DEVELOPMENT OF OPTICAL FIBER SENSOR FOR MEASUREMENT OF TSS IN WATER

BY

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Thesis Submitted in Fulfillment of the Requirement for the
Degree of Master of Science (Engineering)
Open University Malaysia

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OPEN UNIVERSITY MALAYSIA

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Supervisor: Associate Professor Mohd. Zubir Bin Mat Jafri, Ph.D.

The development of optical fiber sensor for water quality measurement is based upon spectroscopy approaches in the measurement of total suspended solids (TSS) in natural water. TSS is considered to be one the most significant contributor towards the distortion of water quality for human consumption and ecological system. This research focused on the development of optical fiber sensor that is very sensitive towards low level of light and can be further applied in various spectroscopy applications. The study utilizes the emission of incident monochromatic light and detection of scattered and transmitted light through plastic optical fiber (POF) cables as key elements of the design.. The design is an innovative approach to make the measurement of water quality mobile, online as well as cost effective. The first approach in the research is to measure the backscattered light from the water sample, 180° away from the transmission light. The second measurement approach is to measure the amount of light that undergo no scattering (0° scattering) or also called as transmission light through the water sample. Both of the measurement technique stated above will be detected by two different systems. One is name as BLUE System, consisting detector circuit that has a peak response at 470nm and light source (LED) with typical wavelength of 470nm. Second is name as RED System consisting detector circuit that has a peak response at 635nm and light source (LED) with typical wavelength of 635nm. The final result of detection is submitted to Basic Stamp 2 microcontroller for processing and the result will be displayed either through Stamp Plot Graph, "debug" command or 7-segment display unit. The final result of detection will be represented in RCTIME value. The RCTIME value is inversely proportional to the intensity of light detected by the sensor. In the backscattering measurement, the higher the concentration of TSS, the lower the value of RCTIME recorded. In the transmittance measurement, the higher the concentration of TSS, the higher the value of RCTIME recorded. The experiment conducted for the backscattering light measurement has proved the systems capability to detect the concentration of TSS in water with resolution of 10mg/L. In the other hand, the measurement of transmittance light has successfully measure the concentration of TSS with resolution of 20mg/L.

Keyword: absorb, backscattering, Basic Stamp 2, LED, POF, RCTIME, scattered, Stamp Plot Graph, spectroscopy, transmitted, TSS.

Abstrak tesis yang dikemukakan kepada Senat Open University Malaysia sebagai memenuhi keperluan untuk Ijazah Sarjana Sains (Kejuruteraan)

PEMBINAAN SISTEM PENDERIA FIBER OPTIK UNTUK PENGUKURAN TSS DALAM AIR

Oleh

AHMAD FAIRUZ BIN OMAR

2008

Penyelia: Professor Madya Mohd. Zubir Bin Mat Jafri, Ph.D.

Pembinaan sistem penderia fiber optik untuk pengukuran kualiti air adalah berdasarkan konsep spektroskopi untuk pengukuran jumlah pepejal terampai (TSS). TSS dianggap sebagai antara penyebab utama kerencatan kualiti air untuk kegunaan manusia dan sistem ecologi. Kajian ini tertumpu kepada pembinaan penderia fiber optic yang sensitif kepada penerimaan cahaya yang sangat kecil dan boleh digunakan untuk pelbagai aplikasi spektroskopi. Penyelidikan ini menggunakan penyebaran cahaya tuju monokromatik dan pengesanan cahaya yang terserak dan terpancar menerusi kabel fiber optik plastik (POF) sebagai kaedah rekabentuk yang utama. Perekaan sistem ini adalah kaedah inovatif untuk mengukur kualiti air dengan cara yang mudah alih, *online* dan murah. Kaedah pertama ialah untuk pengukuran cahaya yang terserak kebelakang daripada sampel air, 180^{o} menjauhi cahaya tuju. Kaedah kedua ialah untuk pengukuran kadar cahaya yang tidak terserak (terserak pada 0^{o}) atau juga dipanggil sebagai cahaya yang menembusi sampel air. Kedua-dua teknik pengukuran di atas akan dijalankan dengan menggunakan dua sistem yang berbeza. Yang pertama dinamakan sebagai Blue System, mempunyai litar penderia yang memiliki tindak-balas kemuncak pada panjang gelombang 470nm dan sumber cahaya (LED) dengan panjang gelombang normal pada 470nm. Yang kedua dinamakan sebagai Red System, mempunyai litar penderia yang memiliki tindak-balas kemuncak pada panjang gelombang 635nm dan sumber cahaya (LED) dengan panjang gelombang normal pada 635nm. Keputusan pengesanan akan dihantar kepada *Basic Stamp 2 Microcontroller* untuk tujuan pemprosesan dan hasilnya akan dipamerkan sama ada melalui *Stamp Plot Graph*, melalui arahan "*debug*" atau melalui litar *7-segment.* Hasil pengesanan terakhir akan diwakili oleh nilai RCTIME. Nilai RCTIME adalah berkadar songsang dengan kadar cahaya yang dikesan oleh penderia. Dalam pengukuran cahaya terserak kebelakang, semakin tinggi kandungan TSS, semakin rendah nilai RCTIME yang direkodkan. Dalam pengukuran cahaya yang menembusi sampel air, semakin tinggi kandungan TSS, semakin tinggi nilai RCTIME yang direkodkan. Kajian yang dijalankan untuk pengukuran cahaya terserak kebelakang telah berjaya membuktikan keupayaan sistem untuk mengukur kandungan TSS dengan resolusi 10mg/L. Manakala, kajian yang dijalankan untuk pengukuran cahaya yang menembusi sampel air telah berjaya membuktikan keupayaan sistem untuk mengukur kandungan TSS dengan resolusi 20mg/L.

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CHAPTER 1
INTRODUCTION

World now is experiencing a consistent development in various industries and a rapid urbanization in major cities. This however has left the issues on environment receiving less precedence by the society and as a result has leads to the instability of natural ecosystem. Man made disaster or so-called pollution is becoming a major treat to human health. Water pollution, for instance, is one of the significant results of this scenario. Water pollution can be stated as a qualitative condition of impurity or uncleanliness in hydrologic water (Preul, 1998) and occurs when water has been tainted by harmful wastes (EPA Manual, 1999). Pollution causes loss to purity of water through contamination due to its contact with outside source (Preul, 1998) through human activities and some cases are caused by natural phenomena (EPA Manual, 1999). When the water is no longer fit for its intended use, water is considered to be polluted (Krantz and Kifferstein, 1997). Natural balance of hydrologic water cycle is disrupted by waste materials discharged from various sources. Pollutants may be brought into the waters of the hydrologic cycle at any point. Distilled waters (H_2O) signify as the highest state of purity. Hydrologic cycle's water may be said as natural, but they are not pure (Preul, 1998). Water pollution will also causes disturbance to the environment and natural eco system. Organic wastes, such as sewage, demand high oxygen consumption on the receiving water. This will leads to decreasing capacity of oxygen in the water and will affect the aquatic life that needs oxygen to survive. This can potentially cause severe impacts on the whole eco-system. In the other hand, variety of pollutants discharged by industries in their wastewater including heavy metals, resin pellets, organic toxins, oils, nutrients, and solids. Silt-bearing runoff from human activities such as construction sites, deforestation and agriculture can disallowed the penetration of sunlight through the water column. All these situations will then blanketing the lake or river bed from receiving sunlight and thus restricting photosynthesis which for a long run will damage ecological systems (Wikipedia). As an example, the construction of a road linking the small town of Pos Slim in Perak to Kampung Raja in Cameron Highlands, Pahang has slowly caused the destruction to the natural ecological system. The nearby Kinta River, which is the water supply for around 40% of Ipoh residents, has been polluted by mud and clay due to the road construction. The condition worsens each time it rains since the rain water will carry the mud and clay from the terrain down to the river. The turbidity level of Kinta River was measured to be more than 10000 NTU at that time, compared to only 50 to 60 NTU in the past (WWF Malaysia, 2000).

1.1 Total Solids and Water Pollution

Water is said to be polluted when there is a foreign substances or so-called "solids" mixed with the natural water. Total solids are referring to a material that is either suspended or dissolved in water and related to the specific turbidity of the water. American Public Health Association, 1998, stated that total suspended solids is the portion of total solids in the natural water retained by a filter and total dissolved solids is the portion of solids that able to passes through a filter (Murphy, 2007). The total of solids present in the water varies with the water quality. There may also be many pollutant embedded in the water in the form of solids. Factories or any other production facilities may dispose solid pollutants into a stream or other body of water. The high amounts of pollution solids can badly destroy the quality of water of a stream (Ipsaro, 2007).

1.1.1 Total Dissolved Solids

Total Dissolved Solids (TDS) are solids in water that can pass through a filter with a pore size of about 0.45 micrometers. TDS is a measure of the amount of material dissolved in water. Examples of these materials are carbonate, bicarbonate, chloride, sulfate, phosphate, nitrate, calcium, magnesium, sodium, organic ions, and other ions. Aquatic life would benefits from a certain level of these ions. However, the changes in TDS concentrations can be unsafe to the aquatic life since the flow of water into and out of an organism's cells will be determined by density of the water. Besides, water clarity will be declining due to the high concentrations of TDS and this will contribute to a decrease in photosynthesis process since the sun light may not be able to penetrate the water surface. TDS can represent the amount of ions in the water and it can be used to estimate the quality of drinking water. Water with high TDS often has a high water hardness or bad taste and could also result in a laxative effect (Murphy, 2007).

1.1.2 Total Suspended Solids

Total Suspended Solids (TSS) are solids in water such as silt, clay, decaying plant and animal matter, industrial wastes, and sewage that can be trapped by a filter. High concentrations of suspended solids can course many problems to ecological system and aquatic life (Murphy, 2007). The amount of suspended solids normally is higher at greater depth of water since the suspended solids usually have a higher density than the water in which they are present. Suspended solids may also be found at the surface of the water when the density of solids is lower than the water (Ipsaro, 2007). High level of TSS in water can prevent the sun light from penetrating into the water surface and reaching underwater vegetation. As a result, the rate of photosynthesis will decline and less dissolved oxygen will be released into the water. If light is totally blocked from reaching the plants, the oxygen will no longer be produced by the plants and the plants will die. The bacteria, from the decomposed plants, will consumed even more oxygen from the water and for a long run, can cause death to aquatic life that needs oxygen to live. TSS will also absorb energy from light and this will leads to the increment of water temperature. Same like TDS, TSS can decrease the clarity level of water and this will make it difficult for fish to find food. Suspended solids in water can as well block fish gills, reduce growth rates and decrease resistance to disease (Murphy, 2007). Figure 1.0 showing the categories of particles found in surface water.

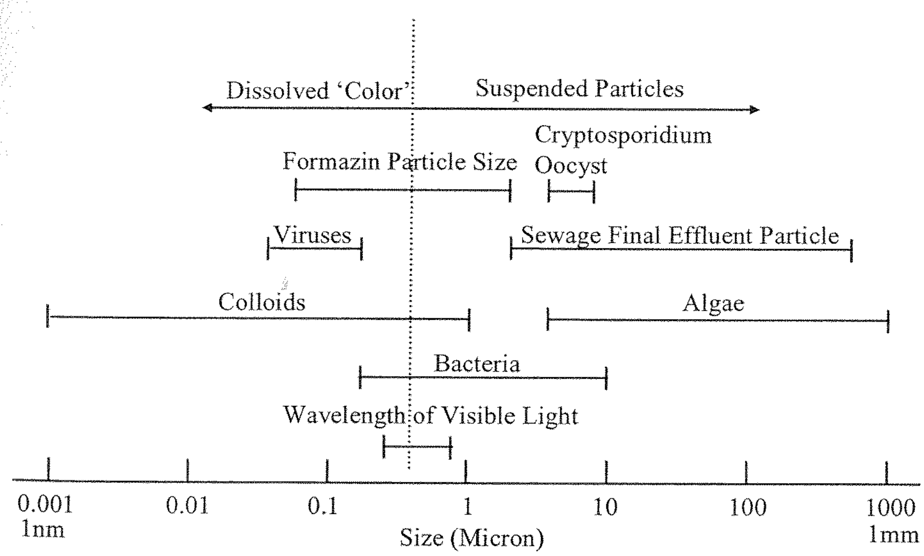

Figure 1.0: Categories of Particles found in Surface Water (ABB Instrumentation)

1.2 Turbidity

Turbidity is the measurement of the amount of particulates suspended in water. Turbidity measures the light scattering as an outcome that suspended solids have from light emitted on them. Higher intensity of scattered light means higher turbidity of water (Lawrence, 2002). It is caused by the presence of suspended and dissolved solids, such as clay, silt, finely divided organic matter, plankton, microscopic organisms, organic acids and dyes. This can make water appear cloudy or muddy. Turbidity measurement can be affected by the color of water, whether it is due to dissolved compounds or suspended particles (Anderson, 2005). American Society for Testing and Materials (ASTM), 2003, defines *"turbidity as an expression of the optical properties of a liquid that causes light rays to be scattered and absorbed rather than transmitted in straight lines through a sample"* (Anderson, 2005). According to the Environmental Protection Agency (EPA), 1999, *"turbidity is the cloudy appearance of water caused by the presence of suspended and colloidal matter. In the waterworks field, a turbidity measurement is used to indicate the clarity of water. Technically, turbidity is an optical property of the water based on the amount of light reflected by suspended particles. Turbidity cannot be directly equated to suspended solids because white particles reflect more light than dark-colored particles and many small particles will reflect more light than an equivalent large particle"* (EPA Manual, 1999).

Water clarity is vital when manufacturing drinking water for human consumption because excessive turbidity in drinking water may leads to a health concern. Pathogens may receive their food and shelter from turbidity and for long term, it may leads to waterborne disease outbreaks. Protozoa have been recognized as the source of half of the waterborne outbreaks. Even turbidity is not a direct pointer to human health threat; several studies show a strong connection between removal of turbidity and removal of protozoa (EPA Manual, 1999).

Sources of turbidity in drinking water include:

- Waste discharges.
- Runoff from watersheds, especially those that are disturbed or eroding.
- Algae or aquatic weeds and products of their breakdown.
- Humic acids and other organic compounds from decay of plants, leaves, etc. in water sources.
- High iron concentrations which give waters a rust-red coloration.
- Air bubbles and particles from the treatment process (EPA Manual, 1999).

The following are what most people think of the relationship between total suspended solids and the appearance of the water:

- Water with a TSS concentration less than 20 mg/l to be clear.
- Water with a TSS concentration between 40 and 80 mg/l tends to appear cloudy.
- Water with a TSS concentration over 150 mg/l usually appears dirty.

However, the nature of the particles that comprise the suspended solids may cause these numbers to vary (EPA Manual, 1999).

1.3 Light Scattering Essentials

Turbidity can be defined as a qualitative water optical property since it can measure the light's scattering effect on suspended particles in water. When light is transmitted onto a water body, the suspended particles will block the transmission of light from going through the water sample. In pure or very clear water, the light transmission will stays uninterrupted, with a small scattering effect. The pattern of interaction between light and suspended solids is relying on the size, shape and composition of the particles in the solution and to the wavelength of the incident light. Besides the scattering effect, the transmitted light will also be absorbed and attenuate in its intensity by the particles (Sadar, 1998; Anderson, 2004; Downing, 2005 and Wagner. 2000). Both this effect will result in light being scattered in forward and back scattering as shown in Figure 1.1.

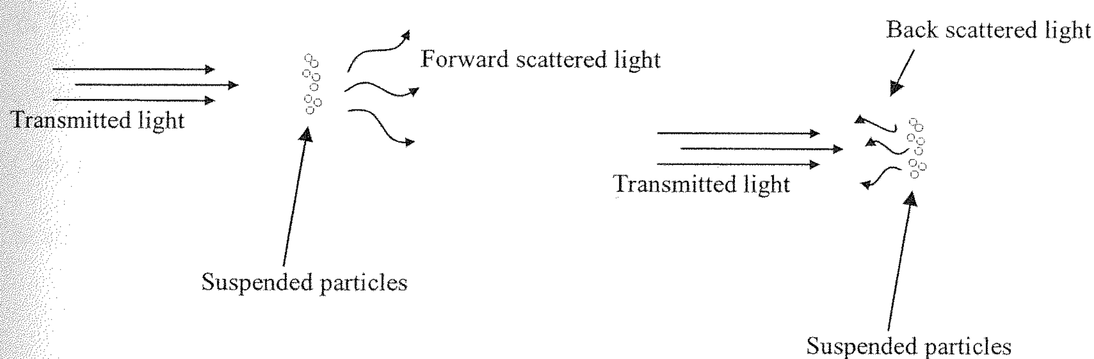

Figure 1.1: Forward and Back Light Scattering

1.4 Turbidity Measurement

Turbidity analysis is an optical measurement of scattered light. The direction of transmitted light path will undergo changes when the light hits the particles in the water sample. If the turbidity level is low, less light will be scattered away from its original direction. Light scattered by these particles will enable the detection of particles in water (Egan, 2006).

Measurement of turbidity using a light transmission method can be done in two ways:

1) Measurement of the amount of light that is able to pass directly through the medium, referred to as light attenuation measurement or absorption measurement.

2) Measurement of the light that is scattered by suspended solids, referred to as nephelometric measurement (Arjay Engineering Ltd).

The fundamental requirements to measure the level of turbidity in water are a light source with a well defined constant radiation together with a precise light detector. In 1900, measurement and quantifying turbidity was done by using a candle as the light source and the human eye as the detector and the instrument was known as the Jackson Candle Turbidimeter (Sadar, 1998; Anderson, 2004; Downing, 2005 and Wagner. 2000) as shown in Figure 1.2

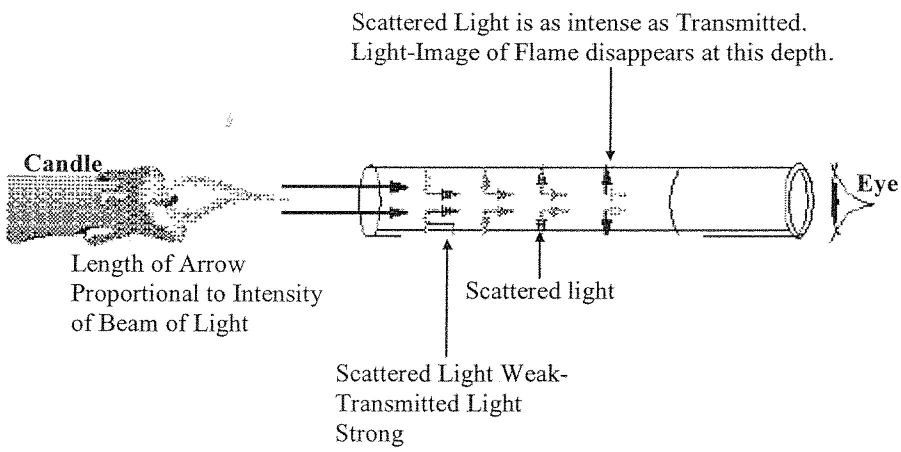

Figure 1.2: Jackson Candle Turbidimeter (EPA Manual, 1999)

Advance in the development of photo detector sensor, later design of turbidimeter was able to detect a very small change (attenuation) of transmitted light intensity through a fixed volume sample. However, the design still lack of capabilities to measure a high or very low level of turbidities. For sample with low turbidities, the scattering intensities will be so small and hard to be detected since the signal might be lost in the electronics noise. While for higher turbidities, the existence of multiple scattering will interfere with the direct scattering. The method used to improve the signal to noise ratio is by measuring the turbidity using nephelometry technique as shown in Figure 1.3. This technique measures the light scattered at an angle to the incident light. 90^{o} detection angle is considered to be the most sensitive angle to measure scattered light (Sadar, 1998; Anderson, 2004; Downing, 2005 and Wagner. 2000).

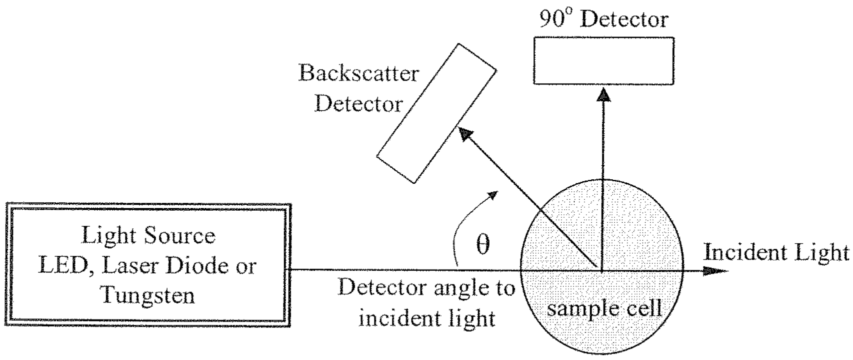

Figure 1.3: Nephelometric Sensor (Sadar, 1998; Anderson, 2004; Downing, 2005 and Wagner. 2000).

1.5 Problem Statement

The U.S. Environmental Protection Agency has defined that the municipal wastewater treatment plants must provide treatment to meet total suspended solids (TSS) limits of 30 mg/L as a monthly average and 45 mg/ as a 7-day average (EPA Manual, 1999). INQWS (Interim National Water Quality Standards) stated that the acceptable range of TSS for Malaysian rivers is 25 to 50 mg/L and threshold level of TSS for supporting aquatic life in fresh water ecosystems is 150 mg/L. In addition, according to International standards the acceptable level of turbidity of water for domestic use ranges between 5 to 25 NTU. However, Malaysian Ministry of Health has set a threshold level of low water turbidity at 1000.00 NTU (Gasim, Toriman, Rahim, Islam, Tan and Juahir, 2006). The optical fiber sensor developed can be well-suited the requirement for monitoring the level of TSS in water in accordance to the limit set by US-EPA, INQWS as well as Malaysian Ministry of Health. The usage of plastic optical fiber enable the monitoring system to be conducted in-situ, real-time and online (continuous measurement).

1.6 Research Objectives

The main objectives of this research are:

1. To design a very high sensitivity optical sensor through the usage of plastic optical fiber (POF) in detecting a very low level of light (approximately 0.01 lux).
2. To establish and implement new idea of design for measurement of TSS in water through optical fiber sensor. The system is targeted to have the sensitivity to measure the concentration of solids (or so called TSS) less then 100mg/L.
3. To perform spectroscopic analysis, this includes observation of the interaction of different wavelengths of light (blue (470nm) and red (635nm)) with solids suspended in water at different angles of observation (180^{o} and 0^{o} scattering).

This research is focusing on the development of optical fiber sensor for spectroscopy analysis. The system can be applied in measuring surface diffuse reflectance, light scattering at various angles as well as transmittance light. The system also introduces a mobile and cost effective solution for spectroscopy analysis that is based upon selected wavelength-sensitive responsivity. Overall cost of complete system is approximately RM700. In this research, however, the design is calibrated for the measurement of TSS in water, as a tool to test on system sensitivity and reliability. The application of optical fiber cable as a light transferring medium is an innovative approach in measuring the level of TSS in water. The flexibility of the optical fiber cable enables the measurement to be made at hard to reach area, in situ, real-time and online. Nonetheless, the success in the establishment of this sensory system may be very useful in other spectroscopy application such as detection of organic materials, biological tissue as well as other type of pollution, e.g. air pollution. The emission of light by the emitter system onto the sample and the retrieving of resultant light signal after the light has undergone interaction with water sample will be established through the implementation of plastic fiber optic cable (POF) with core diameter of approximately 1mm. The system will be able to identify the amount of solids suspended in water (in mg/L). The two measuring techniques introduced in this research are illustrated in Figure 1.4 and Figure 1.5.

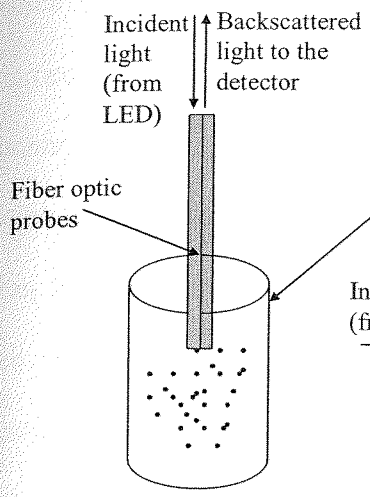

Figure 1.4: Coordination of the fiber optic probes for 180° backscattering measurement

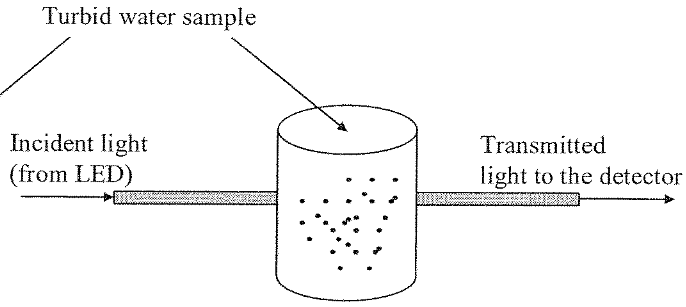

Figure 1.5: Coordination of the fiber optic probes for 0° scattering measurement

The optical fiber system design will consist of two parts; emitter system and detector system. The emitter system will consist of light source that has a good reliability to be coupled with fiber optic cable. Besides, the component selected as light source must also have a good luminous intensity, so that the detector system will be able to interpret the light signal that is emitted or scattered to it. Two high efficiency light source that can emit blue (470nm) and red (635nm) monochromatic light is needed. The selection of this wavelength is because there are coming from almost at different ends of visible light spectrum.

The detector system is made of two separate light detector circuitry that is sensitive to blue (470nm) and red (635nm) monochromatic light. The light detector must have a good responsivity towards the light scattered onto it. A thorough selection process for the suitable sensor is needed here. The output from the sensor will be supported by electronics circuitry to boost up its signal and convert it into a suitable signal to be sent to the microcontroller. The final result of detection will be submitted to Basic Stamp 2 microcontroller for processing and transferring the analysis into graph form through compatible software called Stamp Plot. Via Stamp Plot, the behavior of the backscattered light can be well-observed continuously throughout a user-defined range of time. To enhance the mobility of the system, a separate display unit will be designed and connected together with the detector system. Sets of data will be gathered through experimental procedures to shows the relationship between the solids suspended in water with light detected by the detector system. The graph plotted will be simulated to obtain the value of linear correlation coefficient, R^2 to see on the accuracies of the data collected in term of linear relationship between the capacity of solids (in mg/L) with the intensity of light (RCTIME), where the value of $R^2 = 1$ represent the theoretically perfect fit. The overall system implementation is illustrated in Figure 1.6.

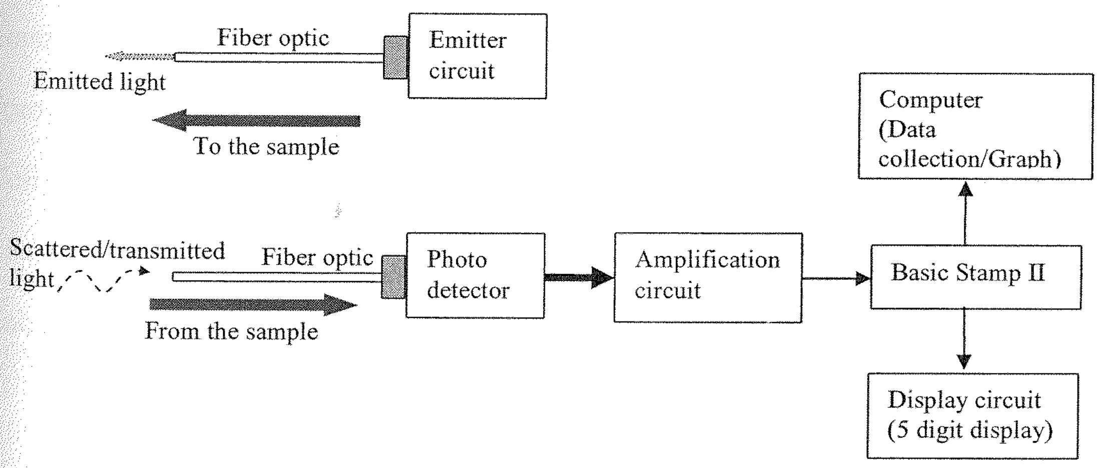

Figure 1.6: Illustration of Overall Design Concept

1.7 Outline of the Thesis

The following is the brief discussion on every chapter available in this thesis. Chapter 1 is an introduction chapter which discusses on the causes of the water pollution and some issues on water quality. Besides, this chapter also introduce original concept of water quality measurement. Chapter 2 discusses on existing methodology and system in measuring water quality (or conventionally used as to measure water turbidity). This chapter will basically focus on standards set for the development of water quality sensor. Chapter 3 discusses on the properties of light, especially when light (at different wavelength) interacts with matter. This chapter falls under physical concept of spectroscopy analysis. Chapter 3 will provide a foundation of theoretical reasons of the results attained in Chapter 5. Furthermore, the parameter used in selection of sensor responsivity and light luminous intensity is discussed in Chapter 3. Chapter 4 explains on the step by step design process, focusing on the components selection and rationale behind the components and design implementation. Chapter 5 will expose on the complete system design, from the hardware configuration as well as software (programming) establishment. The results attained from the testing of the complete design and the discussion on the reasons behind the results will be unveiled in this chapter. Finally, chapter 6 will wrap up the overall findings in this research and possible enhancement that maybe conducted in the future.

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