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DESIGN OF AN OPTICAL DISSOLVED OXYGEN SENSOR USING LOW-COST MEMS VISIBLE SPECTROMETER

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ABSTRACT

The level of dissolved oxygen in water strongly affects the growth of organisms in aquaculture and profoundly affects economic in fishing industries. Continuing measure and monitor this level is very important. However, commercial sensors are expensive and not easy to apply to the aquaculture industries. Methods to measure the level of oxygen in the water have been developed long time ago using chemical, mechanical, and electrical principles. The optical principle has been recently utilized in this type of sensor in which Stern-Volmer law is used to estimate the quencher concentration. This work uses a very simple, low-cost, off-the-shelf MEMS visible spectrometer to measure the ratio of the intensity lights generated from the reaction when oxygen reacts to the fluorescent agents under excitation of the blue light. The sensor was built and tested against the commercial devices made by Extech (Model 407510). The heart of the sensor is the AS7262, a 6-Channel Visible Spectral ID Device made by AMS, and the fluorescent dye. Experimental results show a promising device which is very low cost, simple, low maintenance, and easy to use in the field to support aquaculture industries and environmental agencies.

Keywords: dissolved oxygen, low-cost sensor, low maintenance, optical sensor, visible spectrometer.

1. INTRODUCTION

Dissolved oxygen (DO) is the oxygen molecules dissolved in water. DO plays a key role to maintain life in water since survival and growth of aquatic organisms require oxygen. Not enough oxygen in water causes reduction in growth and may lead to death to adult and juvenile fishes [1,2]. Oxygen in the air is added to water mostly through turbulence such as water tumbling (natural or manmade), wave action, and photosynthesis from plants. An increase in the water temperature also causes a reduction in DO and water holds less oxygen at the higher altitudes. Aeration and oxygenation are normally used to generate more DO in the water [3-5]. If the replenishment of the oxygen is not sufficient to balance the use of it, the amount of oxygen in the water is reduced. The reduction to an alarm level below acceptable ranges will cause severe effect on the aquatic organisms such as dead fish shown in Figure-1. Dissolved oxygen is generally considered as an indication of water quality. Dissolved oxygen concentration is reported in units of mg/L, this unit is also referred to as parts per million (ppm). The maximum dissolved oxygen level in water is 9.03mg/L (a saturation due to the equilibrium between water and air at the air oxygen level of 20.3% at sea level pressure and a temperature of 20^0C). Another term directly relates to DO is the chemical oxygen demand (COD). This is an indicative measure of the amount of oxygen that can be consumed by reactions in a measured solution [6]. COD is useful in terms of water quality by providing a metric to determine the effect an effluent will have on the receiving body.

There are many methods used to detect DO content in water [7-12] and authors in [12] have listed the methods, cost, labor, errors, etc… *Iodometric* can be considered as the benchmark method and it is done in the laboratory. The method is complicated, expensive, and time consuming but providing the best in accuracy. The electrochemical method is based on redox reaction. Electrodes are used to detect the current generated from the reaction. This method is classified by the detection principle either polarographic or galvanic cell type. Many commercially available DO sensors based on these two principles are on the market [13, 14]. The drawbacks of these methods are in addition to the cost of the device itself, routine maintenance is an additional hurdle as the operators must frequently replenish the electrolyte solution in the probes and calibrate the devices. The bottom line is the initial and annual costs of the system, in particular, routine measurement is required in the remote areas. Up until now, research and development have kept going to work to improve DO sensors [15-19]. The latest developed method can be classified as optical sensor as the detection and estimation involve light. Material and optical components in the sensor itself contribute to the high cost. There are benefits of the new technique compared to the previous sensors, in particular the reduction in maintenance frequency [20-23]. Our work develops an optical DO sensor using low-cost components in order to reduce the price of the sensor itself and decrease the cost of maintenance. Such sensor is very convenient for aquaculture industries and environmental sector to monitor the oxygen levels in the water.

Figure-1. Dead fishes in a fish farm in Vietnam on May 16, 2019 due to low dissolved oxygen in the water (<3.1mg/L) and an aeration in a shrimp farm to provide more dissolved oxygen.

2. BACKGROUND AND SENSOR DESIGN

Fluorescent quenching is used in the optical sensor, including fluorescent lifetime detection and fluorescent intensity detection [24,25]. This method has more benefits compared to the other methods mentioned above as it has faster response, no warm-up time, low drift over time, and low maintenance frequency. Mechanism of the fluorescent quenching process follows the Stern–Volmer relationship related to the kinetics of a photo-physical intermolecular deactivation process [26, 27]:

$$\frac{I_f^0}{I_f} = 1 + k_q\tau|Q| \qquad (1)$$

where I_f^0 is the intensity, or rate of fluorescence, without a quencher, I_f is the intensity, or rate of fluorescence, with a quencher, k_q is the quencher rate coefficient, τ is the lifetime of the emissive excited state of A without a quencher present (A is one chemical species), and $|Q|$ is the concentration of the quencher.

Figure-2 illustrates the working principle. The cap of the sensor is submerged in the water. Dissolved oxygen penetrates into the probes and under the excitation of blue light on the luminescent dye, red light is emitted and the light is measured using photodiode after the light passing through a series of optical devices. As shown in Figure 2, the main task in the detection is the measurement of the fluorescence signal intensity of anaerobic water and of the water samples. This tedious light processing work involves optical grating and filtering in order to detect the glow of red. Traditional techniques to perform optical processing are complicated and expensive. Fortunately, newly-developed technologies in MEMS and electronic circuits have reduced complexity, size, and cost of the detection of the visible (VIS) spectrum. This work takes these advantages to design a simple DO sensor system at a very low cost.

Figure-3 shows the structure of the sensor prototype. It consists of two main parts, the sensing and the data collection and processing. First, oxygen dissolved in the water must penetrate to the enclosure through a semi-permeable membrane. The thin silicone membrane allows oxygen atoms passing through and prohibits other larger particles (such as H_2O or others substances) to enter the chamber. As soon as O_2 enters the enclosure, with the excitation of blue light on the carefully-selected fluorescent dye, red light will be emitted. The amount of red light is proportional to the oxygen concentration (quencher) as shown in the Stern-Volmer equation in the quenching process. The red light will be detected by the visible spectrometer. Photograph of the designed prototype is also included in the figure.

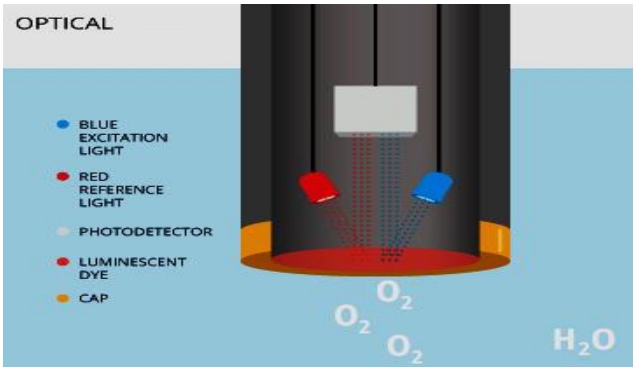

Figure-2. Cross-section of an optical dissolved oxygen sensor [28].

The Red LED, CLM4B-AKW.RKW, 50mA, 624nm, made by Cree Inc. is used as the reference light. This LED is arranged so that it can be turned on or off manually as desired while measuring. The Blue LED, OVS5MBBCR4, 0.48W, 465nm (460nm ~ 470nm), made by TT Electronics/Optek Technology is used in this prototype. This high brightness LED can be turned on or off to excite or stop the quenching process.

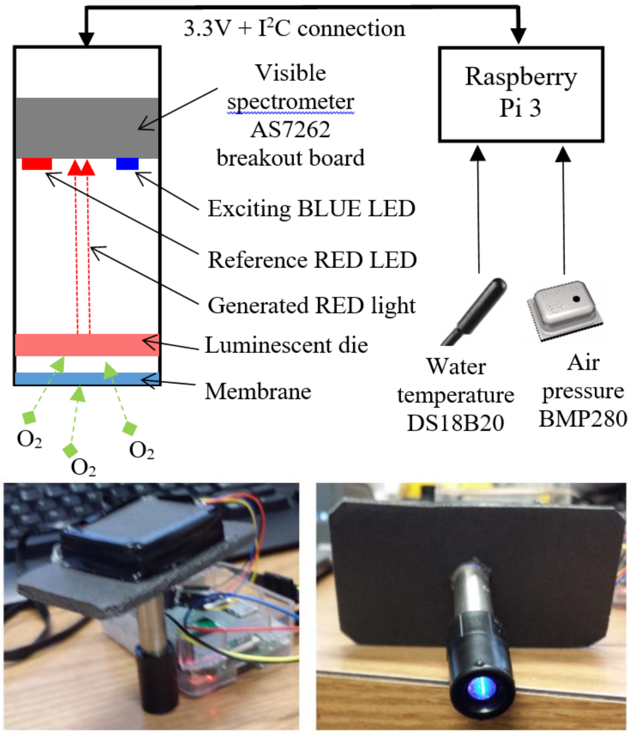

Figure-3. Sensor prototype, clockwise: general structure, sensor and Raspberry Pi is used to collect data, the probe is excited with blue light.

There is also a white light LED on-board of the spectrometer to be used on the same purpose as desired but this LED is turn off permanently in this design although there is blue light in the white spectrum. An important component used in this sensing probe is the luminescent dye as the quenching process emits light. A coordination compound called *Tris(bipyridine)ruthenium(II) chloride* with the formula [$Ru(bpy)_3$] Cl_2 is employed in this sensor [29]. This red crystalline salt is used as the fluorescence indicator because of its highly-emissive metal-to-ligand charge-transfer state, long lifetime, and strong absorption in the blue-green region of the light spectrum [30]. These characteristics of this salt well suit to the high-brightness blue LED in this design.

The most important component in the sensor is the compact, low-cost, advanced technology system-on-chip spectrometer, the AS7262 made by AMS [31]. This highly-integrated device delivers 6-channel multi-spectral sensing in the visible wavelengths from approximately 430nm to 670nm with full-width half-max of 40nm as shown in Figure 4. An integrated LED driver with programmable output current is provided for electronic shutter applications. Control and spectral data access can be implemented through either the I²C register set, or with the high-level AT Spectral Command set via a serial UART [31]. In this design, the I²C communication between the spectrometer and the Raspberry Pi 3 (RP3) is used for controlling the spectrometer and data collection. A 3.3V DC power supply to the sensor is provided by the RP3 as shown in Figure 3. Air pressure (BMP280, SPI interface to the RP3) and water temperature sensors (waterproof DS18B20, 1-wire communication with the RP3) are also included in the system for future data analysis to improve DO concentration accuracy.

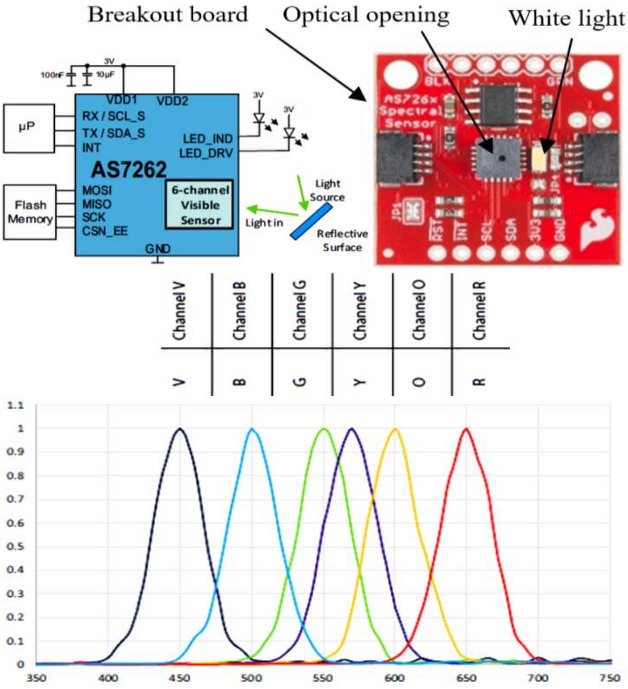

Figure-4. The visible spectrometer AD7262, clockwise: Block diagram, breakout board, and optical characteristics (normalized intensity) [31].

In this sensor prototype, the RP3 is used to provide power to the sensors and establish communication links to the AS7262 and others. Every second, the VIS spectrometer AS7262 sends 3 sets of 6 numbers representing the amplitude of 6 colors in the VIS spectrum shown in Figure-4. The RP3 is programmed (in Python) to receive and save data into a file (in Excel format) while the sensor is in operation. Data files are then transferred to a computer for viewing and processing. Virtual Network Computing (VNC), a graphical desktop sharing system, is used to remotely control the RP3.

3. EXPERIMENTAL RESULTS

The prototype was built and tested against the Heavy Duty Dissolved Oxygen Meter (Model 407510) made by Extech Instruments (USA). Data collected from the measurements are post-processed to calculate the concentration of oxygen dissolved in the samples. The post-processing includes determining the relationship between the oxygen concentration with the light intensity captured by the spectrometer (i.e., find the Stern-Volmer coefficient). The coefficient is a constant since the relationship between $\frac{I_f^0}{I_f}$ and concentration of the quencher is linear as shown in Eq. 1.

Figure-5 shows an example of the measurement setup in which the sensor prototype was sitting on top of the tainted water jar (center) while the probe of the Extech 407510 DO meter was placed in the clean water jar. The Extech was used to measure the DO content (mg/L) of the samples after calibration according to the manufacturer's recommendation. An air pump, third from the left, was used to pump the air into the sample through the clear plastic tube to increase the level of oxygen dissolved in the water while recording readings from the Extech meter and collecting data from the designed sensor were performed at the same time.

Figure-5. Measurement set-up in the laboratory environment.

Figure-6 displays the measurement results of the experiment setup shown in Figure-5. Note that data were the readings from the spectrometer AS7262 in counts/(μW/cm^2) and converted into the ratio $\frac{I_f^0}{I_f}$. Data were collected in the RP3 and transferred to the laptop for analysis. As seen in this figure, the intensity ratio changes instantaneously when the blue light excites the luminescence process. The response time of the sensor is very fast compared to the Extech 407510. The Extech takes between 1-2 minutes before the reading becomes stable. The reading of the sensor is also quick to come to the stable state. As soon as the blue LED is turned off, the process stops right away. The reading is in the continuous mode and can be transferred to the Cloud when the sensor is equipped with IoT-capable devices.

The temperature was also recorded in each case. The air pressure in the experiment period was 101.2kPa. For now, temperature and air pressure were not taking into account in calculating the concentration of oxygen dissolved in the water. The system response in reading the oxygen level in the air is slower compared to the water which is unexplainable at this time and this seems not consistent when the experiment was repeated.

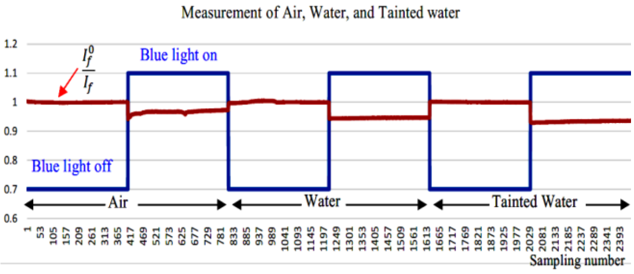

Figure-6. DO measurements of Air (7.7mg/L, 22.9^{O}C), Water (6.6mg/L, 23.5 ^{O}C), and Tainted Water (5.6mg/L, 23.9 ^{O}C). The blue light is off for 2 minutes (for calibration purpose) then turned on for 2 minutes (for measurement) for all three cases. The air pressure is 101.2kPa.

Table-1 summarizes the experimental results in the measurement of DO in air, water, and tainted water. The Extech readings were taken at the same time with the data collection of the sensor. The average ratio was calculated for the 405 readings (around 2 minutes) and the DO levels were estimated and the errors were computed against the Extech readings. The results show an acceptable result compared to this commercial device. The error can be improved in the future as temperature and pressure are taken into the calculation.

Table-1. Measurement values of the results in Figure-6. The average is for 405 readings from the spectrometer for 2 minutes during the measurement

Measured media	Temp. (^{O}C)	Extech 407510 DO (mg/L)	Low cost optical device			
			Average $\frac{I_f^0}{I_f}$	STDEV $\frac{I_f^0}{I_f}$	DO (mg/L)	Error wrt Extech 407510 (%)
Air	22.9	7.7	0.9675	0.0032	7.9	2.97
Water	23.5	6.6	0.9459	0.0009	6.8	3.01
Tainted water	23.9	5.6	0.9338	0.0019	6.1	10.11

Figure-7 illustrates the experiment result of turning on the air pump providing more oxygen in the water. In this experiment, the probe was placed in the water of 23.4^{O}C and 7.2mg/L DO (measured by the Extech 407510). In the first 2 minutes, the air pump and the blue light were off, in the next 6 minutes, both of them were on. During this time, air was pumped into the water to increase the oxygen level in the water through aeration (the DO increased from 7.2mg/L to 8.1mg/L after 4 minutes measured by the Extech 407510). After that, the pump was turned off and the sensor read the Red light intensity by turning off the Blue light for 2 minutes then turning it back on. As shown, the air increases DO level when the pump was turned on and the amount of DO was kept in the water for the next 10 minutes.

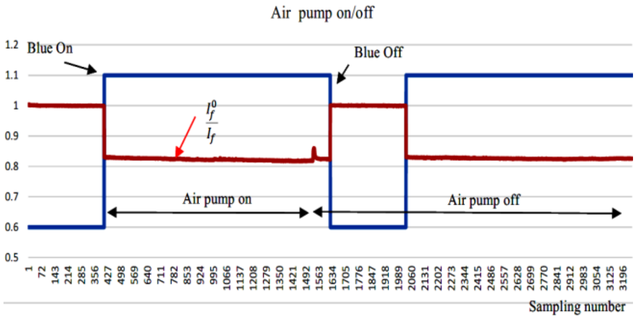

Figure-7. Turning air pump on/off to provide different levels of DO in the water.

Experiments were also conducted with the changing the amount of luminescence dye in the chamber (normal amount, double amount, and triple amount). There was not much change in the results. This proves that the amount of dye does not play an important roles and the reduction of the dye is minimum for each measurement. This observation concludes that the frequency of probe maintenance is very low compared to the requirement of chemical refill in the polarographic or galvanic cell type DO sensors.

Figure-8 shows the long-term stability test in which the probe was put in the water and the readings were collected continuously for 2 hours. The device readings are very stable for a long time without a lot of drifting. Temperature and air pressure change tests were not conducted at this time due to limitation in controlling the variables. These are left for future testing to have higher accuracy in the commercialized device.

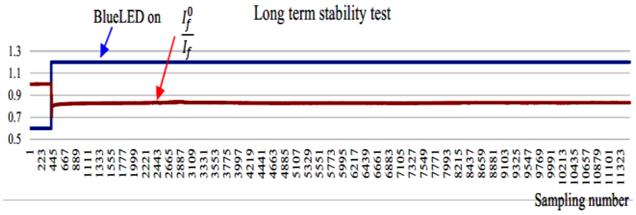

Figure-8. Long term stability (2 minutes blue light off, blue light on for 2 hours), the average of the ratio $\frac{I_f^0}{I_f}$ of 0.831 with a STD of 0.023.

4. CONCLUSIONS

The proposed optical DO sensor is very simple, compact, fast response, and very low cost since the design takes advantages of the newly developed system-on-chip visible spectrometer. Experimental results show a comparable to the commercial DO sensor. One of the most benefits of this optical sensor is its low maintenance and ease of use. High maintenance cost is one of the hurdles preventing the popular use of DO sensors from the people in aquatic industry. In this type of sensor, without excitation of blue light, there is no chemical reaction, therefore, no luminescent powder is lost. This leads to the low maintenance in replacing the sensor cap. In using the Extech DO meter, it is difficult to know when to replenish chemical solution in the probe. Self-calibration also inherits in this designed sensor and the calibration is performed automatically for each measurement. This feature is an advantage over the manual calibration of the electrochemical DO sensors.

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