High Sensitivity Fiber-optic Liquid Level Sensor Using Biconical Tapered Fibers

A. Judez *, D. Leandro, R.A. Perez-Herrera, M. Galarza and M. Lopez-Amo
Universidad Pública de Navarra, Dept. of Electrical and Electronic Engineering and ISC, Campus de Arrosadia, 31006, Pamplona, Spain
**aitor.judez@unavarra.es; phone +34 948 16 9328; fax +34948 16 9720;*

Abstract: : A liquid level sensor is presented using a biconical tapered standard single-mode fiber, being its main characteristic an outstanding sensitivity for a low cost transducer. Temperature compensation is enabled with the same interrogation equipment.

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1. Introduction

Fiber optic tapers have been used for sensing since two decades ago. They are especially well suited for applications such as bioanalytical tests. A number of demonstrated sensors for these analyses have been carried out using optical fiber tapers for evaluating the biological concentrations, when samples are lower than 500µL [1]. Because of this, a volumetric compensation is desirable by means of fluid level real-time measurements, which would lead to a more exact analysis. Taking these two aspects into consideration, a desirable way to carry out bioanalytical tests could be the utilization the same type of sensors both for the concentration and for the fluid level. This strategy could lead to an integrated analysis system based on the same measuring principles and equipment.

Different classes of optical fiber fluid level sensors (FLS) have been previously investigated, such as diaphragms that incorporate fiber Bragg gratings (FBGs), quasi-distributed fibers[2], single mode fused to multimode fiber showing a sensitivity of 0.58 nm/mm in the best case [3], coded fibers for digital applications, strategies based on level estimation by means of the multipoint pressure sensors, plastic optical fibers (POFs), D-shape single-mode fibers, or structures based on Mach-Zehnder interferometers where optical fiber tapers are used to excite the cladding modes [4] among others. Likewise, these sensor systems show some drawbacks (depending on the sensor type) such as lack of robustness, complex setup, low resolution, low sensitivity, or the need of using specific and expensive equipment when distributed measurements have to be carried out.

As it was mentioned above, optical fiber tapers are structures widely used as sensors and also suitable for liquid level measurements. However, the fabrication of long waist tapers, maintaining a constant optical fiber diameter, is one of the main hitches of this technology for its use in this particular application. By means of new taper manufacturing stations such as the utilized in this work this problem is solved nowadays.

In this work, a novel, low-cost and simple fluid level optical sensor is presented and experimentally demonstrated. This sensor, based on a standard single mode optical fiber taper presents a high sensitivity to liquid level, particularly compared to other fiber optic solutions. Moreover, an interrogation technique for obtaining absolute measurements is proposed and validated. This approach is based on real-time monitoring the position of the main frequency component in the magnitude spectrum of the fast Fourier transform (FFT) [5]. These results are also compared to the collected by monitoring the phase of the FFT. In addition to this, the cross-sensitivity to temperature is also evaluated. These preliminary but promising results enable the development of high resolution sensors for real time monitoring of liquid levels.

2. Experimental set-up and principle of operation

Figure 1 illustrates the experimental setup of the proposed liquid level sensor based on a biconical tapered standard single-mode fiber. The tapered fiber was previously pre-strained and glued to a mount with a C-shape. This mount was fixed on a lineal actuator that was immersed into the liquid at a constant speed. The fabrication of the tapered fibers were done by means of the Taper Manufacturing Station, model TMS-01-0400 (3SAE), which allows to manufacture tapered fibers both single direction or bi-directional tapering with low losses and a remarkable repeatability.

In order to evaluate both the room and the liquid´s temperature, two FBGs were glued in the walls of the liquid container, one of them in the inner wall of the container and the other one in the outer wall, labelled in Fig. 1 as FBG_1 and FBG_2 respectively. The container was filled with methanol, in detail NCAS: 67-56-1, which presents a refractive index of 1.317 at 1507nm. The lineal actuator was programmed to slowly immerse the tapered fiber into the liquid at a constant speed. The sensor’s performance was measured using an optical sensor interrogator from Micron Optics (Hyperion si155). This interrogator measures simultaneously the FGBs reflected signals, and by means of the FFT of the wavelength spectrum, the taper´s response. The emitted light from the channel 2 of the interrogator passes through the tapered fiber and through an optical isolator in order to avoid reflected light at channel 2. In this manner, the transmitted response of the sensor is monitored at ch. 3.

The sensor itself consists on a standard optical fiber tapered from its nominal outer diameter of 125µm until obtaining a microwire with a uniform diameter waist of 17µm as depicted in Fig.1. The transitions between the original optical fiber and the uniform waist of the taper were abrupt with a length of 2.5mm approximately. As seen in Fig. 1, the total length of this tapered fiber was about 40mm. When a fiber taper is illuminated, the central section can transmit low confined modes which are easily altered by changes of the refractive indices of the external medium. All the modes present an exponential decreasing evanescent field as a function of the distance to the axis of the taper. When the refractive index surrounding the tapered fiber is modified, the propagation constant of the transmitted modes is altered so it is produced a “concertina effect” in the interference pattern [6]. The performance of the sensor system is shown in the following section.

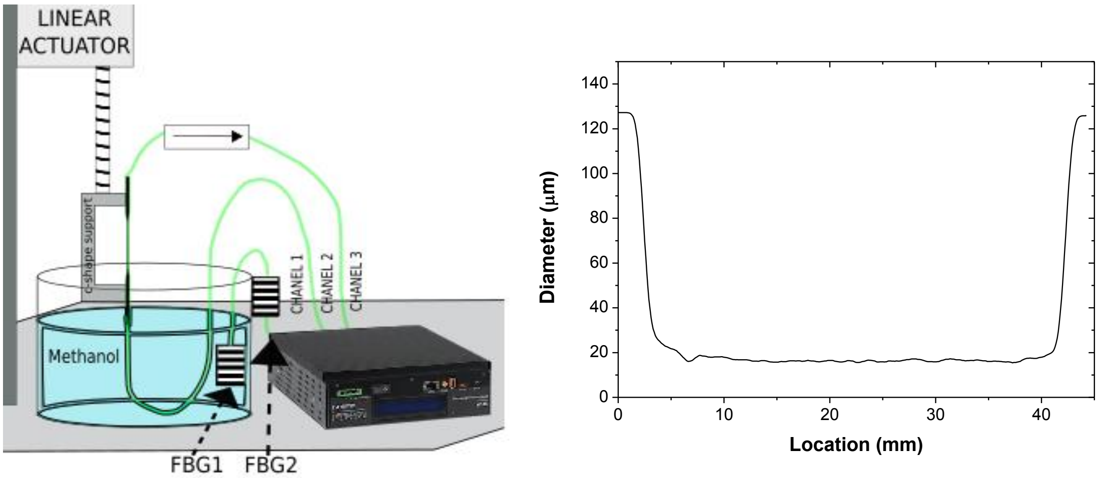

Fig. 1. (a) Experimental set up for the fiber-optic liquid level sensor and (b) the measured taper dimensions.

3. Experimental results and discussion

The optical spectrum given by the tapered fiber can be seen in Fig. 2(a). It shows a multi-frequency interference, with one main and two secondary components located at the spatial frequencies 0.11, 0.2 and 0.32 nm^{-1} respectively. These contributions are clearly seen using the fast Fourier transform representation of the spectrum, displayed in Fig. 2(b).

In order to evaluate the behavior of the sensor as liquid-level sensor, several tests have been carried out. Initially, the tapered fiber was gradually immersed in methanol to evaluate the sensitivity of sensor to the level of liquid. During the immersion, a large phase displacement is observed in the optical spectrum. To evaluate this effect, it is monitored the phase of the FFT at the spatial frequency of the main component as in [7], instead of measuring a shift of a peak (or a valley) in the spectrum. As a consequence, the measuring process is simplified and offers a higher resolution than conventional techniques.

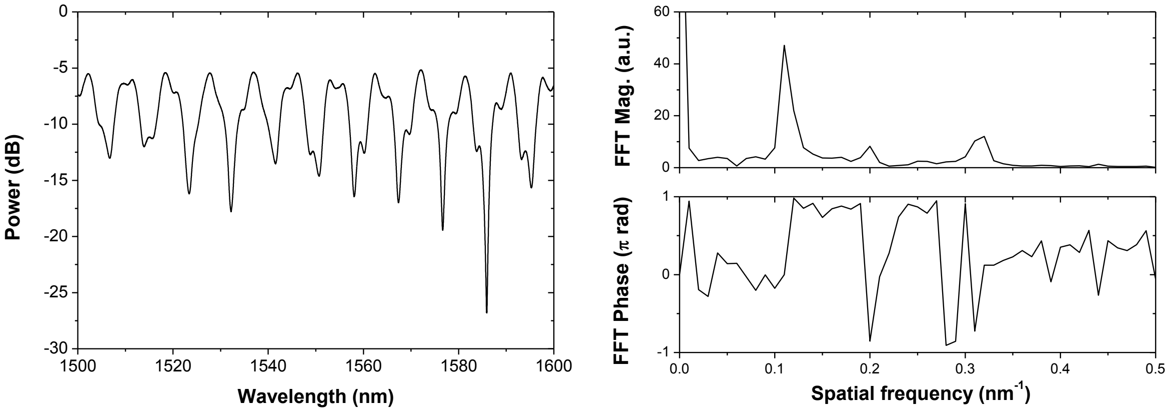

Fig.2. (a) Spectral response in transmission of the proposed sensor and (b) its fast Fourier transform (magnitude and phase).

The FFT phase of the peak of the main component is depicted in Fig. 3(a) versus the depth of the immersion. The sensor presents a linear response with a sensitivity of -1.662 rad/mm with a fitting error R^2=0.999. This sensitivity (equivalently 2.4 nm/mm) is outstanding compared to other fiber optic liquid-level sensors. It should be said that the main limitation of using the FFT phase for the measuring process is that the dynamic range is ideally limited between $\pm \pi$. However, this problem has been straightforwardly handled by software if the interrogation frequency is fast enough compared to the measurand variations. In addition, interferometric sensors present another limitation, which is that they are generally limited to relative measurements. This is due to the fact that the measuring process is phase-based (in the optical or in the FFT spectra) and measurements are referred to an initial position. To avoid this limitation, it is proposed in this work a solution employing the position of the peak in the FFT magnitude spectrum.

The phase change measured is actually generated by a slight change in the period of the interference. That change is generally small and almost indiscernible in a single period of the optical spectrum. It is then necessary to compare the accumulative variation in a high number of periods [8]. However this is not straightforward if the interference consists of several frequency components, as in this work. To overcome this limitation, the position of the main component peak in the magnitude spectrum can be monitored. This effect is evidenced in Fig.3(b) where the FFT magnitude is displayed for three different sensor positions (sensor fully, half and no immersed). Even though the spatial frequency resolution is low (0.01 nm^{-1}), the adjacent samples can be tracked to calculate the centroid and derive a precise position of the peak. In this manner, the centroid position represents the value of the average interference period during the tests. The results of the peak position variation versus the immersed length of the sensor are depicted in Fig. 4(a). It can be seen that the system behaves linearly with a sensitivity of $3.16\times10^4 nm^1/mm$ and a fitting error R^2=0.997. These results validate this alternative measurement technique which offers an absolute value of the measurand at the cost of lower resolution. It should be noticed that the reliability of this technique is directly linked to the sensitivity of the sensor. I.e. this approach can be successfully employed due to the high sensitivity of the tapered fiber to the liquid level. It should be observed that the secondary peaks in the FFT spectra present double and triple sensitivity and can also serve for the interrogation, but with an increased noise due to the smaller amplitude of the component.

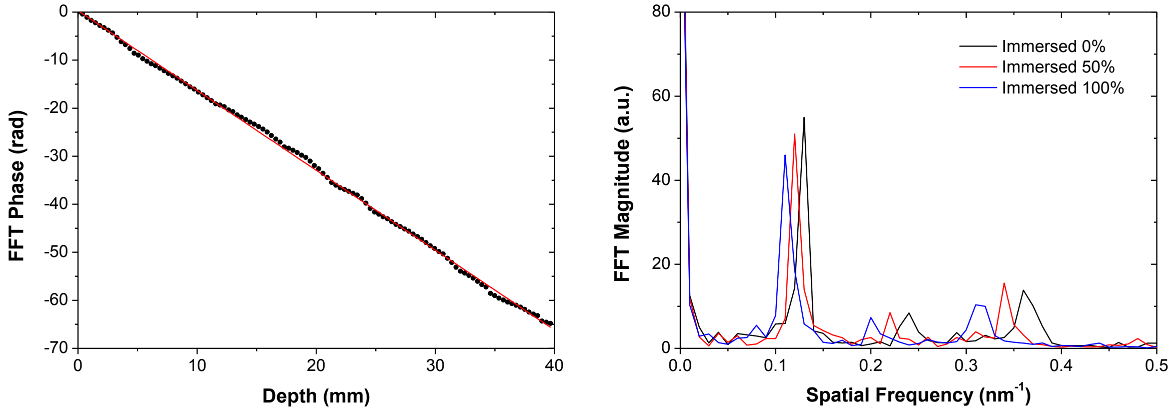

Fig.3. a) FFT phase at the main component versus depth of the immersion b) FFT Magnitude traces for different immersion depths.

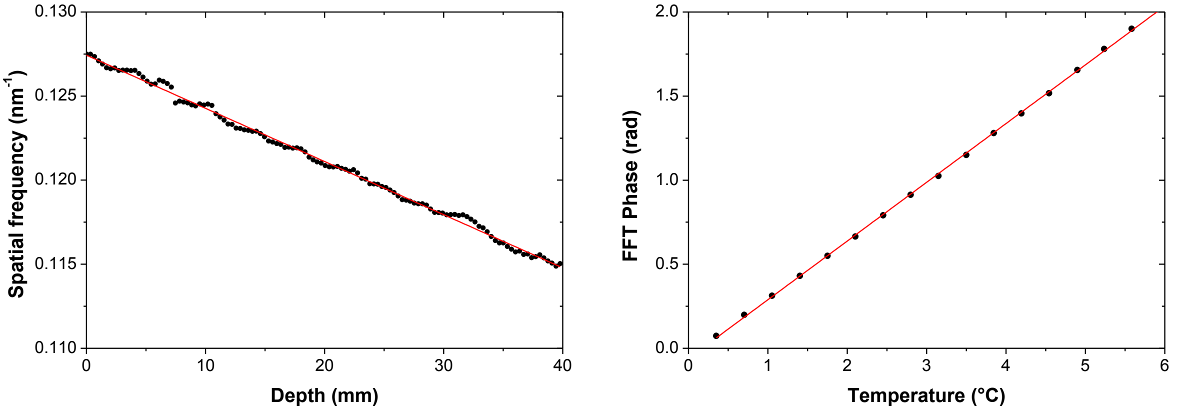

Fig.4. a) Spatial frequency position of the main frequency component versus immersion depth and b) FFT phase versus temperature.

As an important aspect to be considered, the cross-sensitivity of the sensor to temperature variations has been analyzed. Typically, temperature-compensation should be done to obtain a reliable value of liquid level. To evaluate the effect of temperature in the level measurements, the sensitivity of the tapered fiber to temperature has been evaluated. Figure 4(b) shows the phase variation in the FFT for a temperature change of 6°C. As expected, the phase varies linearly with temperature showing a sensitivity of 0.349 rad/°C and a fitting error R^2=0.999. This temperature sensitivity is low compared to the variation induced by the immersion depth. Thus, a temperature variation of 4.75°C generates an uncertainty of 1 mm in the level value. Consequently, high-resolution measurements are expected to be obtained after a proper temperature compensation; further work is being done is this regard. Finally, a stability analysis of the system has been carried out by monitoring the stationary sensor response and compensating the temperature tendency given by the FBGs set in the setup (Fig. 1). The errors induced in the measurement by the instabilities of the two methods (FFT phase and the position of the peak in the FFT magnitude) are approximately 0.3µm and 0.31 mm respectively. These values evidence the superior resolution of the FFT phase technique, at the cost of producing relative measurements and having some restraints in the dynamic range. Research is being done to improve the data treatment and improve the accuracy of the centroid calculation.

4. Conclusions

A biconical tapered single-mode fiber has been proposed and evaluated in real-time as liquid-level sensor, showing a high sensitivity for a measurement range of 4 cm. The sensor behavior has been analyzed in the Fourier transform domain, showing a sensitivity of -1.662 rad/mm in the FFT phase. Additionally, it has been proposed an alternative interrogation method to obtain absolute measurements in multi-frequency interferometers. This technique evaluates the centroid of a frequency component in the FFT magnitude spectrum and evaluates its position. In this manner, the position of the magnitude peak is directly related with the sensor reading in absolute terms. This approach has been validated obtaining a sensitivity of $-3.16\times10^4 nm^1/mm$. Finally, the cross-sensitivity of liquid-level to temperature has been evaluated, presenting 1 mm level uncertainty every 4.75°C.

The high sensitivity offered by this preliminary study, in combination with the FFT measuring process and an adequate temperature compensation could be potentially employed for obtaining high-resolution liquid-level measurements. Further work is being done in this respect, in particular in the design of longer tapered fibers with higher sensitivity. Moreover, the improvement of simple post-processing in the FFT domain could lead to absolute high-resolution results. In addition, the use of uncorrelated temperature/level sensitivities is being analyzed to achieve temperature compensation.

5. Acknowledgements

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