OPEN ACCESS

2nd International
Electronic Conference on
Sensors and Applications
15–30 November 2015

www.mdpi.com/journal/sensors

Conference Proceedings Paper – Sensors and Applications

Detecting Layered Liquids Using Long Period Fiber Grating Sensors

Ying Huang [1],* and Hai Xiao [2]

[1] Department of Civil and Environmental Engineering, North Dakota State University, Fargo, ND, 58108-6050, USA

[2] Department of Electrical and Computer Engineering, Clemson University, Clemson, SC 29634, USA

* Author to whom correspondence should be addressed; E-Mail: ying.huang@ndsu.edu;
Tel.: +701-231-7651; Fax: +701-231-6185.

Published: 11 November 2015

Abstract: Layers occur when insoluble liquids meet each other such as water and oil. The monitoring of the interfaces among various liquid layers are of paramount importance for chemistry purifications, liquids storage in reservoirs, oil transportation, and chemical engineering. However, studies for layered liquid detection are limited. Visible examination has been used as a common practice to distinguish liquid layers, which is rough and in most cases hard to operate for chemical processing. In this paper, a long-period fiber grating (LPFG) based optical fiber sensor was investigated to detect the boundaries between layered liquids. The LPFG when bonded on an object as a sensing device will respond to the change of the refractive index between various liquid layers. Laboratory experiments showed that the refractive index difference between layers will induce a sudden change of the LPFG's resonant wavelength if the LPFG sensor is moving through the layer boundary. Higher sensitivity was observed for higher cladding modes in a LPFG for boundary detection between layered liquids. With further approval, the LPFG sensors could be potentially use for accurate liquid layer sensing which is highly demanded for chemical processing and liquid storage.

Keywords: layered liquids; long period fiber grating; liquid level

---

1. Introduction

Boundary occur between liquid and gas or insoluble liquids such as water-air, and water-oil. The detection of boundary between liquid-gas or insoluble liquids is significant during chemical processing, liquid storage and transportation such as the storage of oil and gas or hazard chemical products. The measurements of boundary between liquid and gas if only one layer of liquid associated, usually known as liquid level sensor, which is popularly existed. For example, every car, truck and motorcycle is equipped with a fuel level sensor to measure the amount of gasoline left in the fuel tank. Since these liquid level sensors have been in place for a long time, various technologies are available to detect the boundary between liquid and gas, including mechanical floating devices, hydronic pressure measuring devices [1], magnetic approaches [2], electrical conductivity measurements [3], capacitive sensing technology [4], ultrasonic and acoustic sensors [5], and others. However, in order to save space, weight and cost or to increase the reliability and safety of these sensors, there are still some evolutions ongoing and require manufacturers to consider new solutions such as the use of fiber optic sensors.

Fiber optic sensors, due to their advantages of compactness, immunity to EMI and moisture, and long life cycle, have been widely applied in chemical engineering. Various optic fiber sensors such as intensity-based sensors [6], fiber Bragg grating [7,8], and long period fiber gratings, had been investigated for liquid level sensing. Among these fiber optic sensors, long period fiber gratings (LPFG), for their high sensitivity of environmental changes, they have been widely applied in chemical, temperature and strain sensing [9]. A long-period grating in a single mode fiber couples the core mode to a co-propagating cladding mode which decays rapidly as they propagate along the fiber axis owing to scattering losses at the cladding-air interface and bends in the fiber [10]. The cladding mode experiences total internal reflection at the interface between the cladding and the surrounding environment when the refractive index of the cladding is greater than the refractive index of the surroundings. From the dispersion relation, it is known that the effective index of the cladding mode depends on the refractive index of the surroundings, leading the long-period grating to be an effective sensor of the surrounding environments, which can be potentially used to detect liquid level changes. Khaliq *et al* (2001) [11] first applied LPFGs to roughly demonstrate for oil level detection. The sensor showed a large linear range, with sensitivity of 4.8% change in transmission per millimeter, for a LPFG with a length of 40 mm and a periodicity of 400 mm. Grice et al (2009) [12] repeated the 100 mm-long grating sensor for liquid level detection. Their result for the level change of the liquid with a specific refractive index was both a shift in wavelength and a change in the attenuation level of the selected loss band. Huang *et al* (2013) [13] developed LPFG sensors for water level sensing, and simultaneous measurements of liquid level and refractive index.

Although sensors to detect the boundary between liquid and gas are very popular, there are limited techniques available for boundary detection between various insoluble liquids, say, layer liquids. The common means used for detecting the interfaces among various liquids are visible examination, pressure measurements, or electrical capacitive sensors [14], which is very inaccurate, and in most cases hard and not safe to operate. In this paper, a long period fiber grating sensor for detection the boundary between layered liquids has been developed. Its sensor design and sensing principle had been investigated both theoretically and experimentally. With the advantages of high measurement accuracy and great durability, the proposed optical fiber sensing device could be applied for layered liquid detection in various applications such as fuel storage systems, chemical processing, and aerospace engineering.

2. Sensor Design

2.1. Principles of Operation

The long period fiber gratings used in this paper is fabricated by CO_2 laser irradiation technique. All the LPFG sensors used in this study were fabricated as described in reference [15]. The fabrication process introduced a residual stress between the cladding and core of an optical fiber, resulting in a negative change of effective index at grating locations. All the LPFGs used in this paper were fabricated using 80~90 points of CO_2 laser radiation with a period of 0.363~0.375 mm, which amounts to a sensor length of approximately L = 30~32 mm. A typical spectrum of one CO_2 laser-induced LPFG is presented in Figure 1. Each valley in Figure 1 corresponds to one cladding mode. Similar to a FBG, the resonant wavelength (λ_{res}) of a LPFG sensor can generally be expressed as a linear function of its grating period (Λ) and effective refractive indices of the core ($n_{eff,co}$) and the cladding mode LP0m ($n_{eff,cl,m}$) as follows [9]:

$$\lambda_{res} = (n_{eff,co} - n_{eff,cl,m})\Lambda \tag{1}$$

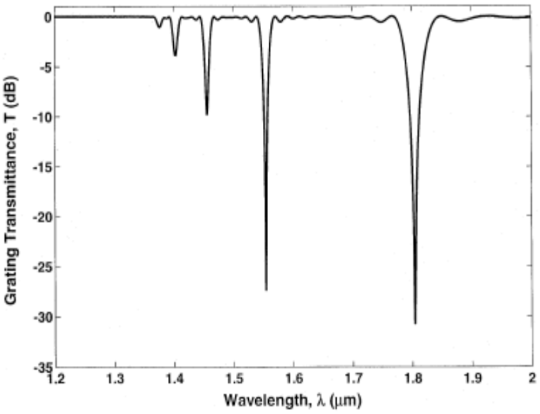

Figure 1. Representative LPFG transmission response.

Since the effective index of the cladding mode LP0m ($n_{eff,cl,m}$) depends on the refractive index of the surround mediums, the increasing of the surrounding refractive index (n_s) will bring in a corresponding increase of the effective index of the cladding, which results in the center wavelength of the cladding modes of LPFG shifting to the left. The sensitivity of the LPFG for the surrounding refractive index (n_s) could be expressed as [16]:

$$\frac{d\lambda_{res}}{dn_s} = \lambda_{res} \cdot \gamma \cdot \Gamma_s \tag{2}$$

where, γ describe the waveguide dispersion, Γ_s expresses the dependence of the grating to the surrounding refractive index and is defined by [16]. In (2), Γ_s is negative for all the cladding modes, however, γ is positive for lower cladding modes and negative for higher cladding modes and the turning point of γ is highly dependent on the resonant wavelength range [16]. A higher cladding mode results in a larger Γ_s, thus, a higher sensitivity to measure the surrounding refractive index changes. However, too high cladding mode will induce a turning point in spectrum which is undesired. Thus, in this study, LPFG with cladding modes of LP06 and LP07 have been investigated. All the two cladding modes are visible in a 400nm wavelength range. For these two cladding modes, no dual resonance will occur with the surrounding refractive index changing from 1.0 to 1.46, which is the common range for liquids.

2.2. Sensor Design

To measure the boundary between insoluble liquid layers, the sensor is expected to be robust and ease to be mobile. However, a single LPFG itself, which is made up by glass fiber with a diameter of 125 μm, is too weak to be a probe for field detection of layered liquids. To have an effective sensor to detect the layered liquids, in this paper, the sensor will consist of two components: one LPFG and one rod or tube with ruler. The material of glass or plastic can be used for the rod or tube. The LPFG is attached on the surface of the rod or outer surface of the tube to achieve a united sensing device. Figure 2 shows a schematic of the sensor device. The light from the broadband light source will go through the transmission fiber and the LPFG sensing unit. Through moving the rod/tube up and down manually, the LPFG sensor device is able to be to detect the refractive index changes of the surrounding environments and induce spectrum change of the transmitted light. As long as the boundary between liquids goes through any location of the length of the LPFG, the spectrum of the LPFG will change corresponding to the changes of refractive index between liquids. The spectrum change of the transmitted light through the LPFG, thus, will be picked up and recorded continuously using the optical spectrum analyzer. A personal computer which is connected to the optical spectrum analyzer, thus, can further analyze and plot the sensing data, which is further related to the boundary in between layers of insoluble liquids.

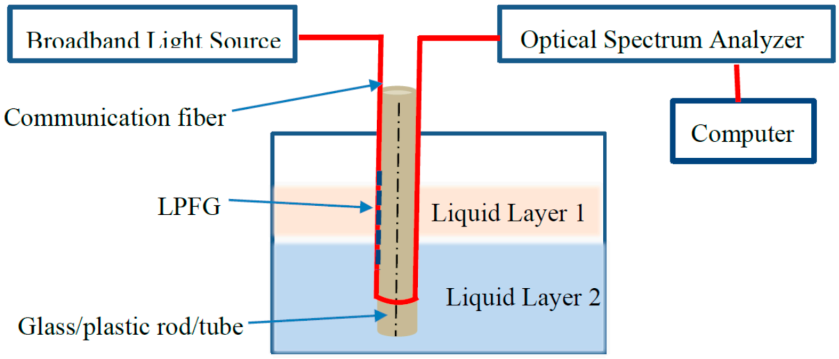

Figure 2. Schematic of the sensor device.

3. Experiments and Discussion

3.1. Experimental Setup

To validate the developed sensor device for layered liquid detection, laboratory tests were performed on the sensor using the layered liquids of Decane and water. Decane is an alkane hydrocarbon with the chemical formula $CH_3(CH_2)_8CH_3$, which is one of the components in gasoline (petroleum). Like other alkanes, it is nonpolar and therefore will not dissolve in polar liquids such as water. Its CSA number is 124-18-5. It has a density of 0.73 g/ml, a refractive index of 1.4103 to 1.4123, a melting point of

−27.9 °C, and a boiling point of 174.1 °C. Since Decane is not solvable in water (refractive index of 1.3) and has a smaller density when compared with water, when mixed with water, Decane will stay on top of water. Figure 3 (a) a photo for Decane on top of water. In this paper, the developed sensor device is used to detect the boundary between Decane and water. Figure 3 (b) shows the experimental setup for the detecting the layered liquids. The developed sensor was hold using a steel holder and placed inside a graduated cylinder. Water was added into the graduated cylinder followed by Decane. The spectrum changes of two different cladding modes of the LPFG sensor including LP06 and LP07 were recorded all the way through with the adding of various liquids.

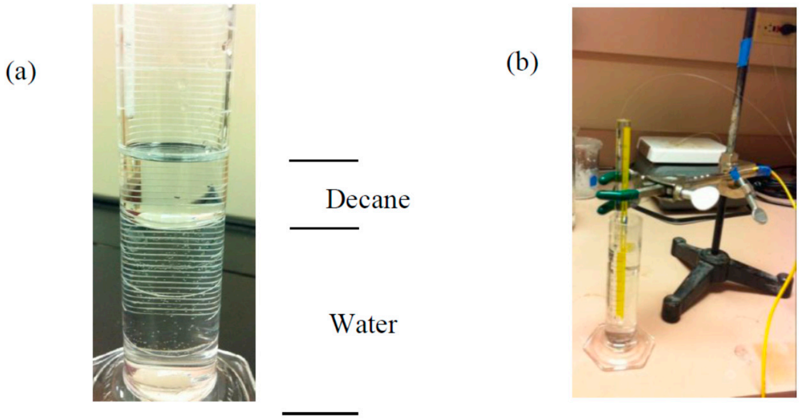

Figure 3. (**a**) Layered liquids and (**b**) **e**xperimental setup.

3.2. Experimental Results and Discussion

Figure 4 (a) is a close look at the spectrum change of LP06 with the adding of water and Decane. Figure 4 (b) shows the center wavelength changes of the LP06 with the adding of water and Decane. It can be seen that when the adding liquid was water, the center wavelength of the LP06 was gradually shifting to the left. When the liquid was changed from water to Decane, the center wavelength of the LP06 had a sudden shift from 1313 nm to1320.5 nm with a change of 2.5 nm. After the liquid change, the center wavelength returned back to a gradual change with the further adding of Decane. The boundary between water and Decane was clearly detected by the LP06 cladding mode of the developed LPFG sensor.

Figure 5 (a) shows the spectrum changes of the cladding mode of LP07 of the LPFG sensor and Figure 5 (b) shows its center wavelength changed with adding water and Decane. Similar phenomenon as LP06 was observed for LP07, however, with higher sensitivity for LP07. On the condition when only water was added, the center wavelength of LP06 shifts to left with a sloop of −0.279 nm/mm. As Decane started to add when portion of the LPFG was in water, the center wavelength of LP07 had a sudden shift from 1552.1 nm to 1549 nm, introducing a center wavelength change of 11.1 nm on the boundary between the water and the Decane. After the formation of the boundary, the center wavelength of LP07 continued shifting to left as the level of Decane increases at a rate of −0.307 nm/mm. The location of the boundary between the water and Decane was identified at 12.5 mm away from the LPFG starting point.

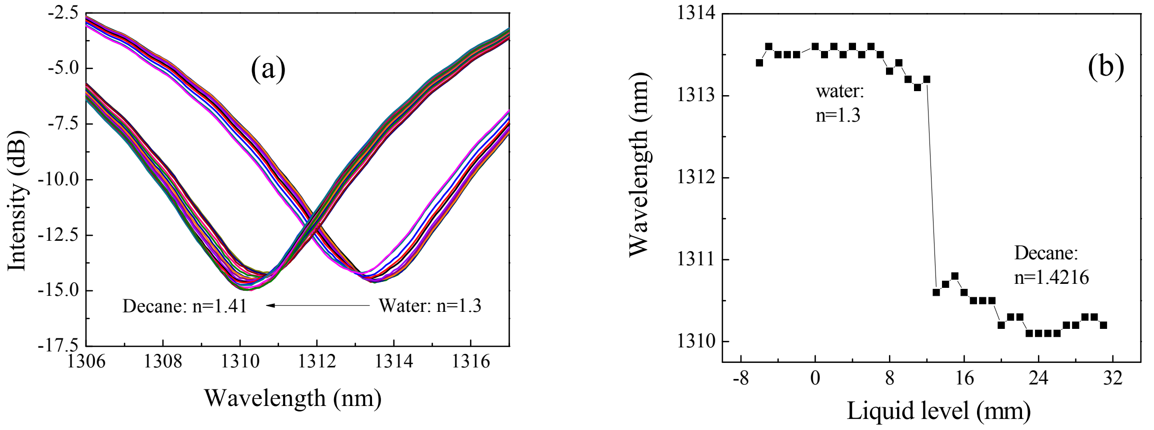

Figure 4. (**a**) Spectrum changes and (**b**) Center wavelength changes of the LP06 with adding layered liquids.

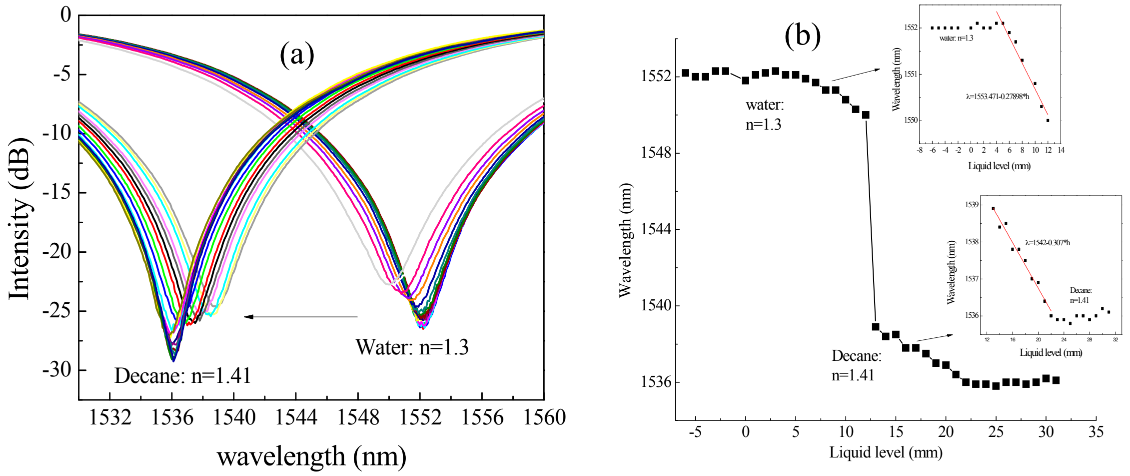

Figure 5. (**a**) Spectrum changes and (**b**) Center wavelength changes of the LP06 with adding layered liquids.

The comparison between Figures 4 and 5 indicates that a higher cladding mode of a LPFG sensor will have a higher sensitivity when detecting the layered liquids. A LP07 mode will have four times more sensitive than the LP06 mode. In addition, it is demonstrated that the developed sensor not only can detect the boundary between layered liquids but also the liquid level changes of the associated liquids at the same time, resulting in a multi-functional sensor device which could be further applied to various layered liquid detection.

4. Conclusions/Outlook

In this paper, a sensor device based on LPFG was developed to detect the boundaries between insoluble layered liquids. The sensor device was formed by attaching an LPFG on the surface of a glass or plastic rod/tube. When moving the sensor device up and down through the layered liquids, the optical spectrum and corresponding center wavelength will change with the sudden changes of the refractive index between various liquid layers. The laboratory experiments demonstrated that for water and Decane, both cladding mode LP06 and LP07 of the developed LPFG sensor device can detect the refractive index difference between layers, which was indicated by a sudden change of the LPFG's resonant wavelength if the LPFG sensor was moving through the layer boundary. The cladding mode LP07 had been demonstrated to have four times higher sensitivity towards the measurements of boundary between layers when compared to the cladding mode of LP06. Thus, it is recommended that the further study of the detection of layered liquids uses higher cladding modes. However, more tests are required to investigate the potential of identification of specific liquids in addition to identify boundaries, which is in process. More future work will also be directed to the field applications of the developed sensor device and the calibration of the sensor devices for practical applications.

Acknowledgments

Financial support to complete this study was partially provided by the U. S. DOT PHMSA under Agreement DTPH56-13-H-CAAP05. The findings and opinions expressed in the paper are those of the authors only and do not necessarily reflect the views of the sponsors.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Beutel, T.; Ferreira, N.; Leester-Schädel, M.; Büttgenbach, S. Robust pressure sensor for measurements in boundary layers of liquid fluids with medium total pressures. *Proc. SPIE 8066* **2011**, *Smart Sensors, Actuators, and MEMS V*, 80661U.
2. Infineon Technologies AG, Liquid Level Sensing Measuring Liquid Levels Using Hall Effect Sensors. Application Note, Rev. 1.0, 2009.
3. Makanjuola, N. T.; Shoewu, O. O.; Akinyemi, L. A.; Ajasa, A. A., Design and Development of Microcontroller Based Liquid Level Detector with Graphical Output. *The Pacific Journal of Science and Technology* **2015**, *16*, 173–181.
4. Kumar, B.; Rajita, G.; and Mandal, N. A Review on Capacitive-Type Sensor for Measurement of Height of Liquid Level. *Measurement and Control*, **2014**, *47*, 219–226.
5. Meribout, M.; Habli, M.; Al-Naamany, A.; and Al-Busaidi, K. A New Ultrasonic-based device for Accurate Measurement of Oil, Emulsion, and Water Levels in Oil Tanks. Proceedings of WSSEA conference 2003, paper no. 464–177, 2003.
6. Wang, A.; Gunther, M. F.; Murphy, K. A.; and Claus, R. O. Fiber-optic Liquid-level Sensor. *Sensors and Actuators A: Physical*, **1992**, *35*, 161–164.
7. Guo, T.; Zhao, Q.; Duo, Q.; Zhang, H; Xue, L.; Huang, G.; and Dong, X. Temperature-insensitive Fiber Bragg Grating Liquid-level Sensor Based on Bending Cantilever Beam. *IEEE Photonics Technology Letters*, **2005**, *17*, 2400–2402.
8. Wang, D.; Cao, M.; Li, C.; Li, D.; Chen, Y.; Xu, X.; Xu, J.; Li, Y.; Wan, Z.; and Wang, B. Fiber Bragg Grating Liquid Level Sensor with Double Pressure and Temperature Sensitivities. *Procedia Engineering*, **2011**, *15*, 704–709.

9. Ye, X. W.; Su, Y. H.; and Han, J. P. Structural Health Monitoring of Civil Infrastructure Using Optical Fiber Sensing Technology: A Comprehensive Review. *The Scientific World Journal*, **2014**, Article ID 652329, 11 pages
10. Bhatia, V. Optical fiber long period grating sensors. *Optic Letters*, **1996**, *21*, 692 – 69.
11. Khaliq, S.; James, S. W.; and Tatam, R. P. Fiber -optic liquid - level sensor using a long - period grating, *Optic Letters*, **2001**, *2*, 1224–1226.
12. Grice, S.; Zhang, W.; Sugden, K.; and Bennion, I. Liquid level sensor utilizing a long period fiber grating, *Proceedings of SPIE*, **2009**, 7212, 72120C-1.
13. Huang, Y.; Chen, B.; Chen, G.; Xiao, H.; and Khan, S. U. Simultaneous detection of liquid level and refractive index with a long-period fiber grating based sensor device, *Measurement Science and Technology*, 2013, 24(9), 095303.
14. First-sensor.com, Measuring transition points in liquids with different densities with CLC and CLW capacitive level sensors, Application note, E-11160.
15. Li, Y. J.; Wei, T.; Montoya J. A.; Saini, S. V.; Lan, X. W.; Tang, X. L.; Dong, J. H.; and Xiao, H. Measurement of CO_2 laser irradiation induced refractive index modulation in single mode fiber toward long-period fiber grating design and fabrication, *Applied Optics*, **2008**, *47*, 5296–5304.
16. Shu, X. W.; Zhang, L.; and Bennion, I. Sensitivity characteristics of long period fiber gratings, *Journal of Lightwave Technology*, **2002**, *20*, 255–266.