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An Integrated Optical Instrumentation for Measuring NO_2 Gas Using One Dimensional Photonic Crystal

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Abstract- air pollution is one of main problems in human health, especially in big cities. There are five pollutants material which is indicated as a source of air pollution, one of them is nitrogen oxide (NO_2). The proper environmental monitoring system for air pollution management has demanding requirements. We have designed an integrated optical sensor to measure NO_2 gas concentration using 1-D photonic crystal. The phenomenon of photonic pass band (PPB) has been used as a frequency filter in liquid concentration measurement. Photonic crystal, LED, and photodiode were designed to operate in NO_2 absorption spectra that are in the range between 557.23 and 558.01 nm. The NO_2 gas concentration is inversely proportional to intensity of peak PPB spectra. We built electronic signal conditioning circuit which is consisting of: current to voltage converter, voltage follower, active low pass filter, and instrumentation amplifier, to get an appropriate signal. The experimental results show that our optical integrated instrumentation is able to measure NO_2 gas concentration, while requiring a filtering circuit addition because of the presence of internal noise.

Keyword: absorption, photonic pass band (PPB), low pass filter, photodiode, amplifier.

I. Introduction

Air pollution is one of main problem in human health, especially in big cities. Whereas, according to the last UN-habitat report in 2006, over 50% of the world's population lives in cities [1]. That means that over half of world's population healths are threatened by air pollution which is being uncontrollable. According to Romieu *et al.* [2], acute respiratory infections (ARIs) are the most common cause of illness and death in children in the developing world.

Several hundred different components have been found in the troposphere, many of them potentially harmful to human health and the environment. The parameter Air Quality Index (AQI), also known as the Air Pollution Index (API) or Pollutant Standard Index (PSI), is used by government agencies to characterize the quality of the air at a given location. As the AQI increases, an increasingly large percentage of the population is likely to experience severe adverse health effects. Indonesian government, in this case Ministry of Environmental life has been making own standard based on Indonesian National Standard (SNI) which is called Air Pollutant Standard Index (ISPU). The systematic review focused on fifth pollutants: particulate matter (PM), ozone (O_3), sulfur dioxide (SO_2), carbon monoxide (CO) and nitrogen dioxide (NO_2)[3].

Ensuring environmental sustainability is one of eight points Millennium Development Goals (MDGs) which is endorsed by 189 United Nations member states in 2000 [4]. Therefore, the proper environmental monitoring system for air pollution management has demanding requirements. The real-time data is crucial for decision-making process. The collection of extensive data over time and space is crucial, because it will enable a better understanding of urban air pollution and circulation behavior [5].

Rahmat [6] have proposed sugar solution measurement using optical sensor which is integrated with 1-D photonic crystal as a frequency filter. The basic principles is interaction between electromagnetic with periodical crystal structure. There are two main periodical crystal properties which play important rule, the phenomenon of photonic band gap (PBG) and photonic pass band (PPB). Peak intensity of PPB spectra is very sensitive and inversely proportional to refractive index change, and sugar concentration was measured from this quantities. Because of directly proportional relationship between refractive index and concentration, then refractive index increment indicate sugar concentration increment also. The same principle can be used to measure NO_2 gas concentration with several adaptations.

A system designer is rarely able to connect a sensor directly to processing, monitoring, or recording instrument, unless a sensor has a built-in electronic circuit with an appropriate output format. When optical sensor (e.g., photodiode, phototransistor, etc) generates an electrical signal, that signal often is either too weak to measure directly, or too noisy. Signal from sensor usually has to be conditioned before it is fed into a processing device. An interface which is has a specific purpose to conditioning signal is called signal conditioning circuit [7]. Based on Rahmat [6] research we designed signal conditioning circuit which is consisting of: current to voltage converter, voltage follower, active low pass filter, and instrumentation amplifier.

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In this paper, we present an optical integrated instrumentation for NO_2 gas concentration measurement using 1-D photonic crystal as a frequency filter. The paper is organized as follow. In Section II we present some theoretical background related with the fundamental science, starting from photonic crystal definition to electronic applications. Section III presents research methodology include step by step research activities and research limitations area. In Section IV, the experimental result are provided to demonstrate and examine the effectiveness of the propose method. The results we show in this paper are limited to the effectiveness analog technique in conditioning electrical signal to an appropriate output format. Finally, we conclude this paper in Section VI.

II. Theoretical Background

A. Photonic Crystal

Photonic crystal is analogue with crystal lattice structure in electronic material. The crystal presents a periodical potential to an electron propagating through it. The Kronig-Penney model can be employed to construct the energy band diagrams of an isolated silicon atom and an artificial 1-D periodic silicon lattice [8]. If the lattice potential is strong enough, the gap can extend to cover all possible propagation directions, resulting complete band gap.

In photonic crystal, atoms or molecules are replaced by macroscopic media with differing dielectric constant, and periodic potential is replaced by periodic dielectric function. If the dielectric constants of the material in the crystal are sufficiently different, then the refractions and reflections of light can produce many same phenomena for photons that the atomic potential produces for electrons [9]. It has been proved that Bragg reflection in periodically dielectric structure is common cause photonic band gaps (PBG), preventing light from propagating in certain directions with specified frequencies. When the periodicity was broken by defect in photonic crystal, defect mode localization appears in the range PBG because of light interference change, and there will be amount of light at specific frequency will be propagating that is called photonic pass band (PPB) [10]. Fig 1 show PPB spectra numerically.

Mayditia *et al.* [11] numerically presented for 1-D photonic crystal PPB peak spectra change inversely proportional with outside refractive index change. It has been proved numerically that more flexible similar effect happen at 1-D photonic crystal with two defects. The characteristic of PPB can be used to built frequency filter and optical sensor device. Rahmat [6] has successfully measure sugar concentration from PPB peak transmittance change.

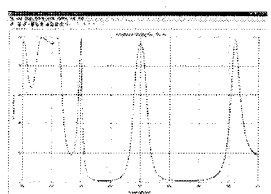

Fig. 1.Photonic pass band (PPB) spectra

B. Optical sensor

Sensor is a device that receives a stimulus or input physical property and converts it into an electrical signal that is compatible with electronic circuits. The processes of optical detection involve direct conversion energy from optical energy (in the form of photon) into an electrical signal (in the form of electron). Detector of electromagnetic radiation in the spectral range from ultraviolet to far infrared are called light detector (e.g Photodiode, phototransistor, light dependent resistor (LDR), etc).

Photodiodes are most common optical sensors which are constructed from p-n junction in reverse biased mode. Current was produced from photodiode directly proportional with incident light intensity, usually in a range microvolt. Recently, many photodiode have narrow incident light spectra for specific purpose. To make it easier in signal processing, often current quantities are converted to an appropriate voltage with electronic circuit [7].

B. Active low pass filter

Active low pass filters are designed using pole and zero locations, which are determined from the frequency respond's transfer function. The operational amplifier (op-amp) is the "active" part of the circuit, buffers one stage from the next so there is no interaction.

There is two kind active low pass filters which common in use, first-order filter selection and second-order filter selection. The first-order is a simple structure comprising a low pass RC network, followed by a buffer. The buffer serves to provide high input impedance. The Sallen and Key provide a second-order all-pole response and is a simple active low pass design. The Sallen and Key filter uses an amplifier with a network of resistor and capacitors at the input. Fig 2 show the Sallen and Key filter circuit.

High-order filters can be produced by cascading second-order section. Odd-order filter can be produced by using a series of second-order sections and then adding a first-order section at the end [12].

C. Instrumentations amplifier

An instrumentations amplifier (IA) has two inputs and one output. It is distinguished from an operational amplifier by its finite gain (which is usually no more than 100) and the ability of both inputs for connecting to the signal sources. The main function of the IA is to produce an output signal which is proportional to difference in voltages between its two inputs:

$$V_{out} = a(V_+ - V_-) = a\Delta V \qquad (1)$$

where V_+ and V_- are the input voltages at non inverting and inverting input respectively, and a is a gain. The IA should have a high common-mode rejection ratio (CMMR), that is, its output signal should be insensitive to the value of V_+ and V_- but responsive only to their difference. Fig 3 show the instrumentation amplifier schematic.

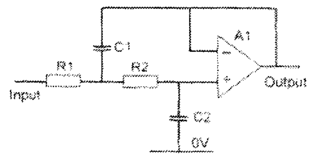

Fig. 2.Sallen and Key low pass filter

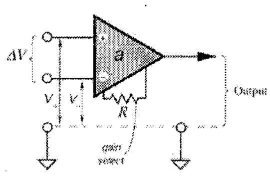

Fig. 3. Instrumentation Amplifier

Presently, instrumentation amplifiers are readily available from many manufacturers in form of monolithic chips (e.g, INA118 from Texas instrumentations, PGA204 from Burr-Brown). In addition to, instrumentation amplifier can be either built from several discrete op-amps, in a monolithic or hybrid forms. In our research we used PGA204 which has advantage controllable gain [7].

III. METHODOLOGY

The integrated instrumentation that we have designed consists of three major subsystems. The first subsystem is optical sensor based on photonic crystal, signal conditioning block, and control data processing block. The sensor subsystem consists of LED with specific wavelength which acts as a light source and photodiode as a photo detector. Based on previously achievement, the peak absorption spectra of NO_2 gas solution was in the range between 557.23 and 558.01 nm. The second defect of photonic crystal is placed between LED and photodiode. Set up of optical sensor integration can be seen in Fig 4.

Signal conditioning block have responsibility to maintenance signal from photodiode to appropriate characteristic in data processing subsystem. These subsystems consist of: current to voltage converter circuit, active low pass filter, and instrumentation amplifier. The last subsystem is a main controller which responsible to control data processing. But in this research the last subsystem was not focused yet. Figure 5 show the integrated instrumentation schematic for NO_2 gas measurement.

Because of NO_2 gas was not in liquid form, we dissolved it with specific reagent that is Griess-Saltzmann reagent. This method has been standardized by Indonesian National Standards (SNI). NO_2 gas concentration was calculated by measuring gas solution refractive index with optical sensor directly. Output quantities are in form of voltage which is inversely proportional with gas concentration. There are two kind gas measurements, directly from air ambient and measurement with dilute gas concentration has known to get optical respond properties and output signal characteristic after being processed by electronic circuit.

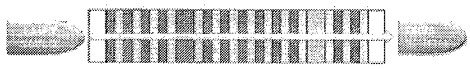

Fig. 4. Optical sensor integration

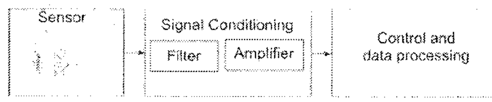

Fig. 5. Integrated instrumentation schematic

IV. RESULT AND DISCUSSION

A. Optical sensor integration

An integration of light sources, photonic crystal, and photodiode was successfully done in form of impinger tube. The impinger tube has two holes section for air circulation process called inlet and outlet. Air sample flowing from the environment react with reagent solution, NO_2 gas will be absorb and air residual will go out through outlet. Photonic crystal placed in bottom side and defect two contacts with solution directly. In the outside green LED acts as light source and selective photodiode as photo detector.

The experimental results show that selective reagent solution was reacting with NO_2 gas that is indicated solution color change, from transparent being pink. Thickness level is increasing directly proportional with the time. This result is exactly same as with SNI method. Fig 6 show the impinger tube design for NO_2 solution measurement.

B. Signal conditioning Circuit

We have successfully built signal conditioning circuit consist of: current to voltage converter circuit, voltage follower, active low pass filter, and instrumentation amplifier with PGA204 monolithic chip. Each part of circuit operates well. Output from signal conditioning circuit is voltage quantities in volt unit with gain 10 times. IA PGA204 provides adjustable gain facilities from 10 until 1000 times. It means, if the output signals are too weak, we only have to increase the gain. Fig 7 show integrated signal conditioning circuit.

Current to voltage converter used LM324 operational amplifier from National Semiconductor in signal processing. Based on photodiode characteristic, we designed one million amplification processes using 1 MΩ resistor to get an appropriate signal in milivolts unit.

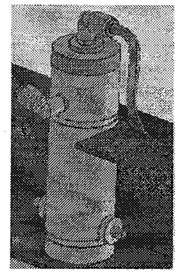

Fig. 6. Impinger tube design

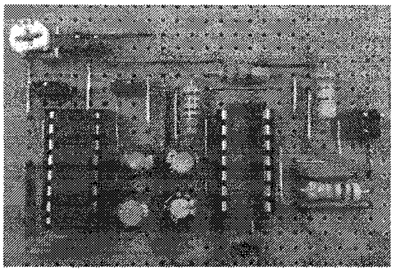

Fig. 7. Signal conditioning circuit

In general, outputs from current to voltage converter have enough stability, but measurements throughout show that output signal still have small amount noise. Noise would be come from internal architecture photodiode or op-amp limitations. We have to ensure in what source noise are produced.

There is an electronic circuit addition in signal conditioning block that is voltage follower. This circuit provides impedance conversion from high to low. A typical follower has high input impedance and low output impedances. These characteristics make it indispensable for interfacing between many sensor and signal processing devices. A follower, when connected to a sensor, makes very little effect on the latter performance, thus providing a buffering between the sensor and the load. The architecture of follower is very simple only using negative feedback in op amp directly; in this case we use LM324, without resistor within.

The next circuit is active low pass filter with op-amp LM324 acts as signal processing core. Frequency cut off we want built is 1 Hz; because we assumed that noise have frequency greater than 1 Hz. All signals which are oscillating over this frequency will be blocking. We use Texas Instrumen Filterpro software from Texas Instrument to simulated active low pass filter to get an appropriate electronic part component. From simulation we get active low pass filter with 1 Hz frequency cut off can be made with C1 = 47 μF, C2 = 10 μF, R1 = 1.8 kΩ, dan R2 = 22 kΩ.

The last subdivision from signal conditioning circuit is isntrumentation amplifier. IA PGA204 was chosen because they have many advantages that is low cost, general purpose programmable-gain, low offset, high impedance, etc. Output signal from sensor is connected with V- input PGA 204 and pin V+ is connected with specific voltage source. Furthermore, IA will subtract the constant voltage with output sensor voltage and the result is voltage which is directly proportional with gas concentration.

C. Experimental result

In General, the experiment result by sampling NO_2 gas form ambient air directly shows that an integrated optical sensor can detect NO_2 gas concentration change in range milivolts. It's indicated with positively gradient voltage change as function of time relation curve as shown in Fig 8. Voltage increasing indicated more NO_2 gas was absorbed by reagent solution.

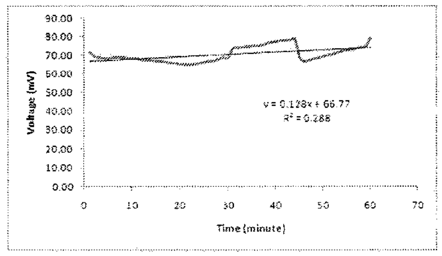

Fig. 8. Voltage as a function of time

Some experimental data showed inappropriate value, just like in minute 30 voltage increase drastically, or decrease drastically that is at minute 45. Increasing voltage drastically could be caused by a lot of amount NO_2 in air ambient, because it is not controllable parameter. Another possibility source is internal noise circuit. Decreasing voltage drastically could be caused by sampling data error or external disturbance. Noises have small possibility to cause that error, because data errors have a different characteristic with noise signal.

The next experimental setup is measure NO_2 gas concentration by dilute mechanism. Voltage was measured for any dilute step that is addition pure reagent to solution every 1 milliliters (mL). Data from experimental result show negatively gradients voltage change as function of reagent addition as shown in Fig 8. NO_2 gas in solution is decrease when we add reagent and electronic circuit can detect those changes. Fig 8 also gives us information about deterministic coefficient around R^2 92.2%, or curve line almost linier. This value can be interpreted as the addition specific amount reagent cause voltage change in the fix range. We can say that addition reagent change 92% inversely proportional with voltage decrease.

In the other side, if we look deeply for each data we will found that output signals are still have a noise. In reagent addition for 0-2 mL voltage decrease is more drastically than other. Whereas amount 4 mL addition voltage decrease slowly. Addition reagent amount 5 mL is almost produce same voltage. The last addition, between 6 – 10 mL produce slowest voltage change.

The difference circuit responds in dilute mechanism indicate the presence of noise which is produce by each electronic part or electronic circuit. Another signal instability source could be from power supply, because experiment was done with power supply which is made by converting alternating current (AC) to direct current (DC) using electronic circuit. Perhaps power supply from batteries produce more stabile signal than before.

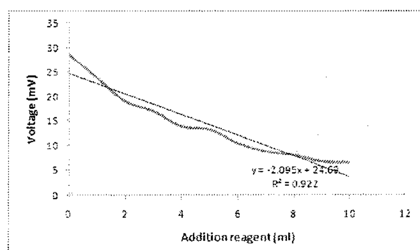

Fig. 9. Voltage as a function of time

V. CONCLUSION

We have presented an integrated optical sensor using 1-D photonic crystal. The PPB phenomenon was used as frequency filter to improve selectivity measurement. Based on NO_2 solution absorption characteristic we built an integrated optical sensor. The selection of LED wavelength, PPB operational wavelength, and selective photodiode were suited with NO_2 gas absorption spectra that are between 557.23 and 558.01 nm.

Electronic signal conditioning circuit consists of: current to voltage converter, voltage follower, active low pass filter, and instrumentation amplifier. The experimental results show that each part of circuit operates well and produce linear curve with deterministic coefficient around R^2 92.2%. Output signal is in form of voltage with range in milivolt.

Data result also showed the presence of noise, where output signal is swing around main data. Noise can be produced by each electronic part or electronic circuit. We have to improve the stability of output signal with using another technique in data filtering like digital filter. And this could be one of our future works.

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