Fiber-Optic Liquid Level Sensor

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***Abstract*—A fiber-optic liquid level sensor based on multimode interference (MMI) effects is proposed and demonstrated. We show that MMI and self-image effects can be effectively applied for multiplexed liquid level sensing, because the natural response as a band-pass filter for each sensor is clearly distinct from each other, in the case for several sensors working at the same time. Using a standard 105/125 step-index multimode fiber (MMF) a simple discrete level sensor was fabricated, that can also discriminate the refractive index (RI) of the liquid during the level measurement. The MMI liquid level sensors are not only inexpensive, but their fabrication is simple.**

***Index Terms*—Liquid-level sensor, multimode interference (MMI), optical fiber sensors.**

I. INTRODUCTION

THE development of optical fiber sensors has experienced a tremendous growth during the last few years. A vast amount of research can be found in the literature with applications ranging from physical, chemical and biological sensing devices and systems. There are several attractive features that make optical fiber sensors (OFS) superior to electrical systems. Some of the key advantages include low power consumption, ability to withstand corrosive and high temperature environments, immunity from electromagnetic interference, large distance between signal generation/detection, and high sensitivity. Among the different physical parameters that can be measured using OFS the detection of liquid level in containers is very important for commercial applications. In particular, liquid level sensing of flammable fluids is one particular application where OFS are well suited since they do not require electrical signals to sense the liquid. In general we can have two types of level sensors: continuous and discrete. Discrete level sensors are typically based on the change in optical reflection from or transmission through the sensor head, due to the change in refractive index surrounding the sensor head, when the tip becomes in contact with a liquid [2]–[7]. Over the years many different configurations have been proposed for discrete liquid level sensors, and whose sensing mechanism is based on special fiber tips. The level sensors based on special fiber tips operate on frustrated total internal reflection which could be obtained through angled or retroreflecting tips [2], conical/tapered tips [3], [6], special fiber tip design [4], or the attachment of reflecting elements as prisms [5]. In all cases the need to have a special fiber tip requires either a special fiber treatment or the attachment of an external component, which increases the sensor complexity and cost. Recently, we have demonstrated the advantages of fiber based multimode interference (MMI) devices for different laser applications [8]. The key advantages of MMI devices are that they exhibit a pass-band filter response, and their fabrication only requires splicing a specific segment of multimode fiber (MMF) between two segments of single mode fibers (SMF).

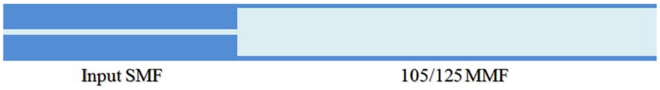

Fig. 1. Schematic of the liquid level sensor.

In this letter, we propose and demonstrate a simple and inexpensive method for discrete liquid level measurement based on MMI effects. The sensor relies on the fact that self-images of the input field passing from the SMF are formed at periodic locations along the MMF due to the MMI effect. By cleaving the MMF at this exact location, the self-image is reflected back to the SMF due to the MMF-air interface. When the MMF tip is immersed in liquids, the reflected self-image is attenuated, and this provides a way to not only to detect the liquid, but also to estimate its refractive index (RI). The MMI effect also allows us to have multiplexed operation by simple changing the length of the MMF section such that each of the multiplexed sensors operates at a different wavelength. The fabrication of the sensors is straightforward and with a minimum cost, which is promising for several applications.

II. PRINCIPLE OF OPERATION

A schematic of the MMI liquid level sensor probe is shown in Fig. 1. The key component is a segment of MMF of precise length that is spliced to a segment of single mode fiber (SMF). After the splicing, no further process is required and the sensor is ready for testing.

The operation of the sensor is straightforward. Light coupled to the MMF through the SMF will excite all the supported even modes, and as they propagate along the MMF the interference between them will form images of the input field along the MMF. By cleaving the MMF at the precise location where an image is formed, a fraction of the image will be reflected back to the SMF due to the Fresnel reflections from the MMF-air interface. This only occurs for a specific wavelength that can be calculated using the following expression,

$$\lambda_0 = \frac{4n_{MMF}D_{MMF}^2}{L}, \qquad (1)$$

Manuscript received June 15, 2011; revised August 03, 2011; accepted September 14, 2011. Date of publication September 29, 2011; date of current version November 16, 2011.

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Digital Object Identifier 10.1109/LPT.2011.2170058

where n_{MMF} and D_{MMF} corresponds respectively to the effective refractive index and diameter of the fundamental mode of the MMF, with λ_0 being the free space wavelength [8], [9]. Light with a different value of λ_0 will form its image before or after the MMF-air interface, and as a result the intensity coupled back to the SMF is reduced. This provides a band-pass response in our sensor without using any especial fiber or structure. As shown in (1), this is entirely controlled by just using a MMF with a different length, which provides a simple and cost-effective way to achieve wavelength multiplexed operation.

The application of the MMI device as a liquid level sensor is achieved by placing it along the vertical direction. This also provides easy attachment of the sensor to any surface and depth within a container. When a liquid makes contact with the MMF facet the reflection coefficient is reduced because the RI contrast between the MMF and the external medium is reduced. Therefore, the light intensity reflected back to the SMF is reduced and is related to the RI value of the liquid. The relative intensity variations can then be used not only to detect the liquid level, but also to estimate the RI of the liquid. We should also note that, in principle, there is no restriction to use any commercially available step index MMF. Nevertheless, it has been shown that as the core diameter of the MMF is increased the bandwidth of the band-pass response is reduced. Therefore, in this work we use a standard 105/125 MMF in all our experiments.

III. LIQUID LEVEL SENSOR USING 105/125 MMF

The response of the MMI liquid level sensor was investigated and tested by coupling light from an Agilent tunable laser (wavelength range from 1460 to 1580 nm) into port 1 of an optical circulator, while the output from port 2 was connected to the SMF of the MMI sensor. The reflected light from the MMF is collected from port 3 of the circulator, and the response was measured using an InGaAs photodetector connected to a Keithley digital multimeter (DMM). The setup was fully controlled through GPIB ports using LabVIEW. The normalized response of the MMI sensor (MMF length of 43.5 mm) in air is shown in Fig. 2. As explained before, the response exhibits a band-pass response as a function of wavelength. Since the response of the sensor will be related to the RI of the liquid, we prepared different mixtures of D.I. water ($n = 1.333$) and ethylene glycol ($n = 1.434$). This provides a wide range of RI that covers most of the typical alcohols used in industrial applications. Each liquid is tested by first making contact with the MMF tip, and then doing a wavelength scan with constant power. As shown in Fig. 2, the peak intensity is reduced more than 90% in the case of water, and is further reduced by 95% when we use pure ethylene glycol (EG). By plotting the extinction ratio (ER) of the reflected peak intensity as a function of the RI of the liquid, we can see more clearly the response of the sensor as shown in the inset of Fig. 2. As shown in the inset, the ER is close to 10 dB in the case of water, and this value is increased up to 13 dB as we increase the RI of the liquid. This level of attenuation is more than enough for interfacing with any electronic control system. A sensitivity of 2.92×10^{-4} can be also estimated for RI measurements. This sensitivity is lower than state of the art RI sensors, but is good enough to discriminate RI of the liquids.

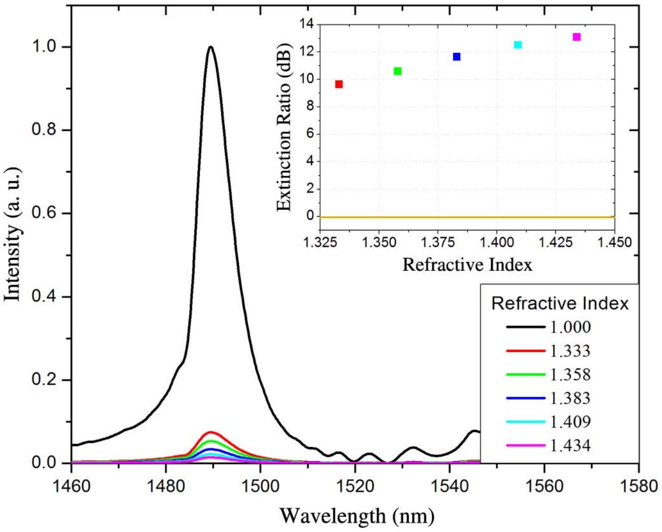

Fig. 2. Spectral response of the sensor using liquids with different refractive indexes (inset) ER as a function of refractive index.

We also performed measurements on the response of the sensor in real time. The experimental setup was similar to the previous one, except that we tuned the laser to match the peak wavelength of the MMI sensor, and the signal from the photodetector was sent to an oscilloscope to monitor the peak intensity as a function of time. The sensor was placed on a linear translation stage that allowed us to insert the MMF tip into the liquids. The sensor was successively inserted and removed from isopropanol (IPA), acetone, and water, one after the other. As shown in Fig. 3(Top), the sensor is not only capable of sensing different liquids in real time, but we can also notice the difference in the detected signal level which is correlated to the RI of the liquid. We can also observe some oscillations in the detected signal right after we remove the MMF tip from the liquid (marked by the red arrows), which is related to residual liquid being evaporated from the tip of the MMF. As a result, in the alcohols we have a fast oscillation and the signal recovers to its original value in air. However, in the case of water the oscillations last for 10 s before the signal recovers to its value in air. In the case of other nonvolatile liquids, such as EG, the signal does not recover after a much longer time. This can be solved if we have a way to make the surface of the MMF hydrophobic. In our case, we choose to rinse the fiber with acetone immediately after every measurement in order to recover the signal. Here we used water, equal parts of water/EG, and EG, corresponding to RI of 1.333, 1.383, and 1.434 respectively. As shown in Fig. 3(Bottom), as soon as we remove the fiber from each liquid (red arrow) the oscillation starts, and it stops as soon as we deep it in acetone. The fiber is removed from the acetone right away and the behavior of the signal is similar to what we observed in Fig. 3(Top) for acetone. We should highlight that the RI difference of the liquids can be easily discriminated in the graph. We should emphasize that the RI discrimination is only available for single MMI operation. As shown below, this is due to small residual signal from adjacent MMI sensors. The response time of the sensor was also estimated. A signal fall time of 15 to 25 ms was measured when going from acetone to

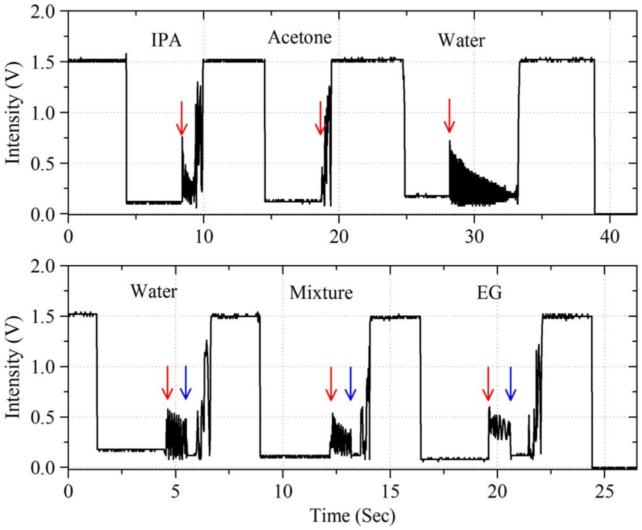

Fig. 3. (Top) Real-time response of the sensor for different liquids (the red arrow indicates when the fiber tip is removed from the liquid). (Bottom) Real-time response using different liquids with the fiber tip being rinsed with acetone as indicated by the blue arrow.

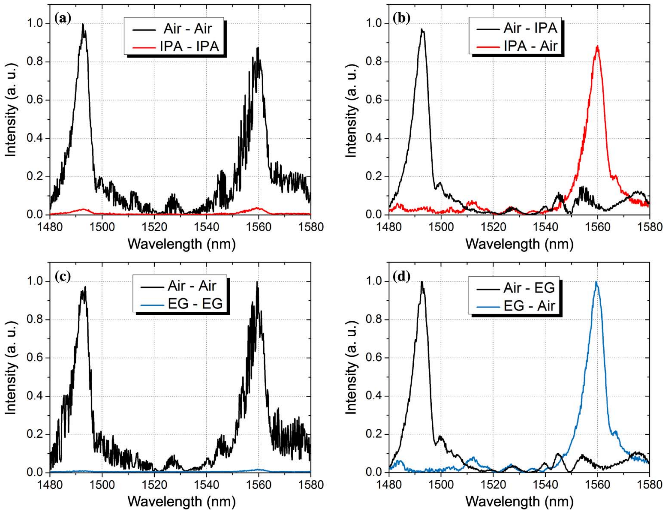

Fig. 4. Multiplexed operation of the sensor using two MMI sensors.

water, while the recovery time measured after the oscillations ended was 40 to 120 ms.

In order to demonstrate multiplexed operation, another MMI sensor was fabricated by cleaving a second longer length MMF (41.5 mm) and obtaining a MMI sensor with a peak wavelength of 1560 nm. The same experimental setup is used as before, but now we add a 1 × 2 3-dB splitter after port 2 of the circulator and the MMI sensors are connected to the two outputs of the splitter. This allows us to monitor the liquid level on two different containers simultaneously. As shown in Fig. 4(a) when both fibers are in air we have two well defined peaks corresponding to each MMI sensor. We should mention that the noisy response in this case, is an artifact due to the high coherence of the source tunable laser. This can be easily removed by using an incoherent broadband source. We corroborated this by using an Erbium doped amplifier. Nevertheless, the tunable laser was used due to its wide tuning range. When the level of IPA is raised in both containers and makes contact with the MMF tip, we can observe that the signal level is reduced in both sensors. We can also see in Fig. 4(b) the situation with one sensor in air and another one in IPA (black line), as well as the reverse scenario (red line). Similar measurements are performed for containers filled with EG, and similar results are observed in Fig. 4(c) and (d). Wavelength multiplexing is then not only simple, but also inexpensive, since we only have to cleave the MMF at a different length.

IV. CONCLUSION

We have demonstrated an all-fiber liquid level sensor based on MMI effects. This sensor presents several advantages as compared to typical discrete level sensors. First of all they do not require a lens, prism, or any other optics to be attached or fabricated on the tip of the sensing fiber. The only requirement is to cleave a 105/125 MMF with a precise length. The length of the MMF also allows us to control the peak wavelength of the sensor, which allows simple and inexpensive wavelength multiplexed operation. Using this sensor we achieved ER ranging from 9.63 to 13.09 dB when detecting liquids with RI from 1.333 to 1.434. This value of ER is comparable with liquid level sensor based on reduction of Fresnel reflections, and much better than some sensors that are based on special fiber tips. We also highlight that the measured signal intensity provides a good estimate of the RI of the liquid, which could be useful in some applications.

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