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Light Guiding Medium Based Optical Tilt Sensor Design

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Abstract

This paper presents a simple, low-cost liquid based optical tilt sensor. The sensor is designed on the basis of the variation of the amount of light passing through liquids composed of two layers placed in a container depending on the tilt angle. Light is transmitted and received by the fibers placed in the container ends. This sensor is highly sensitive to small angle values, especially depending on the fiber radius used. An average of 0.58 V/° sensitivity was obtained in the range of 0-3° by using 2.5 mm diameter fibers. This value is found to be 4.54 times higher than the sensitivity of sensor with single liquid.

Key Words: Fiber Optic; Photodiode; Sensor; Tilt sensor.

1. Introduction

Today, tilt sensors, which are used in many areas of construction from aviation, are used to measure the tilt of a plane. Tilt sensors can measure the inclination are used in landslide risk areas especially for bridges or dams to monitor stability [1-2]. Tilt sensors have various types such as force balance, electrolyt, capacitive, optical. All have the advantages and disadvantages in terms of their working principles [2-3]. Nowadays researchers are trying to discover new methods of measurement techniques to reduce the system complexity in existing solution and try to find out the better accuracy, sensitivity and high resolution in low range of economic policies [3-6]. For this purpose, especially liquid based fiber optic systems have been studied. Also the use of optical ones is increasing each day. This is because the data loss and the tolerance in the optical sensors are small.

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In [4-5] a liquid-based tilt sensor that determines the tilt with respect to the varying light intensity, depending on the refractions and reflections between the water-air boundary is presented. The resolution of the sensor is 0.02° and the sensitivity is 1V/°. In [3] another liquid based tilt sensor with a similar working principle is presented. In this setup, the resolution, accuracy and sensitivity are 0,09°, 0,8° and 50mV/° respectively. A miniaturized dual-axis electrolytic tilt sensor is presented in [7]. This sensor is similar to others in that the liquid inside the container does not change its level depending on the gravity despite the container itself. Here, however, not the light-passing feature of the liquid, but the electricity-passing feature is used. The sensitivity of the sensor in ± 75° is 45mV/°. In this study, the working principle of proposed sensor depends on the reflections and refractions of the light based on environments during the way from one fiber to another and is made using double-layer liquid, unlike other liquid based tilt sensors. The added layer guides the light emitted from the transmitting fiber to the light receiving fiber. However, more precise results were obtained between 0-3° due to the effectiveness of the layer especially around 0°.

2. Principle Of Operation

The proposed system consists of 2 fibers with the radius *a*, a cylindirical container, 2 types of liquid which form the layers, a laser diode circuit and a photodiode. The fibers with the radius *a* are placed axially at the sides of the container with the length 2h. The container is filled with two types of liquid with the refractive indexes of n_1 and n_2. These liquids are chosen to be polar and non-polar for the solubility to be low in each other. The container is filled to the fiber's bottom level with the high density liquid. After that, the low density liquid is filled to the container to form a layer with the height of 2*a* which is the same value as the diameter of fiber. One of the fibers guides the light emitted from the laser diode to the container and is defined as the transmitting fiber. On the other hand the second fiber guides light to the photodiode and is defined as the receiving fiber (**Figure.1.b**).

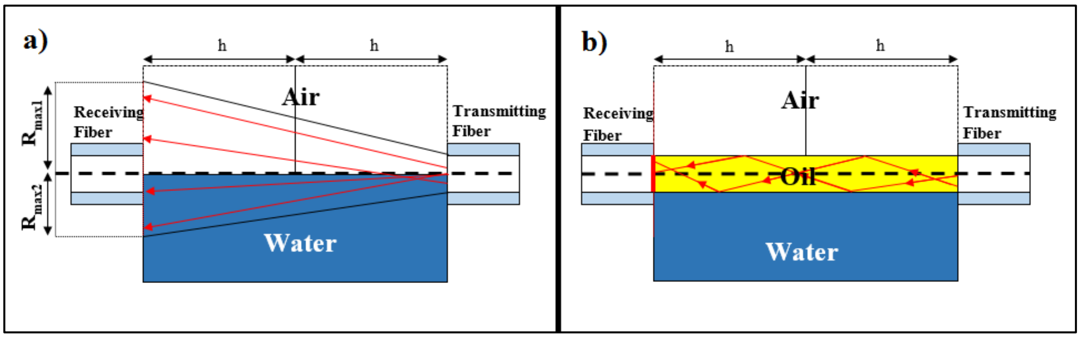

Figure 1: Light intensity distribution difference between water only system [4-5] **(a)** and oil layered water system **(b)**

The working principle of this system basically depends on the reflections and refractions of the light based on environments during the way from one fiber to another. This experiment is basically the improved version of the setup of Bajic and his colleagues with one liquid [4-5] as shown in **Figure.1.a**. The paper of Bazic and his colleagues [5] deals with principle of operation for the single liquid system. In this work, measurements were taken with single liquid (**Figure.1.a**) and two layer liquid (**Figure.1.b**). The oil layer behaves as the light guiding medium (LGM). The light guiding medium doesn't let the light scatter as much as in the single liquid system and increases the transmitted intensity to the receiving fiber. In the zero tilt angle (α=0°), all the light will be transmitted through the light guiding medium depending on the numerical apperture of transmitting fiber. For other values for α, the light collected by the receiving fiber will change due to the change of the LGM's position with respect to receiving and transmitting fibers.

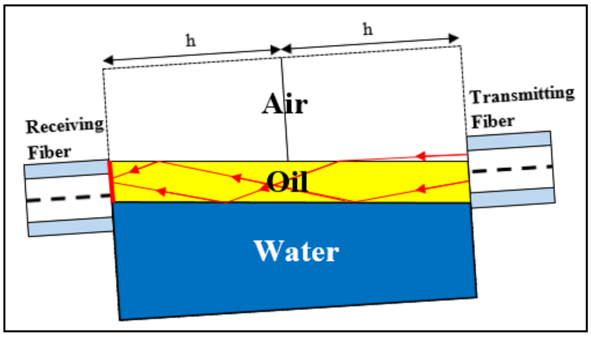

Figure 2: Tilted sensor with tilt angle α

Additionally,when the system is tilted (**Figure.2**), both transmitting and receiving fiber areas in air, in the LGM and in the liquid are changed with respect to zero position. As a result, total power collected by the receiving fiber changes depending on the tilt angle. Due to the fact that the LGM is effective around tilt angle of 0° for transmitting light through transmitting fiber to receiving fiber, exclusively the α values of 0-3° has been examined. To calculate the intensity of light reaching the other fiber depending on α, it is necessary to obtain the light emitted from the transmitting fiber. Fiber areas covered with air,water and oil were calculated (**Figure.3.**). In these calculations it was assumed that the intensity of light is equal to the entire fiber area.

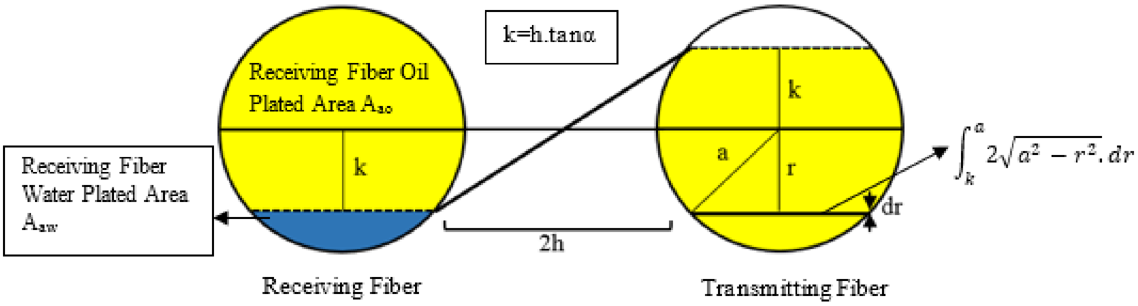

Figure 3: Oil, air and water-plated areas in the case of inclination of the transmitting and receiving fibers

To calculate the intensity of light reaching the receiving fiber depending on α, it is necessary to obtain the light emitted from the transmitting fiber. Fiber areas covered with air, water and oil (**Figure.3.**) determine the transmitted and received power. P_{tfo} is defined as the power transmitted into oil from the fiber, P_{tfa} is defined as the power transmitted into the air from the fiber. Since the refractive indexes of the fiber and LGM are very close, the transmission loss from fiber to LGM can be neglected.

$$P_{tfo} = \int_{k}^{a} I(r) 2\sqrt{a^2 - r^2}.dr \tag{1}$$

$$P_{tfa} = \int_{-a}^{k} I(r) 2\sqrt{a^2 - r^2}.dr \tag{2}$$

Where I(r) is the light intensity distribution at the output of the transmitting fiber.

At the output of the transmitting fiber conical beam of light forms a circular pattern in the receiving fiber plane, with the radius R_{max}. Intensity at the detector plane can be defined as $I_{dp} = \frac{P}{\pi R_{max}^2}$ and $R_{max} = a + 2h \tan(\theta_{max})$, when there is no liquid in the container. θ_{max} is the critical angle. These R_{max} values will be depend on refraction at the fiber medium interface. So in the oil layered water system we need to define 3 R_{max} values because of refractions between media. R_{max1} is defined as the radius of the circular pattern in the air, R_{max2} is defined as the radius of the circular pattern when the container filled with water and R_{max3} is defined as the radius of the circular pattern of oil filled case. A_{dw}, A_{da}, A_{do} are the areas of the segments which light coming from water, air and oil form in the receiving fiber plane, respectively.

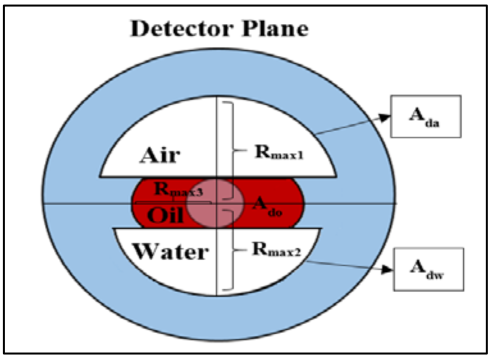

Figure 4: The areas of the segments which light coming from water, air and oil form in the receiving fiber plane

In the oil layered water system, near 0° only the rays in the oil get passed to the receiving fiber. Thus, light rays in the air also get into the oil and effect the transmitted power as it can also be seen in **Figure.2.** P_{of} is defined as the power transmitted to the fiber from the oil and T_{ao} is defined as the Fresnel transmission coefficient for light going through air to oil.

$$P_{of} = \frac{T_{ao} \cdot P_{tfa} \cdot \int_{-a}^{k} 2\sqrt{a^2 - r^2}.dr}{A_{da}} + \frac{P_{tfo} \cdot \int_{k}^{a} 2\sqrt{a^2 - r^2}.dr}{A_{do}} \tag{3}$$

This equation will be valid for flat surface liquids where the effects of adhesion and cohesion were ignored. Also reflections from the liquid-fiber and fiber-liquid interfaces were ignored.

3. Experimental Setup

Implemented tilt sensor is shown in **Figure.5** The container was made of hollow cylindrical glass. The high density (1 g/cm^3) polar liquid was water and low density (0.82 g/cm^3) with high refractive index (1.48) non-polar material was chosen as liquid paraffin. The optical fibers were mounted at the center of the top and bottom base of the cylinder. The cylinder's internal volume was 70ml. The height and radius of the cylinder were 63mm and 18.8mm, respectively. Fiber optic cables with a diameter of 2.5 mm were used. The sensor housing was filled with water to the lower boundary of the fiber and oil on the same level as the fiber. The sensor was mounted on a manual Thorlabs PRM1/M model rotation stage. As the angle of the rotation stage increases, the liquids within the container do not change its level under the influence of the gravity. This causes the changes in angle of the boundary surfaces water–oil and oil-air with respect to the fibers. As a result, the amount of the light, collected by the receiving optical fiber, changes in dependence of the rotation stage angle.

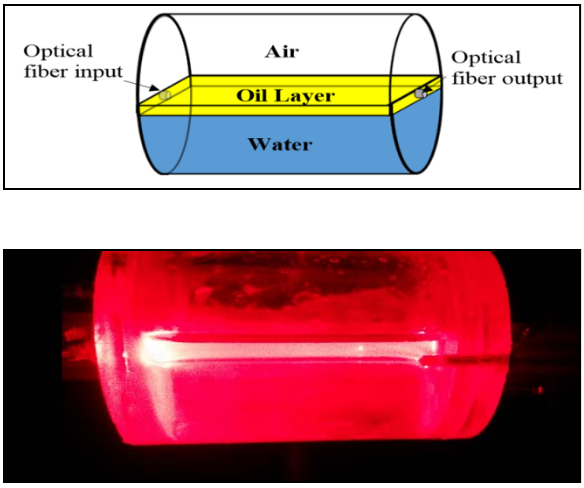

Figure 5: Photograph of the implemented sensor.

A 50mW, 660 nm laser diode was used as a light source. The light from laser coupled to the transmitting fiber directly. For the receiver circuit, 18 kΩ resistor, a voltmeter, a photodiode and a 5 Volt voltage source were used. The circuit is shown in **Figure.6.** The container was covered with black foam to reduce the effect of ambiant light.

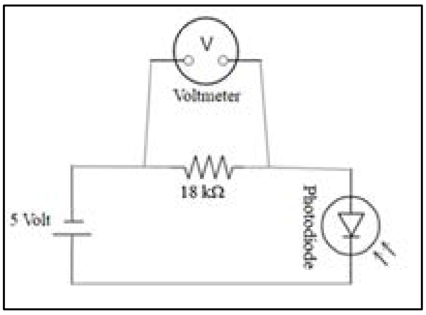

Figure 6: The circuit diagram of the receiver circuit.

4. Results and Discussion

In the theoretical model, small losses in the fibers are ignored. The surface tension of the liquid was also disregarded. When there is an oil layer on the water; because the refractive index of the oil layer is higher than that of water and air and the beam of light emerging from the fiber shows a limited propagation with θ_{max}, 90-

θ_{max} will be the largest reflection angle for the oil-water and oil-air interfaces. And this value is larger than the total internal reflection angle.

Therefore, the light in the oil will reach the plane of the detector by total reflection on the upper and lower surfaces. In comparison to the environment with only water; only in the presence of water, light rays passing through the fiber, are scattered in an area, depending on the fiber exit angle and the detector plane distance (depends on fiber critical angle and NA numerical aperture values). But, the light is limited in the upper and lower parts of the oil layered water, to an area depending on the critical reflection angle between water and oil.

When it is considered that the exit angle of the fiber is at θ_{max} degrees, the oil part increases the light intensity.

Sensitivity test between non-layered water and oil layered water has been done. With this graph, it can be said that oil layered water system is far more sensitive than the non-layered water system in the range of 0-3°. And also this graph shows that the achieved resolution is 0.04° (**Figure.7**).

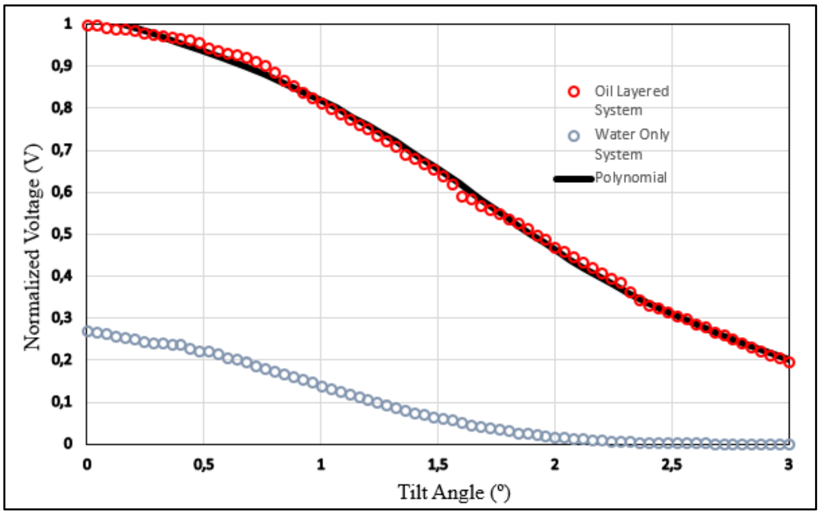

Figure 7: Sensitivity between 0 and 3 degrees between water and oil-layered water was tested.

As shown on the graph, the layer increased the transmitted intensity 4.54 times in the 0°. This due to the area restriction as mentioned before. The difference is also showed in **Figure. 1**. Data fitting has been done for the oil layered system with Excel program. The equation for the polynomial is $\alpha = -6.373V^3 + 11.082V^2 - 8.9601V + 4.4044$ and $R^2 = 0.9968$. Where V is the normalized voltage we obtained.

The decrease between 0-0.5° and 2.5-3° seems to be less than the graph. Eq. (1) shows that the change in the area of the oil coated on the fiber is small and the resulting power differences are small. However, the reduction in the transmitted power in Eq. (3) is the result of less sensitivity to these regions than in the other regions. The increase in light intensity, according to the single liquid system at 0 degrees in the graph, limits the area in which the oil light is scattered, which in turn reduces the denominator in Eq. (3). The light intensity transmitted at this point is increased.

5. Conclusion

A liquid based optical tilt sensor has been developed and presented. With the use of a light guiding medium, the intensity at 0° has been increased. Differences between single liquid[5] and layered liquid systems have been compared and presented. It has been shown that the layered liquid system is 4.54 times more sensitive than the single liquid system. The resolution of the tilt angle measurement of 0.04° has been achieved in the range of 0-3°. The proposed tilt sensor has advantages of low cost, simple fabrication process sequence and high sensitivity.

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