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Discrete liquid level fiber sensor

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Abstract
A novel simple fiber sensor to sense liquid level is presented. The operation principle is based on the relative Fresnel reflective intensity. The sensor consists of a fiber splitter with the configuration of one input to multiple fiber outputs, i.e. 1×4, 1×8 and 1×12 arrangements that act as a discrete liquid level. A broadband source (BBS) is used as the light source supply. The total reflected power intensity is measured using a power meter. Experimental results show that the power intensity decreases as the level of liquid is increased. The sensor has a simple configuration, low cost, and it can be customized for a wide height measurement range spanning from a few centimeters up to a hundred meters.

Keywords: environmental applications, fiber splitter, Fresnel reflection, liquid level sensor, reflected power

1. Introduction

Liquid-level sensing is a requirement in various areas of applications in which accurate knowledge of the liquid volume is essential, for example, in a fuel storage system, the height of water column in dams, industry chemical processing and research of ecological environment. Wide ranges of liquid-level sensing techniques based on electronic, optical and ultrasonic methods have been reported. Electronic and ultrasonic liquid-level sensors are widely employed but their applicability is compromised should the liquid to be monitored is conductive or if the environment is potentially explosive and prone to lightning strikes. Besides that, the corrosion resistance of these sensor types is normally low in extreme environments. Optical fiber sensors offer several advantages as compared to other technologies in terms of their relativelysmall size, lightweight, high survivability in extreme environments, inexistence of electrical signal at the sensor head, immunity from electromagnetic interference, having a remote distance between signal generation and detection, possibility of multiplexing as well as demonstrating high sensitivity. Therefore, several optical fiber liquid level sensors with differing approaches have been extensively developed and applied including liquid level sensor based on the fiber grating [1-4], fiber interferometry sensing [5-7], multimode interference (MMI) scheme [8-10] and fiber bend configuration [11, 12].

However, in consideration of the FBG sensor, a high implementation cost is needed resulting from the requirement for the interrogation unit and complicated photoengraving fabrication of the sensor head. On the other hand, although the interrogation unit is relatively inexpensive for a fiber bend level sensor that is based on optical light intensity, fabrication of the sensor head is prohibitively difficult as it requires a tedious procedure and complicated sensor packaging in order to maintain the right bending fiber structure of said sensor. MMI fiber based sensors provide another alternative in measuring liquid level yet the requirement for chemical etching or polishing to increase their sensitivity especially if the refractive index of the targeted liquid is less than the refractive index of the fiber is a serious limitation. The major drawback shared by the previously described optical fiber sensors is that they are inherently designed to only cater for a small range, generally in micrometers or centimeters.

In this article, we demonstrate a simple liquid level sensor utilizing a fiber splitter based on the Fresnel reflection phenomena. The sensor is based on a fiber splitter with the configuration of one input to multiple outputs, in which the fiber-end of the outputs are cut flat and functions as a discrete level of liquid. The derivation of related theory and experimental work pertaining to this have been included. Since this sensor possesses several advantages

namely custom range spanning from a few centimeters to hundreds of meters, simple design, low cost, and good sensitivity, it could provide better performance for many applications as compared to its peers, especially in aggressive environments applications such as oil and gas exploration, storage system of flammable liquid and reservoir water level monitoring.

2. Research Method

The proposed liquid level sensor is made up of a single mode fiber splitter with a configuration of one input to many outputs, e.g. 1×4, 1×8, or 1×12 arrangement. The splitter is also configured to have equally distributed power at all of its outputs. Optical fibers with certain length are connected at the splitter's outputs and these fibers have flat cleaved end facet. Each of these fiber's end facets is then fixed uniformly at certain height within the measurement site corresponding to a discrete level of liquid. At this individual flat cleaved end facet, the Fresnel reflection principle is used to relatively determine the current level of liquid when the liquid level is rising. This is achieved by accounting for the total reflected power from all the output fiber's end facets, which include those from the fiber-liquid boundaries and fiber-air boundaries. According to the Fresnel reflection principle [13], the fraction of an incident power that is reflected from a boundary of two different media, or reflectance is given by:

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 \qquad (1)$$

where n_1 and n_2 are the refractive indices of medium 1 and medium 2 respectively, with the incidence occurring at normal angle. In case of the proposed sensor, medium 1 is the output fiber core material, and medium 2 could represent either the liquid or the air. Therefore, according to the Fresnel reflection principle, the reflectance should be different when the fiber's end facet is submerged in liquid, compared to when it is surrounded by air. This is correct provided that the refractive index of the liquid and air is dissimilar.

Based on this argument, the total reflected power for the proposed sensor could then be determined as follows. For simplicity purposes, consider a sensor made up of a 1×4 fiber splitter with equally divided output power such as the one shown in Figure 1.
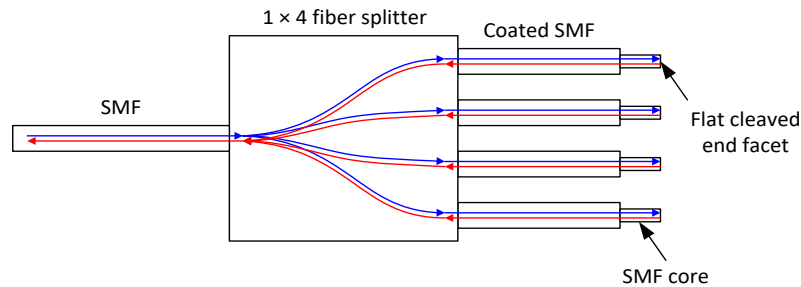

Figure 1. The 1×4 fiber splitter based liquid level sensor

The reflected power from an individual fiber's flat cleaved end facet that is submerged in liquid can be written as,

$$I_{\text{liquid}} = I_0 \alpha \left(\frac{n_{core} - n_{liquid}}{n_{core} + n_{liquid}}\right)^2 \qquad (2)$$

where I_0 is the input power and α is the fiber insertion loss and other losses;
when the end facet is surrounded by air, the reflected power for an individual fiber becomes;

$$I_{air} = I_0 \alpha \left(\frac{n_{core} - n_{air}}{n_{core} + n_{air}}\right)^2 \qquad (3)$$

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consequently, the total reflected power for the 1×4 fiber splitter based liquid level sensor could be obtained through summation of the individual reflected power from all four fiber's end facet. This can subsequently be written as,

$$I_{Total} = (I_1 + I_2 + I_3 + I_4) \tag{4}$$

the calculation of total reflected power for the liquid level sensor based on the 1×4 fiber splitter configuration involves five possible situations. The first situation occurs when there is no liquid reaching the fiber's end facet at the first level. In this situation, the total reflected power is,

$$I_{zero} = I_0 \alpha \left[4 \left(\frac{n_{core} - n_{air}}{n_{core} + n_{air}} \right)^2 \right] \tag{5}$$

the second situation ensues when the liquid fully submerges the first level fiber's end facet. The total reflected power is then becomes,

$$I_{st} = I_0 \alpha \left[\left(\frac{n_{core} - n_{liquid}}{n_{core} + n_{liquid}} \right)^2 + 3 \left(\frac{n_{core} - n_{air}}{n_{core} + n_{air}} \right)^2 \right] \tag{6}$$

the third situation follows when the liquid rises pass the second level and totally immerses the corresponding fiber's end facet. The total reflected power is then becomes,

$$I_{2nd} = I_0 \alpha \left[2 \left(\frac{n_{core} - n_{liquid}}{n_{core} + n_{liquid}} \right)^2 + 2 \left(\frac{n_{core} - n_{air}}{n_{core} + n_{air}} \right)^2 \right] \tag{7}$$

then, the fourth situation occurs when the liquid reaches and completely submerges the fiber's end facet at the third level. The total reflected power is now,

$$I_{3rd} = I_0 \alpha \left[3 \left(\frac{n_{core} - n_{liquid}}{n_{core} + n_{liquid}} \right)^2 + \left(\frac{n_{core} - n_{air}}{n_{core} + n_{air}} \right)^2 \right] \tag{8}$$

the fifth situation signifies that the liquid has totally passed the fourth level, where the corresponding fiber's end facet should be completely submerged. In this situation, the total reflected power is,

$$I_{4th} = I_0 \alpha \left[4 \left(\frac{n_{core} - n_{liquid}}{n_{core} + n_{liquid}} \right)^2 \right] \tag{9}$$

Similarly, the total reflected power for sensor based on the other fiber splitter configurations could be obtained through similar processes. Accordingly, in (4) can be generalized for the calculation of total reflected power of a liquid level sensor based on 1×M fiber splitter as,

$$I_{Total} = I_0 \alpha \left[k \left(\frac{n_{core} - n_{liquid}}{n_{core} + n_{liquid}} \right)^2 + (M - k) \left(\frac{n_{core} - n_{air}}{n_{core} + n_{air}} \right)^2 \right] \tag{10}$$

where $k = 0, 1, 2, \ldots, M$ is the kth level of liquid.

The experimental setup of the proposed liquid level sensor is shown in Figure 2. The sensor was set up using a fiber splitter with one input to many outputs configuration, i.e. 1×4, 1×8, and 1×12 arrangements. The number of fiber splitter's output would affect the resolution of liquid level measurement. The measurement setup comprised of an amplified spontaneous emission (ASE) light source with a wavelength of approximately 1550 nm, a 3-ports optical circulator to separate the reflected light from that of the source, and a power meter. Light from the light source is transmitted to the splitter through the circulator. It is then split equally according to the number of outputs provided. The individual split light then goes

toward the end facet of each output fibers which acts as the sensor head. It is then reflected back at the fiber-liquid boundaries or fiber-air boundaries, depending on the possible situation. The reflected light passes through the splitter once again, but this time the splitter acts as a combiner. It combines all individual lights that arrived back from each sensor head. The combined light now moves through the circulator once again where it is rerouted to the power meter. The power meter now shows the reading of the total reflected power that is affected by the variation of liquid level.

The proposed sensor was experimented using three different fiber splitter types, which are the 1×4, 1×8, and 1×12 splitters. Tap water was chosen as the test liquid with a refractive index of 1.33 and the experiment was performed in a laboratory with a room temperature of 24° Celsius. SMF with core material refractive index of 1.44 was used as the output fibers. Each end facet of these output fibers was flat cleaved using normal fiber cleaver such as shown in Figure 2. This flat cleaved end facet of the SMF forms the sensor head that acts as a mirror to reflect back the light according to the Fresnel reflection principle.
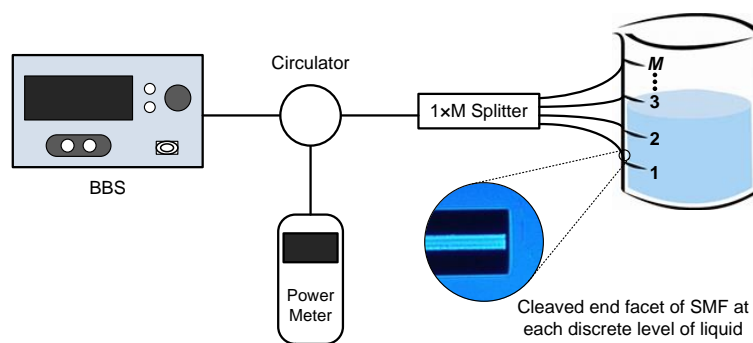

Figure 2. The experimental setup for liquid level sensor based on 1×4 fiber splitter

3. Results and Analysis

The proposed level sensor has been experimented using three different types of fiber splitters. The reflected power intensity of each sensor configuration was measured and the results are shown in Figure 3. Based on the figure, the result for the 1×4 fiber splitter based sensor is characterized by four distinct interval of liquid level. The pattern can be observed to be the same for sensors with the other type of fiber splitters. Sensors with the 1×8, and 1×12 fiber splitters have eight and twelve distinct intervals of liquid level respectively. It can be clearly observed from the graphs that the reflected power intensity decreases linearly with the level of liquid. This phenomenon obeys the principle of Fresnel reflection that was explained by (1) through (10). It clearly indicates that the fraction of incident power that is reflected back reduces when the sensor head is fully submerged within the liquid. The graphs also show that the sensors, i.e. with the 1×4, 1×8, and 1×12 fiber splitters have linear regression coefficient (R2) of 0.9897, 0.9837, and 0.9842 respectively. These prove that the output of all the sensors have response with good linearity.

The correlation in Figure 3 (b) to (d) with regards to the highest and lowest power intensity readings and the readings achieved in Figure 3(a) is that as the splitter output is increased, we can see that the highest power is decreasing too from -13 dBm to -16.5 dBm and -20.4 dBm. This is due to a more outputs splitter would give a more losses. Eventually the lowest power for each of the splitter become decreased too with reference to the highest power reading. Common problem with a liquid level sensor using other fiber based scheme such as the FBG and interferometer [2, 5] is that the range of the liquid level is very limited to short range of a few centimeters. In contrast, the proposed sensor scheme can support greater range from short to very long up to a few meters. The resolution of liquid level can be adaptably constructed according to the type of fiber splitter, e.g. 1×4, 1×8, or 1×12 arrangement. It should be mentioned that the experiment was conducted with the use of a very stable light source. As for the case of unstable light source such as the LED, the instability issue can be solved using the ratio metric technique [14, 15]. Based on this technique, one of the splitter's outputs

can be used to normalize the total reflected power. In addition, it helps in avoiding unwanted signal conditions such as fiber bending effect. For a practical application, LED would typically be the best choice due to its low cost and easy integration in a miniature circuit.
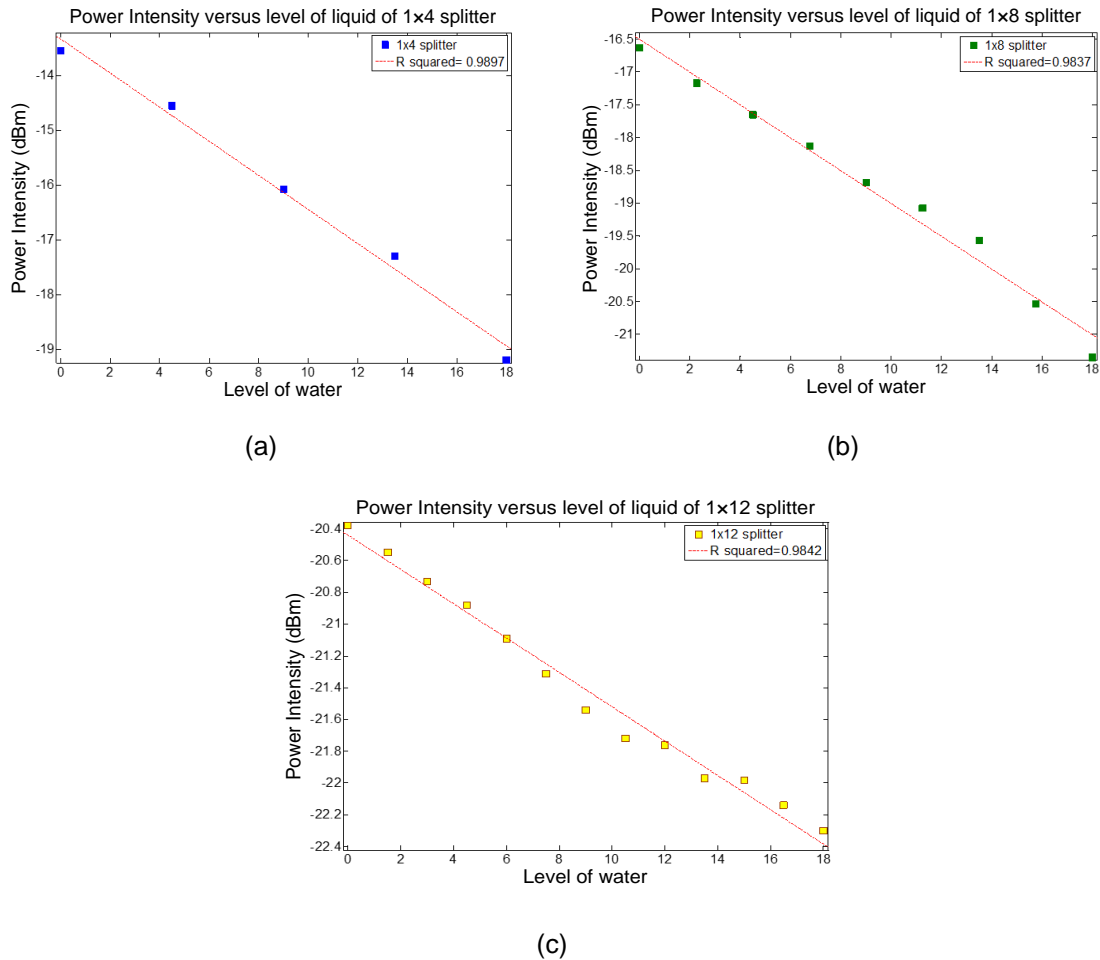

(a)

(b)

(c)

Figure 3. Graph of liquid level measurement using three different fiber splitters i.e. 1×4, 1×8 and 1×12

Figure 4 shows a comparison of the dynamic range for sensors based on different type of the fiber splitters. The figure demonstrates that the 1×4 fiber splitter based sensor has the highest dynamic range value. This is followed by sensors with the 1×8 and 1×12 fiber splitters respectively. The pattern is due to the insertion loss of the 1×4 fiber splitter being the lowest as compared to the others such as shown in the specification of fiber splitters in the inset of Figure 4. The low insertion loss contributes to low overall loss for the total reflected power and hence maximizes the dynamic range of the sensor. The main advantage of this sensor scheme is that it could provide customization of liquid level measurement range up to hundred meters with simple configuration instead of the complicated point measurement scheme employed by MMI [9,16-18], U-shaped [16, 19, 20, 21] and POF [17, 22, 23, 24] based sensors. Since our sensor is based on intensity measurement, it is suggested to have one of the multiple outputs acting as the reference signal using the ratio metric scheme. Thus, the signal error due to light source fluctuation could be compensated. To realize a practical setup for the sensor with a low cost, the transmitter of LED is chosen based on the ratio metric scheme to compensate the flunctuation of the LED. A bare of SMF that act as a head sensor can be changed to FC/PC connector [25] as this connector has a flat cleave like SMF as shown

in Figure 2. The combination of low cost and easy integration of LED and FC/PC connectors will make the system has an easy installation and maintenance.
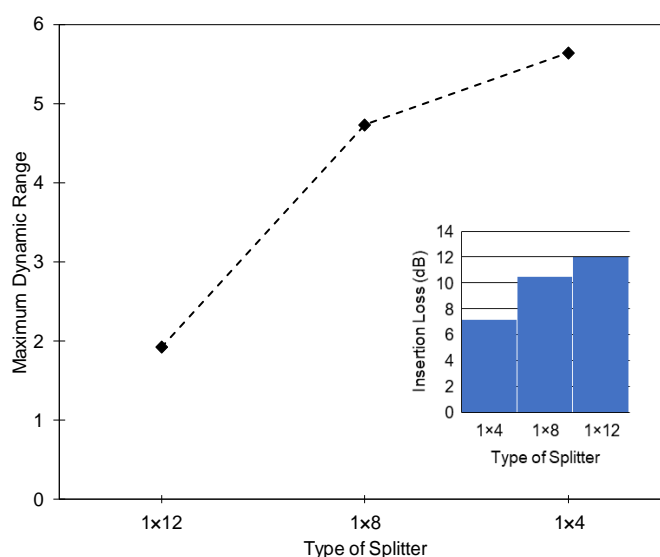

Figure 4. Comparison of dynamic range for all types of fiber splitters
(Inset) fiber splitter insertion loss

4. Conclusion

A low cost and simple fiber based sensor for detection of liquid level has been proposed and demonstrated experimentally. The sensor is based on fiber splitter with the configuration of one input to multiple outputs, i.e. 1×4, 1×8, and 1×12 arrangements acting as discrete liquid levels. The total reflected power intensity was measured using a power meter. According to the result, the level of liquid decreases linearly against the total reflected power intensity which is in-line with the Fresnel reflection principle. The sensor provides the benefit of customization of liquid level measurement range from a few centimeters up to a hundred meters. It could be configured according to specific needs especially for liquid level measurement in the meters range. This fiber sensor would be suitable for high stress applications such as in dam, flood-prone areas and highly volatile contained liquids.

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