liquid state provided it is compressed at liquefaction pressure level and the removal process of heat generated (Freund *et al*., 2013).

Critical point of CO_2 as shown in Figure 1.2 which is at temperature of 31.1 ^oC and pressure of 73.9 bar, CO_2 exhibits its supercritical phase whereby it exists in the gas state. At extremely high pressure level, there is point of gas density which could be enormous that may have approached or even exceeded the density of liquid phase (Freund *et al*., 2013). This has been one of the vital aspects of CO_2's attributes especially related to its storage matters.

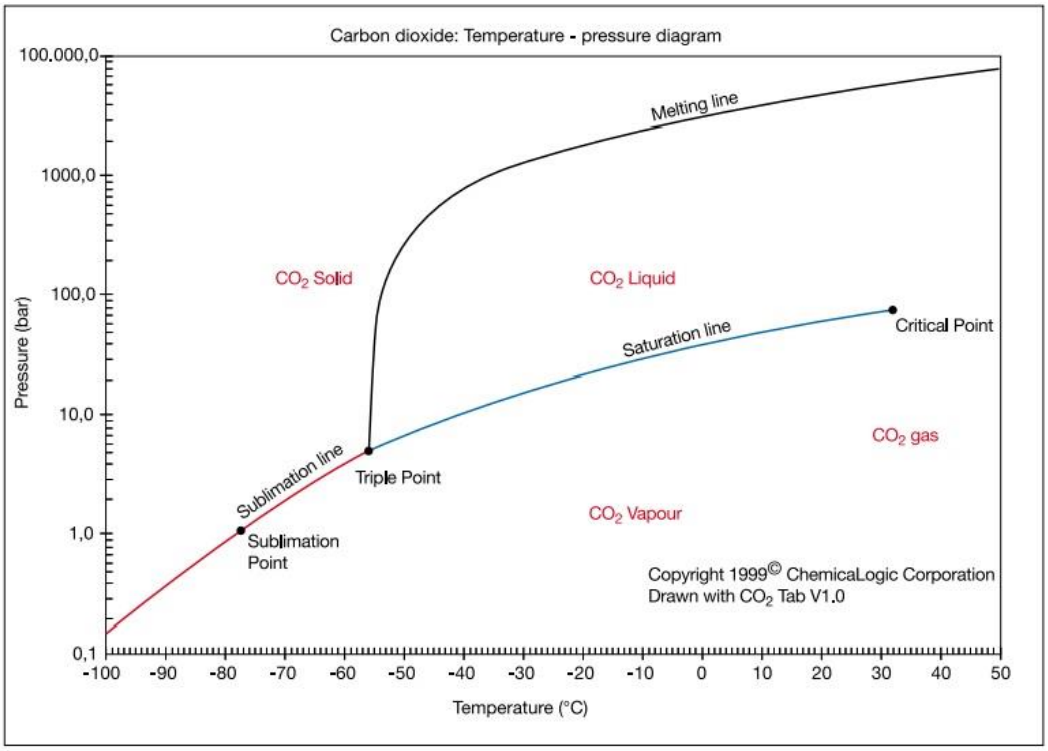

Figure 1.2 Phase diagram of carbon dioxide (reproduced from ChemicaLogic Corporation, Copyright © 1999)

From Figure 1.2, it clearly shows that the transmittance and absorption of heat occurred within the three phase boundaries; between solid and gas phases, between solid and liquid phase and between liquid and gas phases. For the CO_2 phase changes from supercritical point to liquid phase or gas phase, there is no absorbed or even emitted heat will take place (Freund *et al*., 2013). This property is useful for the design of CO_2 compression facilities since, if this can be exploited, it avoids the need to handle the heat associated with the liquid-gas phase change. Table 1.1 shows the basic physical properties of CO_2 (Kirk-Othmer, 1985 and NIST, 2003).

Table 1.1: Properties of CO_2

Property	**Value**
Molecular weight	$44.01\ g\cdot mol^{-1}$
Critical temperature	31.1 °C
Critical pressure	73.9 bar
Critical density	$467\ kg\ m^{-3}$
Triple point temperature	-56.5 °C
Triple point pressure	5.18 bar
Gas density at STP	$1.976\ kg\ m^{-3}$
Specific heat capacity at constant pressure , C_p at STP	$0.0364\ kJ\ (mol^{-1}\ K^{-1})$
Specific heat capacity at constant volume , C_v at STP	$0.0278\ kJ\ (mol^{-1}\ K^{-1})$
Specific volume at STP	$0.506\ m^3\ kg^{-1}$
Viscosity at STP	$13.72\ \mu N.s\ m^{-2}$ (or µPa.s)
Thermal conductivity at STP	$14.65\ mW\ (m\ K^{-1})$
Solubility in water at STP	$1.716\ vol\ vol^{-1}$

1.2 Exposure to Carbon Dioxide

The concentration of CO_2 at atmospheric normal condition is about 0.037%. This amount is generally considered as a non-toxic amount and harmless. CO_2 is a non-flammable gas which is 1.67 times denser than air at STP. Hence, there will be a tendency for any CO_2 leaking from pipe work or storage to collect in hollows and other low-lying confined spaces which could create hazardous situations. The hazardous nature of the release of CO_2 is enhanced because the gas is colourless, tasteless and is generally considered odourless. Provided it is kept and remained at high pressure, the released CO_2 could indirectly create serious health conditions to people such as suffocation and frostbite (Jarrell *et al*., 2002). Hence, it is absolutely necessary to carefully handle and process the CO_2 gas at particular application which includes the use of CO_2 facilities or equipments.

It is reported that people with normal function of neurological, cardiovascular, pulmonary-respiratory may not experience serious health problem under exposure of CO_2 gas concentration from 0.5% to 1.5% within duration of up to 7 hours continuously (Freund *et al*., 2013). However, longer exposure or higher concentration of CO_2 than that has significant effect to human health. It may occur if the minimum level of oxygen in bloodstream or atmospheric air that needed to maintain people life is decreased. Besides that, people may also experience hazardous health condition if the amount of air taken during breathing is altered. For instance, human breathing rate due to physiological effects will become quicker than the effect caused by the displacement of oxygen, relying on the level of CO_2 gas concentration (Freund *et al*., 2013).

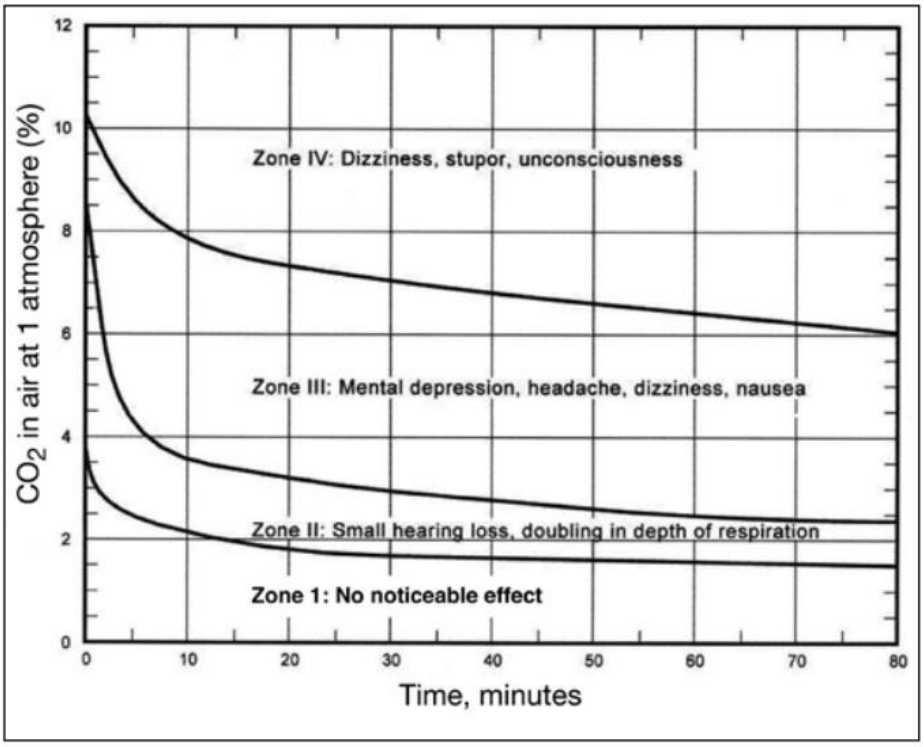

Figure 1.3 Impact of elevated CO_2 concentrations on healthy adults (Fleming *et al*., 1992)

Figure 1.3 shows the impact of elevated CO_2 concentrations on healthy adults in which depending on the level of concentration and duration of exposure. The exposure of CO_2 concentrations up to 1.5% for one hour or more, there will be no noticeable health changes for normal healthy adults. However, young people who continuously exposed under CO_2 concentration between 1.5% and 2.5% for more than one hour may result in small hearing loss and doubling in depth of respiration. For longer exposure of CO_2 even at less than 1% gas concentration, it may remarkably affect the health. The effect will become apparent above this level especially variation in respiration and blood pH level which could increase the heart beat rate. Not only that, the exposure of CO_2 at above this limit will result in discomfort feeling and nausea or even may lead to the unconsciousness condition (Fleming *et al*., 1992).

Figure 1.3 also illustrates the effect of CO_2 exposure to human health at concentration of above 3%. Without a doubt, acute exposure of 3% concentration and above may have a severe impact to human health such as damaged hearing and visual disturbances. Not only that, young people who are doing physical training under the non-stop CO_2 exposure of at 3% and above might be experiencing other bad symptoms which include migraine, impaired vision and mental perplexity. For CO_2 gas concentration between 7% and 10%, CO_2 can act as an asphyxiant and can be fatal at higher concentration. For example, death may occur for the exposure of 20% CO_2 concentration continuously in duration of 30 minutes (Fleming *et al*., 1992). Table 1.2 shows the response of gas exposure to the elevated CO_2 concentrations.

Table 1.2: Reactions to Exposure to Elevated CO_2 (Freund *et al*., 2013)

CO_2 (%)	**Exposure Reaction**	
	Air Product (2004)	**Rice (2004)**
1	Breathing rate will slightly increase.	Increment of respiratory rate by 37%.
2	Breathing rate increases above normal rate (up to 50%).	Respiratory and ventilation rates increased by 50% and 100% respectively.

	Symptoms of headache and tiredness can be felt during continuous exposure at this rate.	Thus increase the flow of brain blood.
3	Twice of normal breathing rate. Symptoms such as headache, impaired hearing could be felt. Increment of blood pressure and pulse rate and small narcotic effect.	At this rate, people who breathe against aspiratory and expiratory resistance will result in the decrement of exercise tolerance.
4-5	Breathing rate will increase up to four times higher than normal rate. Intoxication will become obvious and small chocking could be felt.	Ventilation rate will increase up to 200%, symptoms such as dizziness, confusion, dyspnoea will become evident besides twice of respiratory rate.
5-10	Sharp odour is noticeable. Symptoms such as difficult to breathe, impaired visual, headache, ringing ears may be felt. Exposure of within minutes will cause loss of consciousness.	Between 8% and 10%, symptoms which include very bad headache, confusion, dyspnoea, sweating, feeble vision are noticeable. Severe dyspnoea, vomiting, hypertension, disorientation and loss of consciousness for the exposure of at least 10%.
50-100	State of being unconscious at more than 10% exposure. Continuously exposure of high CO_2 concentration will probably cause death due to asphyxiation.	Not mentioned.

1.3 Uses of Carbon Dioxide

Recently, there are a number of industrial processes which involved with the manufacture of CO_2 on site as the intermediate substance in producing the chemical compound. For example, huge amount of CO_2 are utilized to improve oil recuperation (Blunt *et al.*, 1993). The use of CO_2 have been extended to various types of applications by manufactures nowadays such as in chemicals, pharmaceuticals, food and beverage, health care, metals industry, electronics, pulp and paper and waste treatment. A lot of CO_2 are utilized as a part of the assembling of inorganic carbonates and a lesser sum is utilized as a part of the generation of natural monomers and polycarbonates (Omae, 2012). CO_2 are also used in the manufacture of methanol and polyurethanes using chemical process (Obert and Dave, 1999; Doyle and Carson, 1992). In pharmaceutical process, CO_2 is extensively utilized to give a dormant environment for chemical synthesis's process and supercritical liquid extraction. Besides that, it is also widely used in fermentation of waste water and item transportation at temperature of -78 ^{o}C (Subramaniam *et al.*, 1997; Reverchon, 1997; Rao *et al.*, 2007). In food business however, CO_2 is used in areas such as in bundling of foodstuffs and as cryogenic liquid in chilling process. The use of CO_2 is not limited to food packaging only, but also in the operation of preparing the frozen food. CO_2 as dry ice in solid phase is used as temperature's controller during the dissemination of foodstuffs (Edward and Vicik, 2001). Being part of medical procedure, particularly in the intra-abdominal insufflations, visualization is improved by the use of CO_2 by expanding the tissue or organ's space (Ivankovich *et al.*, 1975).

1.4 Problem Formulation

It is vital to have such adequate CO_2 gas sensor to monitor or control the level of CO_2 in the environment. Uncontrollable exposure of CO_2 to human will definitely lead to harm and could be hazardous indeed. Analyzing and designing the highly sensitive and efficient CO_2 gas sensors have become subject of interest from various research institutions since many years ago in order to fulfil human needs. The existing CO_2 sensors with high level of accuracy and/or sensitivity nowadays are commonly designed and applied to wide range of applications such as monitoring indoor air quality (Ferng and Lee, 2002; Daisey *et al.*, 2003; Kwon *et al.*, 2009; Wang *et al.*, 2012), reducing energy usage in heating, ventilating and air conditioning (HVAC) systems (Koni *et al.*, 2009; Kolarik, 2014; Lin and Lau, 2014), automotive for anti-drowziness monitoring and air-management systems (Arndt and

Sauer, 2005; Frodl and Tille, 2007), intensive spatial field monitoring of CO_2 concentrations in a naturally ventilated dairy cow house (Mendes *et al*., 2015), prime indicator of food spoilage in packed foods (Puligundla *et al*., 2015), monitoring CO_2 using mobile sensor system in permafrost areas (Eberhardt *et al*., 2014) and horticulture to accelerate plant growth and eliminate pests such as whiteflies and spider mites (Poorter, 1993 and Stafford, 2007). They are typically designed to be an optimized and compact structure, hence allowing them to be applied accurately at anywhere and anytime depending on their applications. However, those CO_2 sensors with such capabilities and characteristics normally require high level of cost fabrication due to the uses of expensive material or components and also due to the sophisticated structure design. Hence, it is absolutely necessary to design an economical design structure of CO_2 gas sensor in which having same or even better performances as compared to previously reported CO_2 gas sensors and commercial gas sensors in market nowadays. As discussed previously in Section 1.2, prolonged exposure between 1.5% and 2.5% CO_2 concentration for more than one hour will result in small hearing loss, headache, tiredness and doubling in depth of respiration. It is good to be capable of detecting CO_2 concentration even there is small noticeable physical effects, hence the developed new prototype sensor is specifically designed for measuring CO_2 concentration at below 2%.

1.5 Motivation of Research

This research is primarily conducted to improve the previous existing CO_2 gas sensor and to prove that the optimized gas sensor has capability of measuring CO_2 concentration at below 2% with high accuracy and sensitivity. A developed prototype of CO_2 gas sensor is using low cost components and particularly designed to be an optimized CO_2 gas sensor. The development of an optimized CO_2 gas sensor is intended to fulfil the requirement of current CO_2 gas sensing system such as high level of accuracy and sensitivity. Low cost gas sensor is an economical gas sensor with sufficient concentration measuring capability and constructed by relatively cheap components or element. Low cost components which include optical source, optical detector and collimating elements have been applied to develop the prototype of CO_2 sensor. Besides that, cost effectiveness of this work is improved by the elimination of the optical fibre. An optimum structure of CO_2 gas sensor has been simulated using the most capable optical and illumination design software, ZEMAX®12. It is believed that the developed CO_2 gas sensor can operate effectively due to its superior advantages such as compact, robust and economical.

1.6 Objective of Research

This research can be classified into three main objectives as follow:

1. To design an optimized structure of CO_2 sensor for measuring CO_2 concentration at below 2% using ZEMAX®12.

2. To fabricate the optomechanical design of an optimized CO_2 reflective gas sensor.

3. To analysis and verify the performance of CO_2 sensor in terms of sensitivity and accuracy with the previous work and commercial gas sensor.

1.7 Scope of Research

The research will be focused on designing the working prototype of reflective CO_2 gas sensor which consists of low cost optical elements or components such as CaF_2 window, curved mirror and cylinder tube. This spectroscopic based CO_2 sensor is specifically designed to improve previous reflective CO_2 gas sensor and this sensor is meant for detecting CO_2 gas concentration at below 2% with high accuracy. The compact structure is simulated using ZEMAX®12 to determine the best dimension of optical design and optimization process using Damped Least Squares (DLS) algorithm to determine the optimum radius of mirror. There are few configurations of considered optical design for this project using different number of light sources. The comparison between different configurations is made based on their merit function and level of power detection. Sensitivity analysis is performed for each and every configuration based on its detected power to evaluate and compare the level of sensitivity among all simulated configurations. Next, the optomechanical design is studied, analyzed and presented for fabrication purpose. The design is mainly focused on determining the suitable material and mounting technique for the optical elements and other mechanical components applied. In order to ensure the flow gas is at optimum level, the improvement is made to the housing of the gas sensor at which it is securely placed. Finally, the research is continued with the experimental works to observe the performances and capability of the improved and optimized CO_2 gas sensor.

1.8 Overview of Thesis

This thesis describes the development of an optical gas sensor to detect CO_2 gas. The sensor is based on absorption spectroscopy technique which operates in mid-infrared region. In this chapter, topics related to CO_2 were discussed together with the background of the research. Concrete justification of developing prototype of CO_2 gas sensor is also presented. Chapter 2 introduces the comprehensive literature review on optical gas sensing and technologies apply. This chapter is particularly prepared to give an overall picture of current technologies of optical sensors and their applications. A review of various sensor configurations is presented and the technologies employed are examined and discussed. Comparison between types of sensors, technologies applied and performance of reported gas sensors are carried out and tabulated. In this chapter, theoretical background such as fundamental of absorption spectroscopy and Beer-Lambert Law are also explained.

Chapter 3 discusses instrumentation for CO_2 sensor system. The selection of infrared source, infrared detector, infrared window and structure of proposed gas sensor are presented and justified. The choices of suitable optical components and instruments used in this design are absolutely important to ensure that the developed prototype of CO_2 gas sensor is capable of measuring CO_2 concentration at below 2% with high accuracy and sensitivity. Chapter 4 reports simulation and optimization process using optical and illumination software, ZEMAX$^{®}$12 and the analysis of optomechancial design for the optimized and improved low cost CO_2 gas sensor. The optimization was focused on determining the optimum radius of curved mirror based on its merit function. Few configurations of sensor designs are presented for comparison. Development process of gas sensor, selection of material, determination of physical dimension and mounting techniques for optical-mount interface are explained here.

Experimental tests which were carried out using the developed optical sensor are summarized in Chapter 5. Initial test identify some drawback to the sensing system and some solutions to these are put in place. The system is optimized for detection within the mid-infrared region and subsequent test are carried out to access the effectiveness of the system itself. These experimental tests quantify important attributes of the sensing system such as sensitivity, accuracy, and economy. The achievement and conclusions of this investigation are summarised in Chapter 6. In addition some improvements that need to be carried out in future work are included.

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