Continuous Liquid Level Sensor Based on a Long Period Grating and Microwave Photonics Filtering Techniques

Amelia L. Ricchiuti, David Barrera, Aitor Urrutia, Javier Goicoechea, Francisco J. Arregui and Salvador Sales

Abstract—A fiber optic liquid level sensor based on a long period grating (LPG) is proposed and experimentally validated. The principle of operation is based on a technique used to analyze microwave photonics (MWP) filters. A 4 cm-long LPG cascaded with a high-reflectivity fiber Bragg grating (FBG) are employed to achieve a continuous liquid level sensor. The measurements have been performed using a modulator and a photo-detector (PD) with a modest bandwidth of less than 500 MHz, showing a sensitivity of -12.71 dB/cm and a standard deviation of 0.52 dB. One of the significant advantages of such sensing structure is that it is based on low bandwidth radio-frequency (RF) and off-the-shelf photonic components. Also, the simple proposed scheme presents good repeatable performance and proves to be intrinsically robust against environmental changes, stable and easy to reconfigure.

Index Terms—Fiber optic sensors, liquid level sensors, long period gratings, microwave photonics filters, continuous sensors.

I. INTRODUCTION

LIQUID level sensing is an indispensable requirement in many commercial and industrial applications in which monitoring the liquid's volume is necessary, such as biochemical processing, fuel storage and transportation. Electrical liquid level sensors are widely used in practice, but their applicability, reliability, and safety are compromised if the liquid to be monitored is conductive or corrosive or if the environment is potentially explosive. Moreover, in case of multiple electrical sensors, it is required intensive wiring, and feed-through, unavoidably increasing the system cost and

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complexity. In particular, liquid level sensing of flammable fluids is one specific implementation where optical fibers are well suited since they do not require electrical signals to sense the liquid. Also, optical fiber liquid level sensors offer better performance under these rigorous conditions due to their advantages of several technical merits, such as compactness, ease of multiplexing and remote sensing, cost-effective and high sensitivity. Furthermore, optical fiber sensors are inherently dielectric and thus no-conducting, immune to electromagnetic interference (EMI), chemically inert and spark free [1].

In recent years, fiber optic sensors based on long period gratings (LPGs) have attracted growing interests due to the fact that they are able to measure various physical parameters, such as refractive index (RI), temperature, strain, bending and liquid level, amongst others. Different kinds of liquid level sensors based on such a fiber gratings have been proposed and demonstrated. For instance, in [2] a simple solution for liquid level sensing based on a single LPG was illustrated. The measurement of the liquid level was performed by evaluating the changes in the transmission spectrum of the LPG by means of an optical spectrum analyzer (OSA). Moreover, in [3] two identical LPGs were cascaded to form a Mach-Zehnder interferometer (MZI), in order to improve both measurement range and sensitivity. The part between the LPGs was interrogated by means of a broadband source (BBS) and an OSA. In this way, the measurement was obtained by retrieving the shifts in the interference fringes of the transmission spectrum of the MZI. Also, in [4] a Michelson interferometer was fabricated by employing a LPG and by silvering the end facet of the fiber, in order to create a reflective mirror. The portion between the LPG and the reflective mirror was exposed to the liquid. Here too, a BBS together with an OSA was used and the changes in the interference fringes were monitored, showing good linearity and high sensitivity.

Analogously, excessively tilted grating structures have been investigated, presenting a mode coupling behavior similar to that observed for a LPG, and have been employed as liquid level sensors [5,6]. In this context, liquid level measurements have been performed by examining the optical spectra of such structures by the use of a BBS and an OSA, showing lower temperature cross sensitivity than the LPG based liquid level sensors. However, the manufacturing of excessively tilted

gratings results a complicated issue when compared with the more approachable LPGs fabrication process. Besides, in the context of optical sensing, the analysis of the evolution with wavelength of differential group delay in uniform gratings has been reported with the purpose to realize customized gratings for sensor applications [7].

In this contribution, an approach for interrogating a LPG-based liquid level sensor is proposed and validated via experiments. The fundamental concept behind the proposed method is based on the RI sensitivity of the LPG together with a technique used to analyze microwave photonics (MWP) filters. This is, to the best of our knowledge, the first demonstration of a LPG sensor interrogated with a radio-frequency (RF) based method. MWP is a discipline which collects together the field of microwave engineering with optoelectronics, relying on the interaction between microwave or millimeter waves with optical wave signals. Both microwave and optoelectronics obey to the same electromagnetic laws, presenting common features but also significant differences. In microwave domain, due to the large wavelength of microwave, construction of an interferometer does not require a precision as high as that needed by an optical interferometer. Moreover, microwave interference can be more easily resolved than the optical interference in which the detecting devices are not fast enough to follow the very high optical frequency. This emerging field has attracted great interest in the last decades not only from both the research communities but also from the commercial sector, leading to new possibilities in a variety of application fields such as radar, communications, sensor systems or instrumentation [8-12]. The approach reported here presents the advantages of all-fiber sensors based on LPG together with the advantages of using microwave rather than optical interferences [9-11]. First, the proposed sensor is fabricated using commercial fiber and well-established grating photo-inscription method; second, the sensor results robust since no tapering, etching or metal deposition have been made on the LPG. Third, relying on MWP interferometry and working under incoherent regime operation, the configuration is intrinsically robust against environmental changes, stable, with good repeatable performance and easy to reconfigure. Finally, the liquid level measurements are performed by using RF devices, i.e. modulator and photo-detector (PD), with a modest bandwidth of only 500 MHz and without using any wavelength scanned system, such as OSAs.

II. DESCRIPTION OF THE METHOD

The fundamental concept beyond the proposed technique is inspired on the principle of operation of a MWP filter as schematically depicted in Fig. 1 [11]. The output of a continuous wave (CW) light source is electro-optically modulated with a microwave signal. At the output of the electro-optical modulator (EOM), the modulated optical signal is split into N arms. Each arm has a delay-line and an attenuator (or amplifier) in order to provide a delayed and weighted replica of the original signal. These time-delayed and weighted optical signals are combined together and photo-

detected. In the detection process, the different taps can be mixed according to either a coherent or an incoherent basis. In case of incoherent mixing, the tap combination at the PD is insensitive to environmental effects, stable and with a remarkably good repeatable performance. For these reasons, the experimental setup proposed has been implemented under incoherent operation. The microwave signal is acquired and the electrical frequency response $H(\Omega)$ of such a structure is given by [10]

$$H(\Omega) = \sum_{k=0}^{N} a_k e^{-j\Omega T_k} \tag{1}$$

being Ω the angular frequency and a_k the weight of the k-th replica delayed by T_k. In the sensing configuration proposed here, a two-tap MWP filter is presented for liquid level measurements, based on a LPG. In this case, (1) identifies a transfer function with a periodic spectral characteristic; the frequency period is known as free spectral range (FSR) and it is inversely proportional to the spacing T between taps [10].
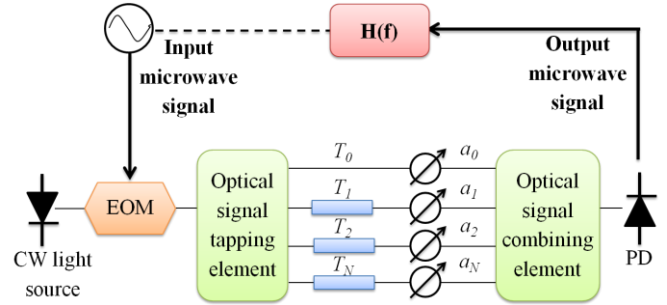

Fig. 1. Schematic diagram representing a N tap MWP filter configuration.

A LPG is an optical fiber device consisting of a periodic modulation of the RI in the fiber core, with the period (Λ) of hundreds of micrometers. Such a structure couples core modes to the cladding modes at different resonant wavelengths (λ_i), resulting in several attenuation bands in the LPG transmission spectra. According to the coupled mode theory, the phase matching condition depends on the difference in the effective RI of the core and cladding modes and on the LPG period [13]

$$\lambda_i = (n_{co\_eff} - n_{cl\_eff,i})\Lambda \tag{2}$$

where n_{co_eff} is the effective RI of the core mode, while $n_{cl\_eff,i}$ is the effective RI of the i-th order cladding mode. This way, when the external environment surrounding the LPG varies (i.e. the RI varies due to changes in the liquid level), the phase matching conditions (i.e. the resonance wavelength) also change. Hence, taking advantages from this RI sensitivity of the LPG, liquid level measurements can be performed.

The experimental setup of the liquid level sensing system is illustrated in Fig. 2. The signal from a CW tunable laser source (TLS1) is mixed with the signal provided by another CW tunable laser source (TLS2), by means of a 3-dB coupler.

Two polarization controllers (PCs) are placed after the optical sources to enhance the modulation efficiency. The signal from the 3-dB coupler is sent into an EOM and hence modulated with a microwave tone (10 MHz - 500 MHz) generated by a vector network analyzer (VNA). The modulated signal is sent into the sensing device through an optical circulator. The sensing device consists in a 4 cm-long LPG having periodicity of 464 μm, written in cascade with a 1 cm-long high reflectivity fiber Bragg grating (FBG). The signal from the TLS1 is set at the Bragg wavelength of the high reflectivity grating, while the signal provided by the TLS2 is set at one of the wavelength resonance of the LPG. In this way, these two signals will travel along two different optical paths. The modulated lightwave at the Bragg resonance will pass through the LPG, before to be reflected from the FBG and then reach the port 3 of the optical circulator (green path, L_1 in Fig. 2). Here a variable optical attenuator (VOA) is placed to control the magnitude of the Bragg reflected signal, in order to make it match as much as possible the weight of the tap related to the LPG. This is a key step for achieving a high visibility of the two-tap MWP filter (i.e. notch filter). On the other hand, the signal at the LPG resonance will pass through the two gratings (red path, L_2); when crossing the LPG this signal will experience a huge attenuation. Finally, the light components from the two different optical paths are combined together and photo-detected. The frequency response of the system is analyzed by monitoring the scattering parameter S_{21}, which relates the RF detected signal to the input modulating microwave signal. By analyzing the amplitude changes in the frequency response of the two-tap MWP filter so created, the liquid level can be retrieved as will be better explained in the following section.
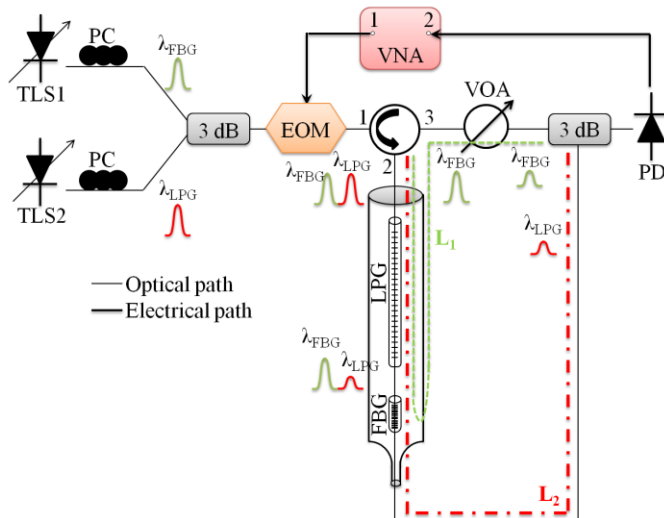

Fig. 2. Experimental layout implemented to interrogate the LPG-based liquid level sensor. The operation principle is based on a technique used to analyze MWP filters.

III. EXPERIMENTAL MEASUREMENTS AND RESULTS

To perform the liquid level measurements, the optical fiber containing the pair LPG-FBG is passed through the nozzle of a syringe and mounted in such a way that the LPG lay within a graduated region, as seen in Fig. 3. During the experiment, the liquid level is controlled with the aid of another syringe. The liquid used in the experimental measurements is water.

The FBG fabricated in cascade with the sensing LPG has a dual purpose: the first function is to provide a second tap and hence allowing the formation of the two-tap MWP filter. The second function is the liquid temperature detection: this is used to compensate the temperature influence on the LPG wavelength shift and will be described afterwards.
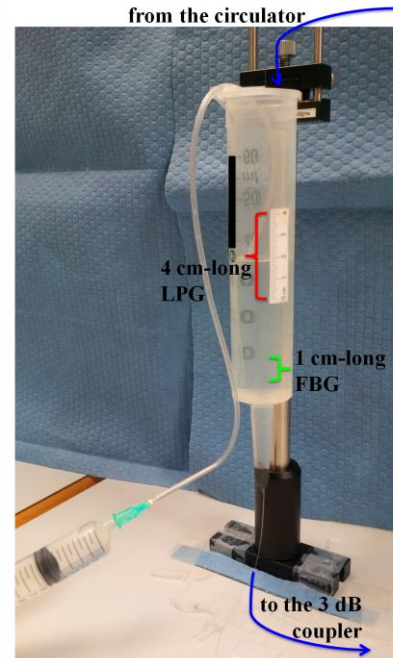

Fig. 3. Picture representing the optical fiber containing the pair LPG-FBG used as liquid level sensor. The fiber is passed through the nozzle of a syringe.

Once the liquid is surrounding the sensor, the first step is the tuning of the TLS1 at the FBG resonance, as described in Fig. 4, while the other laser is kept off. When the TLS1 is step-wise scanned, the relation between the laser wavelength and the FBG resonance can be described as follows: Fig. 4(a) and Fig. 4(e) illustrate the case in which the laser wavelength is far from the FBG central resonance. In such a case, the signal passes through the grating following the optical path L_2, reaching the coupler and then the PD. This tap is photo-detected and a continuous amplitude signal is displayed at the VNA. The case in which the laser wavelength is close to the FBG resonance but just below (above) the FBG central wavelength is illustrated in Fig. 4(b) (Fig. 4(d)). Under these circumstances, part of the laser signal is back-scattered by the grating while the other part passes through the FBG. These two taps follow different optical paths before being re-combined at the 3-dB coupler and then photo-detected. These components of the same laser signal are mixed under coherent basis: this is because the delay between the taps is smaller than the source coherence time [11]. As a consequence, an interference "noisy" trace is displayed at the VNA. In the last case, when the laser wavelength is set at the FBG central resonance, as depicted in Fig. 4(c), this signal is entirely back-reflected by the grating and then reaches the coupler following

the optical path L_1. Hence, a continuous line is visualized at the VNA. Following this procedure, the signal from the TLS1 is set at the Bragg resonance of the FBG. As the Bragg resonance of the FBG has been previously characterized at room temperature of 20ºC, resulting in 1532.8 nm, and taking into account the FBG temperature coefficient, which is 10 pm/ºC, the liquid temperature can be calculated.
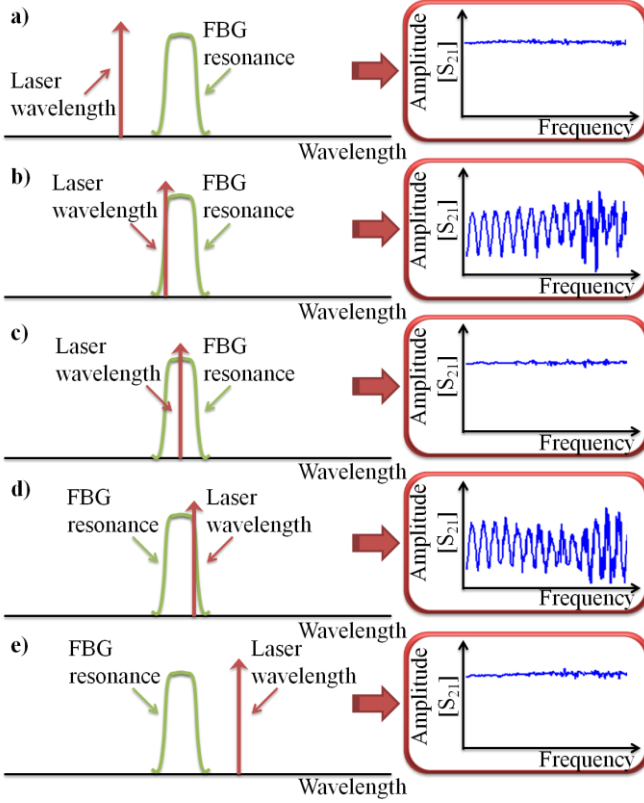

Fig. 4. Schematic representing the wavelength tuning of TLS1 at the FBG resonance. (a) and (e) The laser wavelength is far from the FGB resonance: this signal completely passes through the FBG and hence a continuous line is visualized at the VNA. (b) and (d) The laser wavelength is close to the FBG resonance: part of the light is back-reflected while the other part passes through the FBG, as a result an interference signal is displayed at the VNA. (c) The laser wavelength is set at the FBG central resonance: the signal is completely back-reflected and a line is displayed at the VNA.

Now, the wavelength of the TLS2 is adjusted at the LPG resonance and the magnitude of the tap related to the FBG reflection is opportunely set via VOA (see Fig. 2) in order to match as much as possible the magnitude of the tap at the LPG resonance. This is because by achieving equal amplitudes of the two taps, a large MWP filter visibility is obtained [10]. The liquid level measurements are performed by tracking the changes in the MWP filter visibility, therefore in order to get better accuracy, the number of "dips" of the MWP filter can be suitably controlled by setting the FSR of the MWP filter. This periodic spectral characteristic is inversely proportional to the time spacing T between taps, according to [10,11]

$$FSR = \frac{1}{T} = \frac{c}{n_g \, |L_1 - L_2|} \qquad (3)$$

where n_g is the group refractive index of the fiber and c is the speed of light in vacuum. According to (3), the FSR of the two-tap MWP filter (and hence the number of dips) can be opportunely chosen by tailoring the difference between optical paths $|L_1 - L_2|$.
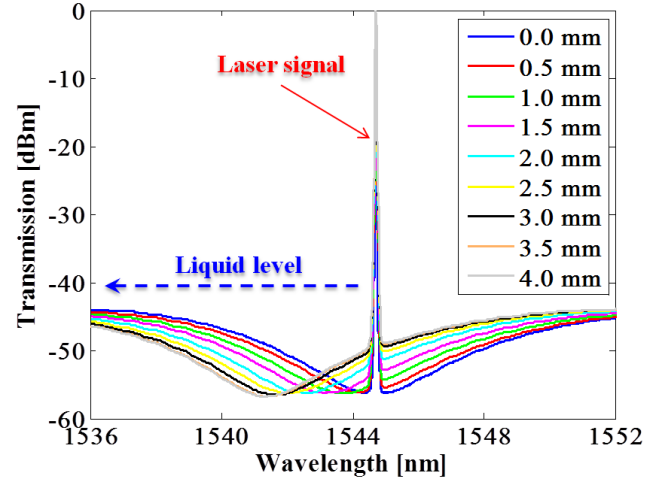

Fig. 5. Measured spectra representing the LPG resonance shift for different values of liquid level. Measurements performed using water.

When the liquid level increases, the LPG resonance shifts towards lower wavelengths as measured and shown in Fig. 5. This shift represents the same behavior corroborated in other works, such as [14]. When this occurs, the magnitude of the tap related to the LPG, grows causing a gradual imbalance between the amplitudes of the two taps of the MWP filter. This intensity imbalance causes, in turn, a stepwise reduction of the MWP filter visibility, as shown in Fig. 6. By monitoring the latter, the measurement of the liquid level can be achieved. For each liquid level, the values of the 21 dips represented in Fig. 6 have been averaged in order to obtain the relationship between the MWP filter visibility and the liquid level.
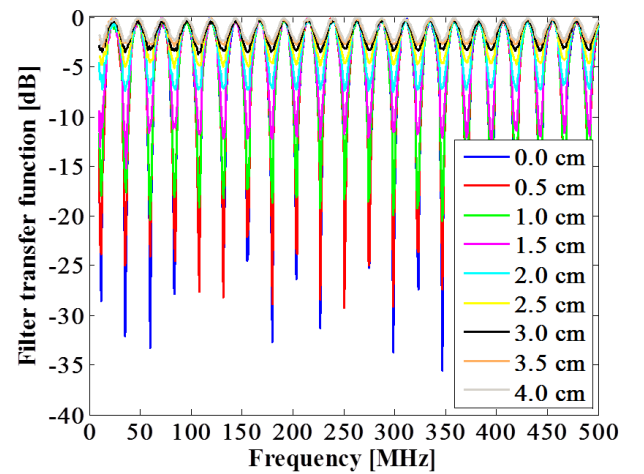

Fig. 6. Two-tap MWP filters obtained for different values of liquid level. When the liquid level increases the notch filter visibility decreases.

Several sets of experimental data have been collected in order to show how good the stability and repeatability of the sensor are. The relationship between the MWP filter visibility

and the liquid level at the sensor is depicted in Fig. 7, from which it is possible to see as the notch amplitude decreases near exponentially with the liquid level. Furthermore, the inset in Fig. 7 proves that the continuous liquid level sensor proposed has very good performance in terms of stability and repeatability, with a measured standard deviation of 0.52 dB. The measurements in Fig. 7 also show a quasi-linear range in the initial region of the liquid level sensor, yielding a sensitivity of -12.71 dB/cm.
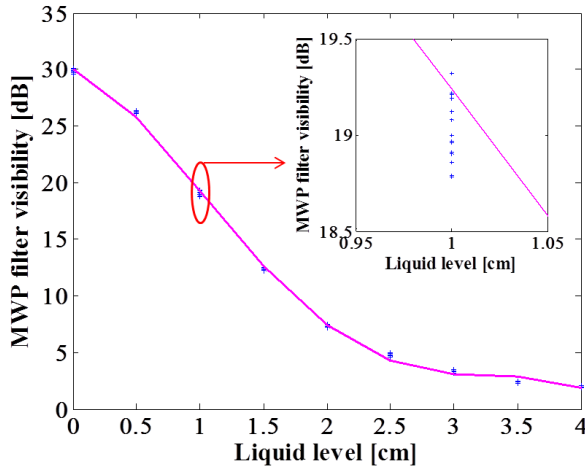

Fig. 7. Relationship between the MWP filter visibility and the liquid level. Inset: Zoom representing the measurements collected for a given liquid level. The set of data shows that the sensor has good stability and repeatability.

Also, a set of simulations has been performed and compared to the experimental data in order to prove the feasibility of the method. The simulations have been implemented for different values of liquid level; the simulated (yellow dashed lines) and measured (blue continuous lines) MWP filter responses for liquid level of 0 cm, 2 cm and 4 cm are represented in Fig. 8(a), Fig. 8(b) and Fig. 8(c), respectively.

These latter graphics show that the experimental results are consistent with the theoretical simulations, proving the feasibility of the pair FBG-LPG as a continuous liquid level sensor.

Besides, it is worth noticing that if the temperature of the liquid is different from the room temperature, this provokes a further wavelength shift of the LPG resonance. However, as previous mentioned, the temperature of the liquid is evaluated by the step-wise tuning of the TLS1 wavelength at the FBG resonance (which is shifted due to the liquid temperature change). Once the temperature of the liquid is known and based on the LPG temperature coefficient, the temperature influence on the LPG wavelength shift can be compensated by setting the signal provided by the TLS2 at the new LPG resonance. This way, once the TLS1 wavelength is set at the FBG resonance and the TLS2 is set at the LPG resonance, the two-tap MWP filters are retrieved for different liquid levels and the measurements are performed using the procedure described above. Experiments have been performed by changing the temperature of the liquid with respect to the room temperature; the measurements show repetitive results when compared with those illustrated in Fig. 6 and Fig. 7.
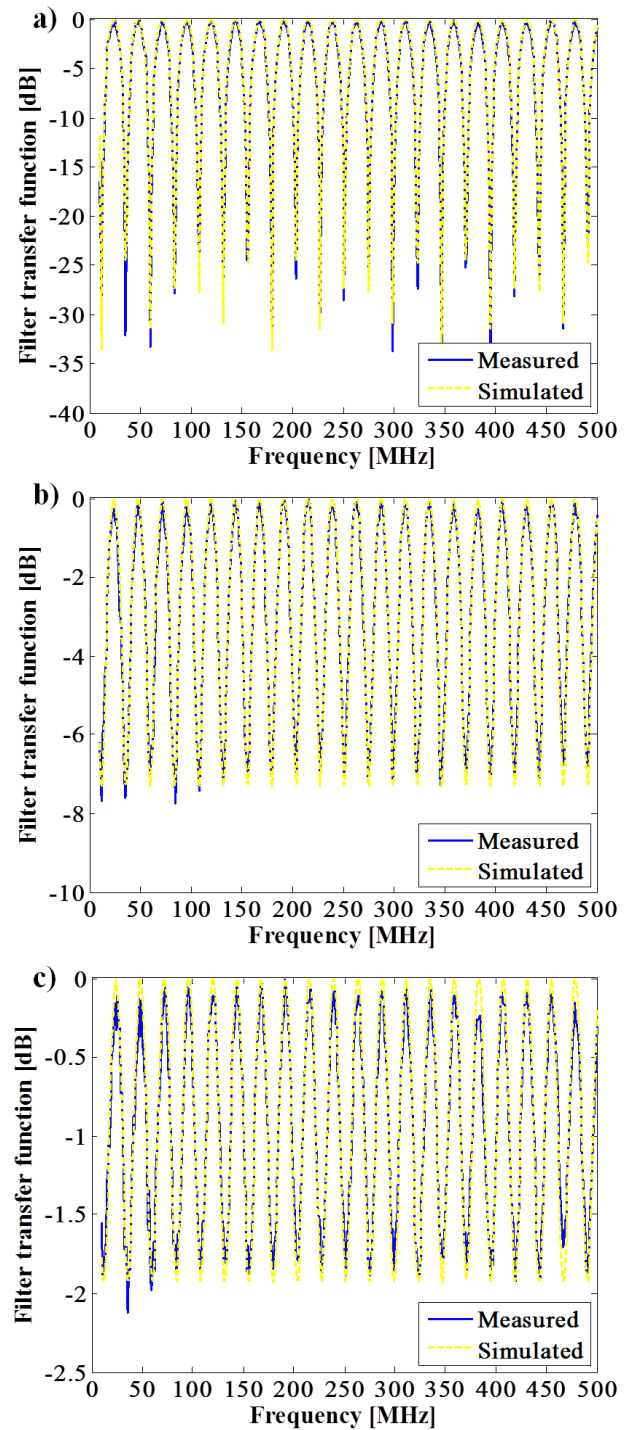

Fig. 8. Simulated and measured MWP filter responses obtained for different values of liquid level: (a) 0 cm. (b) 2 cm. (c) 4 cm.

IV. CONCLUSIONS

A new scheme of fiber optic liquid level sensor based on a LPG and MWP filtering technique has been proposed and experimentally validated. The measurement system is based on the principle of operation of a MWP filter, in particular on the measurement of the amplitude of the electrical S_{21} scattering parameter that characterizes the filter transfer function. A simple layout is used to interrogate a 4 cm-long

LPG, written in cascade with a high reflectivity FBG. The latter has the important function of allowing the measure of the liquid temperature, which is used to compensate the temperature influence on the LPG wavelength shift. The fundamental concept behind the proposed method is based on the RI sensitivity of the LPG. This is, to the best of our knowledge, the first demonstration of a LPG sensor interrogated with a RF based scheme. In fact, the liquid level measurements have been performed by using RF devices, i.e. EOM and PD, with a modest bandwidth of only 500 MHz, without using any wavelength scanned system. The approach presents the advantages of fiber optic sensors together with the advantages of using a photonic-assisted technique.

The sensing features of the LPG-based liquid level sensor have been theoretically and experimentally validated, proving that all measured data are consistent with the theoretical simulations. Several sets of experimental measurements have been collected in order to prove the stability and repeatability of the LPG based sensor. The liquid level measurements have been performed by tracking the changes in the MWP filter visibility, yielding a sensitivity of -12.71 dB/cm and a standard deviation of 0.52 dB. The measurement range of 4 cm is limited by the physical length of the LPG but it may certainly be enhanced by fabricating a longer grating. Moreover, although the use of a VNA may enhance the system complexity and expense, the instrumentation required could be simplified by replacing the VNA with an oscillator and a device able to analyze the magnitude response of the MWP filter generated. Besides, the FSR of the two-tap MWP filter can be suitably chosen by opportunely tailoring the optical path difference of the configuration. By judiciously selecting an appropriate value for the FSR, the operating frequency range of the system can be further reduced below the 500 MHz. This will lower the system cost and complexity and also improve the interrogation speed. Indeed, as the RF tone is swept up to only 500 MHz, the measurement currently takes a couple of seconds. The measurement speed is principally dictated by the RF tone sweeping and hence can be improved by lowering the operating frequency range.

The proposed continuous liquid level sensor presents the advantages of easy and well-established fabrication procedure, good repeatability and stability. Furthermore, the simple scheme investigated proves to be intrinsically robust against environmental changes and easy to reconfigure, and hence results as a very good candidate for several commercial and industrial applications.

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