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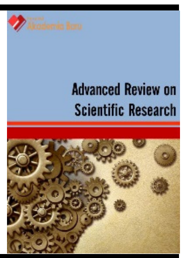

An overview of optical fiber sensor applications in liquid concentration measurements

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ABSTRACT

This paper provides a qualitative overview of different Optical Fiber Sensors (OFS), which play important role in the field of sensors due to their excellent characteristics, spontaneous response and easy handling system. The current state of the art of optical fiber technology is reviewed, namely based on its main characteristics and sensing advantages. In addition, the working principle of OFS and their applications are discussed, particularly for sensor employment.

1. Introduction

Over a few decades, optical fiber sensors (OFS) have been the subject of intense research activities [1]. To date, due to tremendous characteristics, these topics have boost number of research groups, working in developing these sensors for a wide range of applications. OFS is currently employed to sense physical and chemical characteristics, namely light intensity, vibration, temperature, pressure, strain, liquid level, pH, chemical analysis, concentration, density, refractive index of liquids, etc [2]. It offers a number of advantages including spark free, low cost, lightweight, flexible, immune to EMI [3], remote sensing, and no electrical connection to the body [4-6].

The most important measure in monitoring and improving the product quality particularly in chemical, sugar-manufacturing, food, paper-making, and pharmaceutics industries, is to control the concentration of solutions [7,8]. The utilization of optical fibers in measuring concentration is a necessity to many industries since it is safe to be applied in volatile liquids. Besides that, optical fibers based on refractive index (RI) have found in numerous applications such as in environmental, chemical and biological sensing. Theoretically, concentration has a direct relationship with a refractive index of solutions. Sengupta *et.al* have proven this properties, where they examined the

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reflected light in plastic fibers. It was also found that the refractive indexes of solutions were different for various concentrations, which contribute to different current peaks.

Having more knowledge on the relationship of refractive index with liquid concentrations is very useful, where optical instruments can be designed accordingly and the concentrations of liquid substances can be analyzed and therefore applied in specific applications [9,10]. In recent years, several optical fiber sensors based on refractive index properties have been designed, including etched cladding fiber, core diameter mismatch, and relative Fresnel reflective intensity [7]. These research include Gobi Govindan *et al*. [11], who proposed the measurement of refractive index of liquids using fiber optic displacement sensors, while theoretical and experimental fiber optic refractive index sensor based on intensity modulation was demonstrated by A.L.Chaudhari *et al*. [12]. In addition, the optical fiber sensing of salinity and liquid level was reported by Hang-Zhou Yang *et al*. [13] which proposed the liquid refractive index sensing of the solution with high absorption coefficient.

2. Materials and Working Principles

This section briefly reviews the current state of optical methods for liquid concentration measurements. The article is divided into four main sections on optical fiber sensor based on intensity modulation, optical fiber sensor based on Frustrated Total Internal Reflection, optical fiber sensor based on Fresnel Reflection and optical fiber sensor based on Fiber Bragg Grating (FBG).

A. Optical Fiber Sensor based on intensity modulation

M.Yasin *et al*. [2] have proposed a measurement of glucose concentration in the distilled water based on intensity modulated displacement sensor. The experiment setup consists of He-Ne laser light source, fiber optic transmitter, two fiber optic probes which are transmitting fiber and receiving fiber, photodiode, reflective flat mirror, chopper and a lock-in amplifier. Lock-in amplifier was used to reduce the interference of ambient stray light and dc drift. The chopper was employed to modulate the light source. This process works when a yellow light with λ= 594nm from He-Ne laser was injected into the transmitting fiber. At the end of the fiber, the light was emitted to the flat mirror. The reflected light was then collected by the receiving fiber. For measurement, the fiber optic probe was immersed into the glucose solutions. Before that, the fiber optic was dipped into the distilled water. The output intensity in the distilled water was measured with the position of the fiber probe varied from 0 to 10mm within the 50µm steps. Then, the measurements of different concentrations were taken with the concentrations were fixed to 2.5, 5.0, 7.5, 10 and 12.5g per 50ml.

From the observations, the result showed that the light started to overlap when the distance of the fiber to the reflective mirror was increased. It also shows that the peak of voltage value linearly rose with the concentrations of the glucose solution. With the concentrations varied from 0 to 25%, the sensitivity measured was about 0.0103mV. In this experiment, it was found that the refractive index and concentrations of glucose solutions were linearly increased.

D.Sengupta *et al.* [7] demonstrated the measurement of solution concentration by using plastic optical fiber (POF). The experimental set up was consists of LED as the source, two POF's as probes and photodetector. Light from the source interacted with the measurand when the light was moved into the fiber and directed to the sensor head of the fiber. The sensor head includes transmitter fiber end, receiver fiber end, and reflector. The photodetector was used to collect the result of the interaction in the light intensity modulation. From the observation on the experiment, the reflected beam becomes narrower when the concentration of the liquid was increased. The variations of reflected peak intensity with different concentrations of glycerol were also observed. Based on Fig. 1, it shows that the peak of reflected intensity increases as the concentrations become thicker.

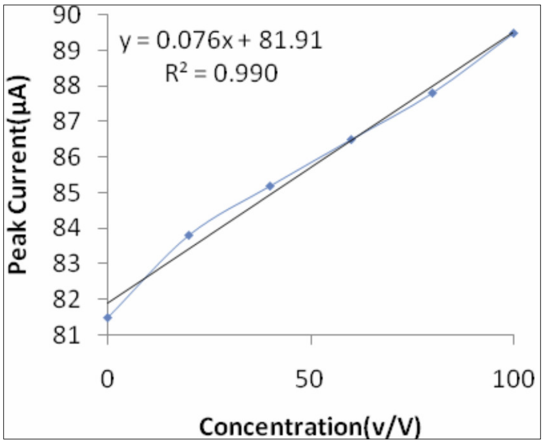

Fig. 1 Variation of peak intensity with glycerol concentration [7]

Other than that, the relationship between refractive index and concentrations of glycerol was also observed. The results show the refractive index corresponded to the concentrations and the sensitivity measured was 53.83µA, with the refractive index has 95% of linearity.

B. Optical Fiber Sensor based on Frustrated Total Internal Reflection

In a different research, P. Nath *et al*. [14] has proposed a different method for measuring refractive index in propylene glycol solutions. The method used was based on total internal reflection. The researcher used multimode optical fiber and polished one side of the fiber ends to form a curve-shaped tip with radius curvature ~ 500µm, to become a sensing area which transmits propagated modes by reflection from the tip-air interface. They also used three different fiber tips curved for comparison. Fig.2 shows the three different curves of the fiber tips that were used which the first curve shape (A) was about ~700µm, (B) the flat-end tip and (C) the curve shape with the radius of ~500µm. When the fiber tip was in the air, the light was reflected back to the fiber port, while, when the fiber tip was immersed in the liquid, the reflected light angle was changed and small numbers of the light reflected back to the port of fiber.

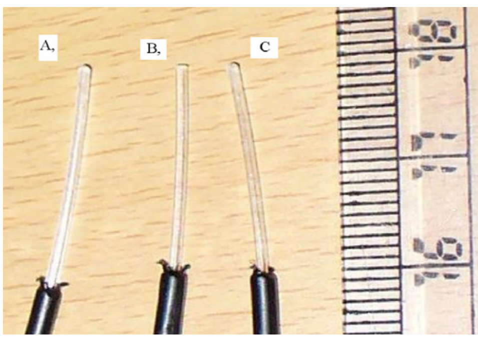

Fig. 2. Different curve shaped of fiber tip [14]

This experiment started when the light source from the laser diode with λ= 670nm was launched and focused at the end of the fiber. The front end-face of the fiber was used as a light source while the other end was used as a sensing probe. The back-reflected light was directed to the photodiode which comes from the beam splitter and another photodiode was used to monitor the incoming light which comes from the light source. The photodiode was used to measure the intensity of the fiber end and also to ensure that was no fluctuation in the light source intensity.

The sensor tip was cleaned with water and dried before being used for each reading. In order to maintain the constant temperature of the solutions, special care should be taken. The data from the experiment shows that, when the index of refraction increased, the critical angle of back-reflected was also increased. In order to make a comparison of the refractometer, a similar experiment was carried out, using the flat-end with other curve-shape with ~700µm fiber tip. Among the curved-shaped fiber tip, the results show that the curved-shaped with ~500µm has the higher sensitivity.

C. Optical Fiber Sensor based on Fresnel Reflection

Chang-Bong Kim *et al.* [15] reported a simple technique for measuring the solute concentration, where the index changed based on Fresnel Reflection from the tip of the fiber. The measured reflected optical power was due to the Fresnel reflected from the fiber-fluid interface. The optical source was divided into two paths, with one of the fiber was immersed into the solution while the other one was left in the air and acted as a reference. The dc-coupled detector was used to detect the re-tuned pulse due to Fresnel reflections at both ends of the fiber. The experimental setup for this method is shown in Fig.3.

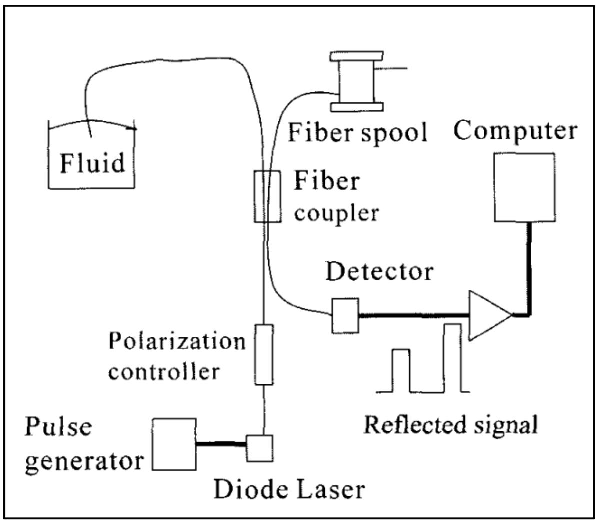

Fig. 3 Experimental setup for measurements of solute concentration in fluids [15]

The data of the lower concentration and higher concentration were different due to the time when the measurement was taken. For the lower concentration, the data was taken for 5 minutes to minimize the temperature and the polarization effects. For higher concentration, the time taken was 150 minutes. In facts, the data of salt concentration also was taken in two different sets, which the first one was taken in the range from $1x10^{-3}$ to $6x10^{-2}$ gram/cm^3 and the other `set was taken in range $2x10^{-4}$ to $1x10^{-3}$ gram/cm^3.

Meanwhile, Hui Su *et al*. [16] presented the simple technique based on Fresnel reflection for measuring of solute concentrations. The salt solution and sugar solution were used as samples. The experiment set up consists of diode laser as a light source, three couplers, two sensing fiber ends with protective cladding and two photodetectors. The measurements began when the light source with λ=1550nm from diode laser was launched into the coupler 3 which split into two beams (beam 1 and beam 2). Beam 1 has higher intensity while beam 2 has lower intensity. Beam 1 was passed through coupler 1 and was used to capture reflected light by sensor solution interface while beam 2 passed through coupler 2 and was used to reflect light by sensor air interface. The experiment set up as in Fig. 4.

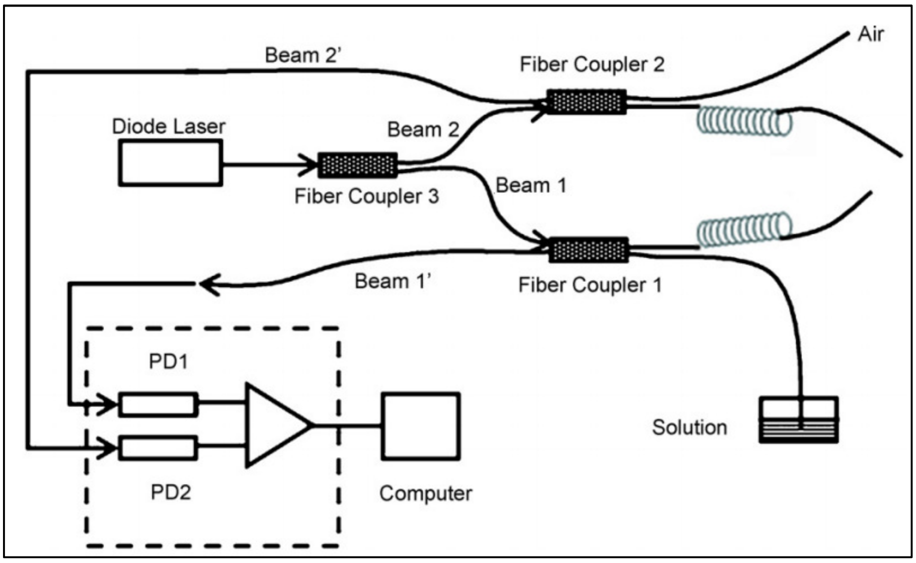

Fig. 4. Experiment setup for concentration measurement of salt and sugar solutions [16]

From this technique, the refractive index of sugar and salt solution were measured. The measured results were reported that both solutions were in good agreement with linear fits. Other than that, the concentration was measured as a function of time to evaluate the stability of the setup experiments.

D. Optical Fiber Sensor based on Fiber Bragg Grating (FBG)

In a different method, U.S.Raikar *et al*. [17] presented the measurement of ethanol solution concentration based on fiber Bragg grating (FBG). The performance was analyzed by using spectrum analyzer (OSA). The broadband source was used as a light source. OSA was used to observe and record the spectrum reflected from FBG when the fiber was immersed in the distilled water, different concentrations of ethanol solutions and also when the fiber was in the air. At different concentrations, the changes of Bragg wavelength were recorded. The relationship between wavelength shift and solution concentration was analyzed by using OSA. From Fig.5, it shows that when solution concentration was increased, it would decrease the wavelength shift.

In fact, at lower concentrations, this set up was able to discriminate the wavelength shift with a resolution of Pico meter range. Other than that, the results show that the sensor sensitivity depended on the solution concentrations. The sensitivity of concentrations was measured as high at 0.002nm/%.

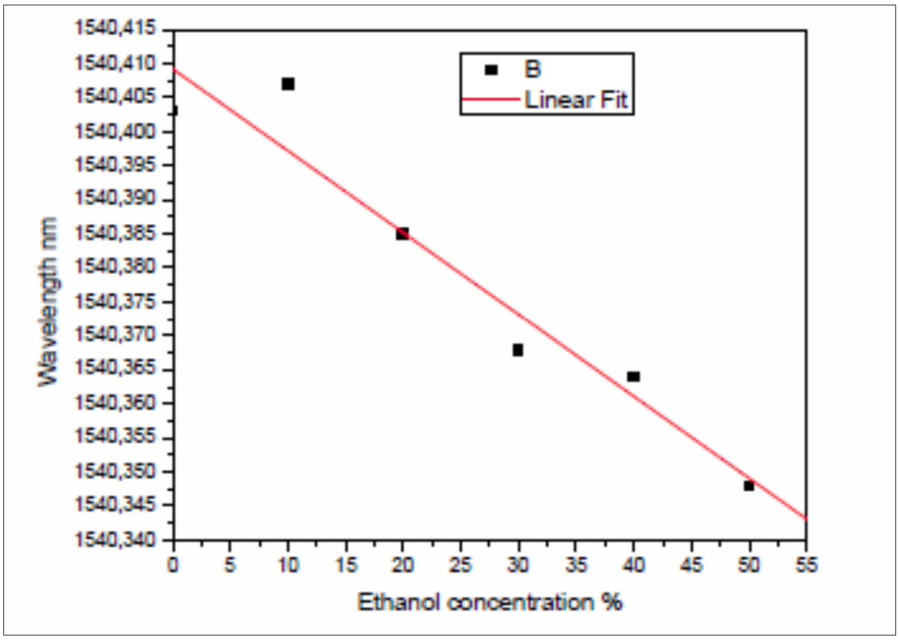

Fig. 5. Wavelength shift vs concentrations of ethanol solution

While Thanh Binh Pham *et al.* [18] demonstrated the determination of low nitrate concentration in water. The main purpose of this experiment was to analyze the characterization of etched fiber Bragg grating sensing probe to detect the presence of nitrate in water. The experimental setup consists of a broadband light source from amplified spontaneous emission (ASE), an optical circulator and an optical spectrum analyzer (OSA). OSA was used to monitoring the wavelength shift. The light source from ASE was launched into the circulator and directed to the OSA, but before that, the light input was reflected by the FBG which act as the reflector. The etched fiber Bragg grating (e-FBG) sensing probe was immersed into the nitrate solution. By varying the concentrations of nitrate solution from 0 to 80 ppm, the reflection spectrums from e-FBG were observed.

From the observation, the result shows when the concentration of nitrate solution increases, the lasing wavelength to shift to longer wavelength range. Besides that, the sensitivity was measured and the result obtained was 3.5x10-3 nm/ppm. To ensure the accuracy of measurements, the e-FBG should be cleaned by de-ionized water before replacing the different sample of solution to avoid the contamination. The measurements should be done at a constant temperature of 25°C.

3. Conclusion

This review briefly presents the recent research and developments of optical fiber sensor technology with the focus on various methods in liquid concentration and refractive index measurement. The overall performance and accuracy were discussed and the applications of the optical fiber sensors were summarized.

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