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Chipless Liquid Sensing Using a Slotted Cylindrical Resonator

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***Abstract*—A method for the wireless sensing of the permittivity and level of liquids is presented. The use of a simple, thin-film slotted cylindrical cavity wrapped around a standard polytetrafluoroethylene pipe is proposed. Wireless interrogation of the slot excites a resonant mode whose frequency is dependent on the liquid currently present within the pipe. The proposed method allows for measurements to be taken *in situ* with no requirement for taking samples of potentially hazardous liquids. The device is capable of sensing materials of high relative permittivity, including water, as well as very lossy liquids. A comprehensive set of results is presented, including measurements of butanol, ethanol, methanol and water, for several device configurations. The proposed sensor is also shown to be sensitive to small changes in liquid level, allowing for accurate water level measurements down to 0.1 ml. This sensor is a good candidate for very low-cost, low-complexity real-time monitoring of liquids.**

***Index Terms*—microwave sensors; microwave measurements; resonant frequency; chipless; liquids; level measurement.**

I. Introduction

The use of sensing techniques has grown rapidly over the past decade, with material characterisation gaining ever increasing interest. A wide variety of applications seek to make use of low-profile, low-cost sensors for the accurate analysis of material samples, or even for real-time monitoring. Many chemicals are hazardous to some degree, and so it follows that wireless monitoring is beneficial for potentially unsafe work environments. The majority of devices available today use resonant techniques to characterise samples, [3]-[6], where active configurations can provide higher accuracy [5]. An extensive review of radio-frequency and (RF) microwave techniques for the measurement of liquids is carried out by Gregory and Clarke in [1], with a particular focus on methods of high accuracy.

In [2], Morales et al. propose a substrate-integrated waveguide (SIW) resonant cavity, as well as an epsilon-near-zero (ENZ) tunnel, for use as chipless RF identification (RFID) sensors. The authors present analysis of both sensors, along with results of complex permittivity measurements. The sensors are further used in [3], where they are incorporated into a measurement system, using two pairs of cross-polarised antennas for the wireless interrogation of the liquid under test (LUT). In [4], a chipless RFID tag is proposed. The authors design a resonant parallel LC circuit tag, coupled to a secondary receiver coil. Liquid is assessed *in situ* in [5], where a small capillary tube filled with liquid is positioned a short distance above a microstrip resonator. The performance of the proposed design in [5] is improved in an active configuration. The authors in [6] similarly sense liquids without the need for samples, incorporating a small polytetrafluoroethylene (PTFE) pipe within a resonant double split ring structure. A high-frequency planar resonator is proposed in [7], featuring a microfluidic channel crossing a coplanar resonant structure. In [8], another planar resonator is proposed, using a double-sided split-ring structure capable of measuring liquid mixtures to a good degree of accuracy.

Some sensors have been designed for specific purposes other than the measurement of permittivity. A cylindrical cavity resonator is utilised in [9] to measure the temperature dependency of liquids inside a plexiglass tube using a power amplifier to dynamically heat the LUT. The sensing of humidity was achieved *via* two quarter-mode SIW resonators in [10], where an array of air holes allowed moisture into the resonant structure resulting in a change in the resonant frequency. In [11], RFID sensors were designed to detect the level of water within a plastic container. Liquid solutions were assessed in [12], where the response of a tuned rectangular waveguide cavity was used to determine concentrations of salt and sucrose within water.

This paper is a comprehensive extension of previous work carried out in [13], where only simulated results were presented. The work used an unplasticised polyvinyl chloride (uPVC) pipe of a larger radius, but was unable to produce experimental results. This work instead makes use of a PTFE pipe of a smaller radius, resulting in far lower losses within the pipe walls. Decreasing the radius allows for operation at a higher frequency, this becomes important when considering the decrease in resonant frequency caused by liquids of relatively high dielectric constant, such as water. The cylindrical resonator is described with a sensitivity analysis and simulated results. Experimental data is presented for a variety of liquids and sensors, along with some comparison of simulated and experimental data. Measurements of relatively small changes in liquid level, the use of multiple sensors, and simultaneous measurement of multiple liquids is also presented. The proposed sensor is extremely low-cost and low-complexity, making it a highly suitable option for real-time monitoring and assessment *in situ*.

This paper is organised as follows. Section II will discuss the basic principle of sensing. Section III will attempt to characterise the device, covering important geometrical parameters. Section IV will present experimental measurements and results, first discussing liquid characterisation in Section A, then level measurements in Section B. Section V will discuss the results and some potential applications. Section VI will provide a conclusion.

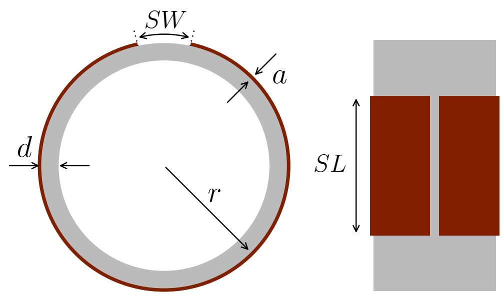

Fig. 1. Cross-sectional and top-down diagram of the sensor geometry, metal thickness scaled up for clarity.

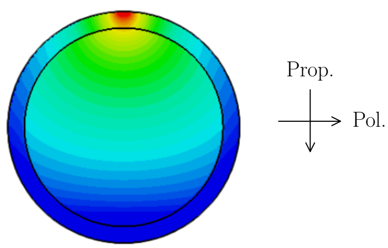

Fig. 2. Plot of the electric field magnitude within the cavity at resonance.

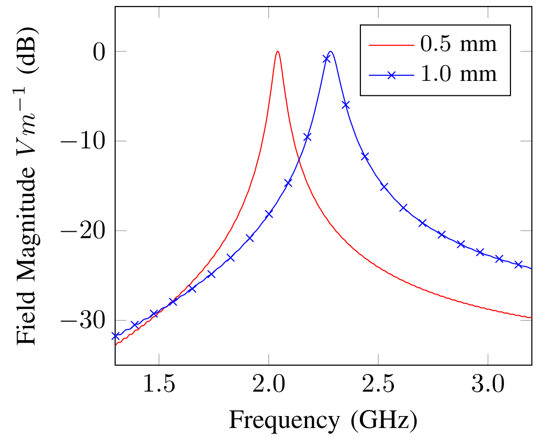

Fig. 3. Normalised field probe magnitude for $SW = 0.5$ and 1.0 mm.

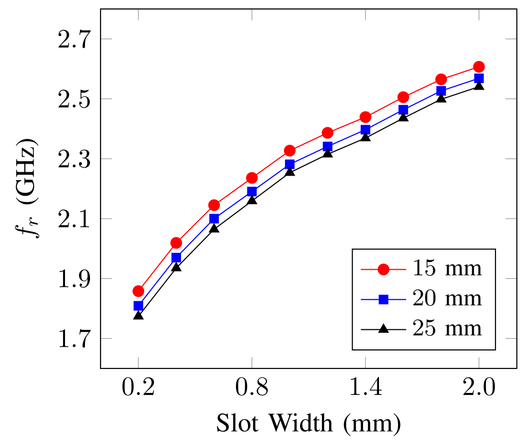

Fig. 4. Effect of SW on resonant frequency for $SL = 15$, 20 and 25 mm.

II. Liquid Sensing Method

The basic principle of operation is to excite a resonant mode within a cavity supported by a standard PTFE pipe, where the resonant frequency is sensitive to the liquid present. The structure is excited wirelessly *via* a plane wave, and the scattering of this wave is used to determine the resonant frequency. Many sensors make use of very small samples of liquid for measurement, whereas the proposed design assumes a scenario in which the pipe will potentially be filled, allowing for real-time monitoring. This presents a highly lossy environment, which can be used advantageously. By placing the device between two antennas, the attenuation seen by the receiving antenna at resonance is used to identify the resonant frequency and hence derive information regarding the liquid present inside the pipe. The independent resonant nature of each sensor allows extension to multiple devices, placed on the same pipe for improved performance, multi-band operation, or on several pipes for multi-liquid sensing. Further to this, the adjustable size of the sensor geometry allows for a variety of configurations, or fine-tuning of the device operation.

III. Device Characterisation

The device, seen in Fig. 1, consists of a thin-film copper sleeve with a slot along its length, of width SW. The slot is etched onto a rectangular piece of 125 μm Mylar film, of copper thickness $a = 35$ μm, which is then wrapped around a PTFE pipe, of external radius $r = 7$ mm and wall width $d = 1$ mm, and soldered along the edge opposing the slot. Excitation of the sensor is achieved *via* an incident plane wave polarised perpendicularly to the slot, as shown in Fig. 2, resulting in a build up of charge along one slot edge. The resulting electric field penetrates the cavity within the pipe, which is separated from the slot by the 1 mm pipe wall. This low dielectric constant PTFE region is advantageous when assessing liquids of higher ε_r and $\tan\delta$, as it allows for adequate energy to enter the cavity. The simulated electric field of the resonant mode can be seen in Fig. 2 for an air-filled pipe.

In simulations of this sensor, the resonant frequency f_r of the device has been defined as the peak field strength observed in the centre of the slot, allowing for a simple plane wave excitation in free space. Fig. 3 displays the normalised result from a field probe for $SW = 0.5$ and 1.0 mm, showing f_r clearly.

The most dominant parameter regarding the resonant frequency is the slot width SW, which effectively controls the circumferential distance around the pipe between each slot edge over which excited currents will traverse. An increase in the slot width will reduce the total circumferential distance between the slot edges, and thus reduce the inductance, L, per unit sensor length. Additionally, viewing the slot edges as a long parallel plate capacitor, an increase in the slot width will also reduce the capacitance, C, in relation to $C \propto 1/SW$. Subsequently, an increase in the slot width will result in an increase in resonant frequency, and *vice versa*, in accordance with $f_r = 1/2\pi\sqrt{LC}$.

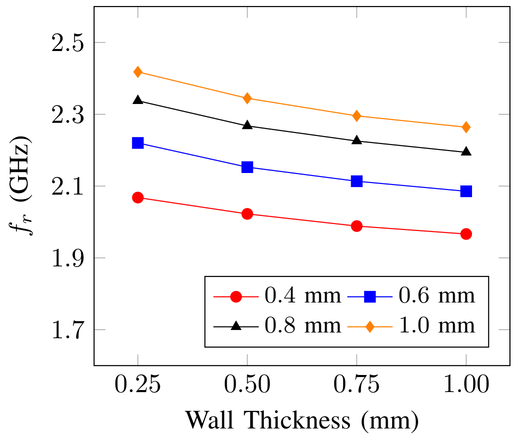

Fig. 5. Effect of pipe wall width on resonant frequency for $SW = 0.4$, 0.6, 0.8 and 1.0 mm.

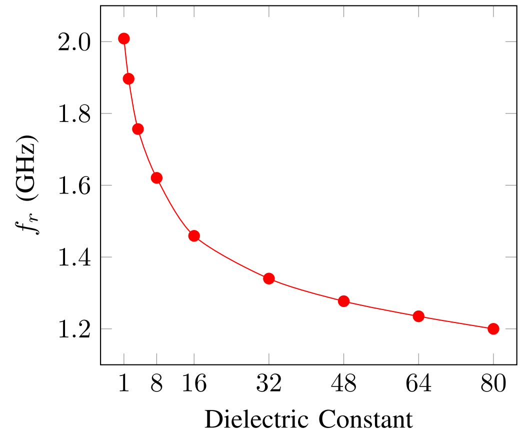

Fig. 6. Effect of the dielectric constant of the pipe contents on the simulated resonant frequency.

The inductance is inversely proportional to the sensor length SL, where an increase in SL decreases L. Given that the slot edges act as a capacitor, and that the total area of the edge face is given by $A = SL \cdot 35 \times 10^{-6}$, the total capacitance will increase with slot length. Through the resultant LC value, we see a decrease in resonant frequency with an increase in the slot length, where the effect is less significant than that of SW due to the cancelling effect of L and C. The effect of slot width and length on f_r can be seen in Fig. 4.

Clearly, the width of the slot is the dominant parameter, and by decreasing the slot width, we easily decrease the operating frequency, and *vice versa*. The length of the sensor can also be thought of as controlling the effective aperture A_e of the device, where a larger SL may absorb a larger amount of energy. However, the incident wave should be considered, as a larger sensor length may result in sections of the device being exposed to more poorly polarised wavefronts due to their distance from the phase centre of the transmitting antenna.

It is worth noting that the pipe radius will significantly change the resonant frequency, where smaller radii will increase f_r. However, as shown by Fig. 1, all results presented here use a pipe of 7 mm radius.

PTFE was selected for its low and well-established dielectric constant, $\varepsilon_r = 2.1$, as well as its excellent loss tangent, $\tan\delta \approx 0.0003$. Additionally, its very good chemical resistance makes it highly suitable for many industrial processes and so a good choice for the proposed sensor.

IV. Experimental Results

Although Fig. 1 specifies a pipe wall width of 1 mm, the effect of this parameter should be considered. As a region of low dielectric constant, its thickness will adjust the effective dielectric constant ε_e inside the sensor cavity. The effect of pipe wall width can be seen in Fig. 5 for various slot widths and a slot length of 25 mm. The increase in ε_e caused by an increased wall width has the expected effect of decreasing f_r when the pipe contains only air. When a liquid of $\varepsilon_r > 2.1$ is present, an increased wall width would clearly have the opposite effect. The use of different pipe widths would allow for the fine-tuning of sensitivity, where a thicker pipe could

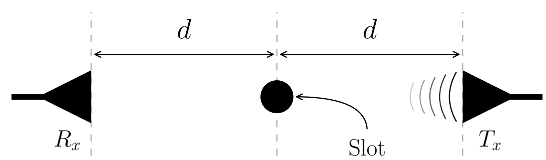

Fig. 7. Top-down diagram of the experimental setup, where the LUT is standing vertically out of the page, $d = 50$ cm and the antennas are polarised perpendicularly to the slot axis.

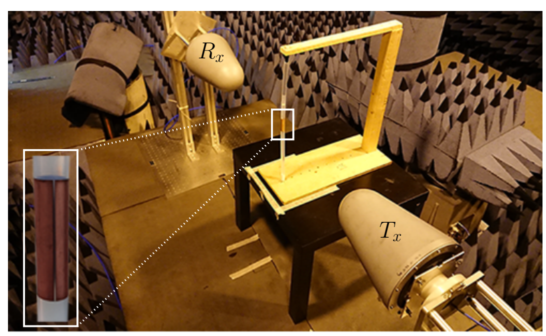

Fig. 8. Picture of the experimental setup, where the antennas are separated by 100 cm and are horizontally polarised.

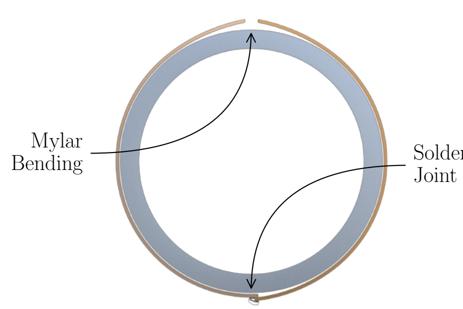

Fig. 9. Cross section of the fabricated sensor.

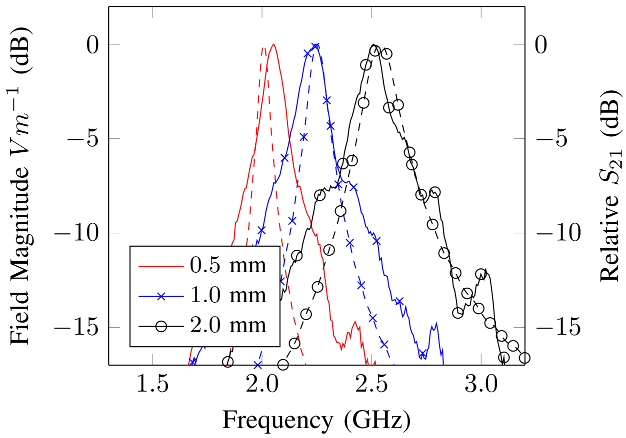

Fig. 10. Normalised comparison of measured (solid) and simulated (dashed) results for varying slot widths.

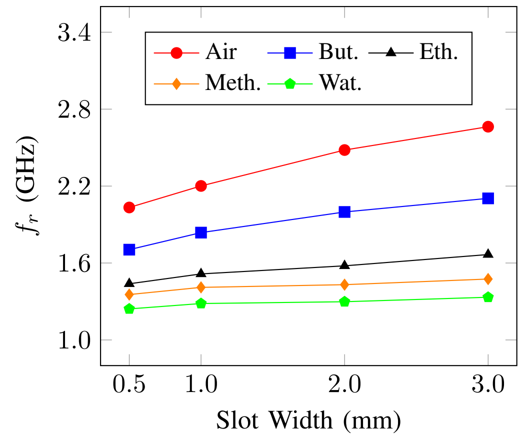

Fig. 12. Measured resonant frequency against sensor slot width for air and all liquids.

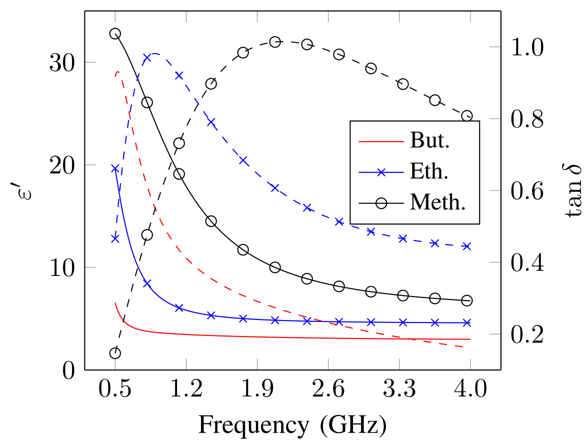

Fig. 11. Real part of the permittivity (solid) and loss tangent $\tan\delta = \varepsilon''/\varepsilon'$ (dashed) for each alcohol.

restrict the operating frequency range for a given range of permittivity values.

For a sensor of SL = 25 mm, SW = 0.5 mm and wall width of 1 mm, the simulated result of changing the dielectric constant within the pipe can be seen in Fig. 6.

The PTFE pipe was mounted in a wooden frame, sealed at the bottom by a nylon bung and held in place at the top by inserting a nylon rod. The experimental setup can be seen in Fig. 8. The structure was placed between two log-periodic antennas without a sensor or liquid in place, and a background S_{21} reading taken and stored. The VNA was calibrated using the TOSM method, where the reference plane lay at the input of each antenna. The antennas were placed either side of the sensor at a distance of 50 cm, with a total separation of 100 cm. Each result presented with a y-axis titled as Relative S_{21} signifies that the result displays the subtraction of the background S_{21} reading from the current measurement.

Fig. 9 shows a cross-section of the fabricated sensor. The deformation of the slot is caused by the difference in rigidity of the copper cladding and Mylar film, causing the slot to bend slightly outward from the pipe. The sensor was soldered while taped to the pipe, to ensure a close fit, where an exaggerated view of the overlapping copper is shown. Additionally, the sensor was soldered with a another piece of Mylar underneath to create a $\approx$ 35 μm gap, allowing the device to be placed onto the pipe with ease, but not slip while in place.

The normalised measured results of three 25 mm long sensors of varying slot widths were compared with simulations in Fig. 10, showing good agreement. Discrepancies in the results could be due to fabrication errors such as those displayed in 9, as well as etching tolerances. The effect on f_r is clearly seen, as well as an increase of bandwidth of the results with an increase in SW. This result also confirms the effect seen in simulations in Fig. 3. Given the improved performance seen from the 0.5 mm slot width, this dimension was used for all remaining measurements unless otherwise stated. It would be expected that an even smaller slot width would improve performance further, but fabrication tolerances have been taken into account with regards to repeatability when producing multiple sensors. Additionally, the sensor was rotated around the pipe and measured in 45^o increments with no more than 2.8 dB difference between results, thus showing that the rotational orientation of the sensor is not critical.

All liquids used in obtaining experimental results were characterised from the models presented in [14]. The real part of the permittivity for butanol, ethanol and methanol at 20^oC can be seen in Fig. 11, as well as their related loss tangents. The dielectric constant of distilled water at 20^oC and around 1 GHz is assumed as ε_r = 78.4, and its loss tangent $\tan\delta$ = 0.158, these values were obtained from the CST material library.

A. Liquid Assessment

The pipe was filled with each liquid and measured with four 75 mm long sensors of varying slot widths. The measured results can be seen in Fig. 12. The results show a clear distinction between liquids, and the common effect of slot width on the resonant frequency, the impact of which is less on liquids of higher dielectric constant.

The highly-lossy nature of the liquids, with reference to Fig. 11, is problematic when using a single sensor for measurements, but can be alleviated through the use of multiple

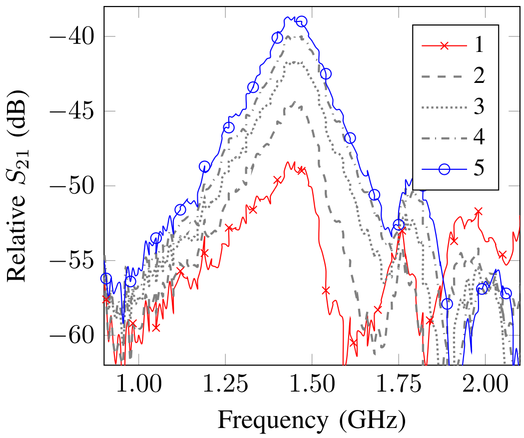

Fig. 13. Improvement of methanol measurement through the use of multiple sensors.

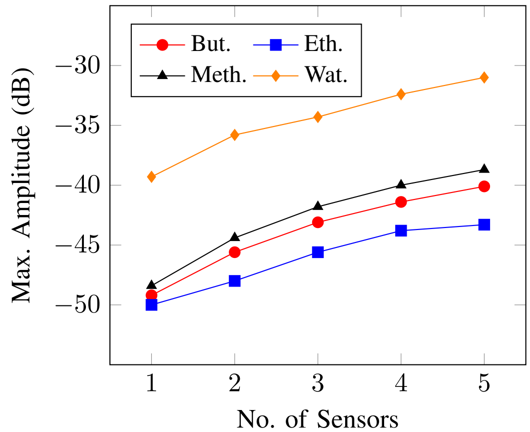

Fig. 14. Use of multiple sensors to increase the maximum measured amplitude.

sensors. To increase the amplitude of the response, it is possible to use multiple sensors of the same dimensions to provide additional resonances at the same frequency. Increasing the number of sensors increases the maximum amplitude of the measured response in addition to reducing the background noise level.

The measured result of methanol with 1 to 5 sensors in place is seen in Fig. 13, showing a very clear improvement. We see that the maximum amplitude has increased by around 10 dB, and the signal-to-noise ratio is greatly improved. This method was used to obtain a similarly improved response for each liquid, which can be seen in Fig. 14 using five sensors of $SL = 25$ mm and $SW = 0.5$ mm. The sensors need only be placed a small distance apart to reduce any significant mutual coupling effects, those in Fig. 14 were separated by 5 mm.

As seen in Fig. 10, a smaller slot width results in a better performance in terms of a qualitative assessment of the Q-factor, and this is also true for slot length, with a larger length increasing the bandwidth of measurements. Therefore, it is desirable to use multiple sensors of small slot width and length to achieve better performance, rather than increasing the length of a single sensor. Indeed, this could extend to covering an entire length of piping with sensors, allowing the possibility of measuring at any number of positions. Fig. 15 shows all liquids measured with the same five sensors in place.

Given the low-cost of the proposed sensor, it is trivial to extend measurements to monitor multiple liquids simultaneously. Three PTFE pipes fitted with sensors were placed alongside one another in the experimental frame, where two were filled with water and butanol, and the third left empty. The result shown by Fig. 16 displays three distinct peaks corresponding to the contents of each pipe. The air-filled pipe was fitted with a sensor of $SW = 1.0$ mm, and the remaining two with $SW = 0.5$ mm. This additional capability allows for larger scale monitoring, still using only a single pair of antennas.

In order to assess the measurement accuracy, each liquid was measured 10 times with five sensors in place, where $SL = 25$ mm and $SW = 0.5$ mm. For each repeat measurement, the experimental frame was removed from the chamber and a new reference measurement was taken. The uncertainty for

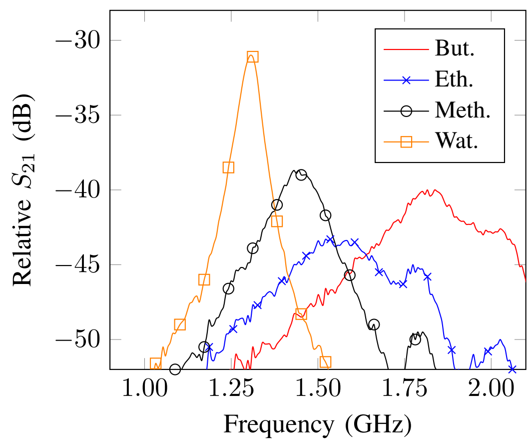

Fig. 15. Measured relative S_{21} for all liquids, using 5 sensors of $SL = 25$ and $SW = 0.5$ mm.

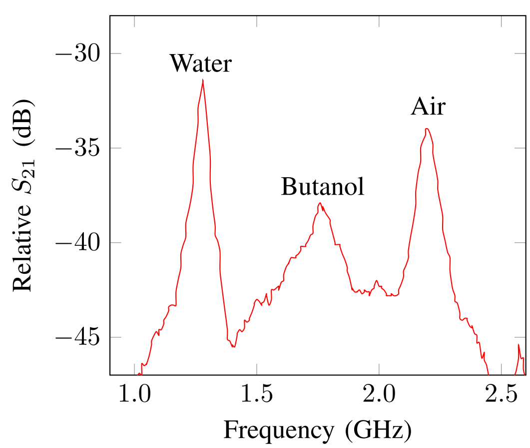

Fig. 16. Simultaneous measurement of three pipes fitted with sensors, filled with water, butanol and air.

TABLE I
REPEAT MEASUREMENT ACCURACY

Liquid	Mean (GHz)	± (MHz)
Butanol	1.848	0.800
Ethanol	1.542	1.330
Methanol	1.414	1.310
Water	1.277	2.080

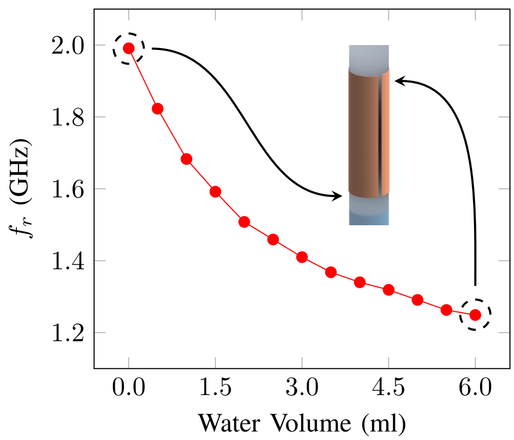

Fig. 17. Measured resonant frequency against water volume, 0 to 6 ml.

each liquid is presented in Table I for a confidence level of 95%.

B. Level Measurements

The geometry of the proposed sensor lends itself well to measuring the level of liquid within a pipe, as may be required in some industrial environments. Given the potentially hazardous nature of liquids used in this paper, level sensing results presented here consider only water due the total amount of time required to perform the suite of measurements. A single sensor of $SL = 50$ mm and $SW = 0.5$ mm was placed on the pipe, and water was added until it reached the bottom edge of the device. From this level, water was added through a syringe in 0.5 ml increments and measurements taken. The correlation between water volume and vertical height is illustrated by the annotations in Fig. 17 for the single sensor, where the total 6 ml almost fills the 50 mm sensor. Results are presented in terms of volume, due to the lack of visibility available to accurately asses liquid level.

Fig. 17 shows the decrease in resonant frequency as the sensor gradually fills with water, where 0 ml refers to a water level at the base of the sensor. The sensor is clearly very sensitive to small changes in water volume, which was exploited in Fig. 18, where water was added in 0.1 ml increments, up to a total volume of 1.0 ml. Throughout both level measurements, the maximum amplitude varied by no more than 3 dB, shown by the results in Fig. 19, providing a highly sensitive and easily distinguishable response. As water was added *via* syringe while the pipe remained in the experimental frame, some droplets remained on the pipe walls due to viscosity. This problem was exacerbated by the nylon rod holding the pipe in place, resulting in only a small space

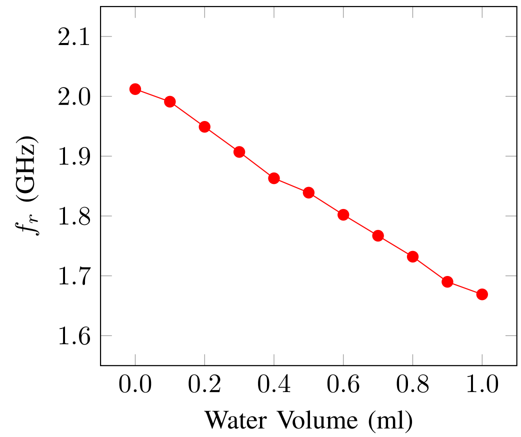

Fig. 18. Measured resonant frequency against water volume, 0 to 1 ml.

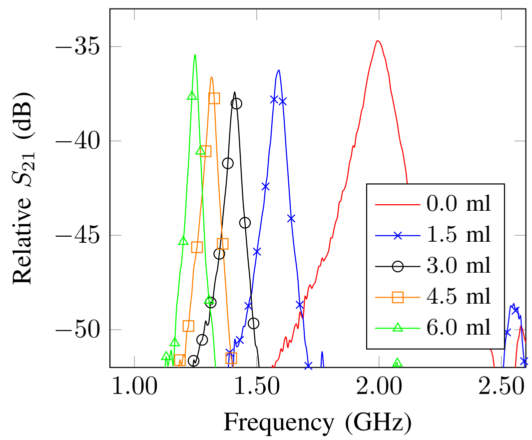

Fig. 19. Relative S_{21} measurements at various water volumes.

for the added water to flow through. In a real-world scenario, we would expect the water level to rise from the bottom of the pipe in response to pressure, resulting in an even better performance when measuring small changes in volume, as in Fig. 18.

A second configuration for level measurements was used in fig. 20, where five sensors of $SL = 25$ mm and $SW = 0.5$ mm were sequentially filled with water. Measurements were taken as the water level rose above each sensor. The result shows the maximum amplitude observed at two discrete frequency samples of 2.05 GHz and 1.25 GHz, corresponding with an air-filled and water-filled sensor, respectively. We see an almost linear increase in amplitude at the lower frequency sample, as more energy is attenuated by sensors filled with water, and thus a single frequency point would be sufficient to measure a discrete water level. Correspondingly, we see a decrease the amplitude at the higher frequency sample. This method could be extended to smaller sensors, where the SL dimension would essentially control the level of discretisation of the total height range being monitored.

V. DISCUSSION OF RESULTS

Fig. 15 displays a clear distinction between liquids, in terms of both frequency and amplitude, and Fig. 4 represents the

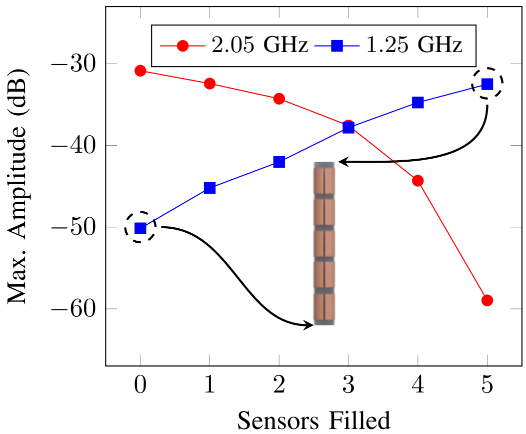

Fig. 20. Maximum amplitude of two frequency samples as the pipe is filled with water, showing the structure and water level for two sample points.

tuning possibilities achieved by altering the slot width. Fig. 14 shows the capability of the sensor to arbitrarily increase the amplitude of the frequency response, as required by the measurement environment. Additionally, the potential for simultaneous monitoring of different liquids with a single antenna pair is displayed in Fig. 16, where water, butanol and air-filled pipes are easily distinguished in a single measurement.

A single sensor level measurement is shown in Fig. 17, displaying a highly sensitive response to small changes in water volume. This behaviour is further exemplified in Fig. 18 for a very small amount of water, allowing for the accurate real-time monitoring in low-volume liquid scenarios. An extension of level measurements to a multiple sensor configuration is seen in Fig. 20, where only a single frequency sample is required to sense water level over a larger volume. Such a configuration could be easily extended to a larger number of sensors for larger volumes, or smaller sensors for higher accuracy measurements.

The sensitivity of the sensor is generally a function of the ε_r range of interest, where lower values cause a greater change in the resonant frequency than higher values, as shown by Fig. 6. Uncertainties in the measurements shown in Table I place a lower limit on the detectable variation in ε_r, where a sensor designed for the evaluation of concentrations or liquid mixes would be more suitable. Indeed, the nature of the presented device is not intended as an accurate measurement tool with the ability to evaluate exact values of complex permittivities. However, industrial scenarios will more likely feature known liquids, allowing the proposed sensor to act as part of a low-cost monitoring system. Potential malfunctions could easily be sensed through a small number of frequency samples, chosen appropriately to correspond with the liquid expected within each pipe. The high sensitivity of the sensor would allow such monitoring for multiple liquids simultaneously, further reducing cost and complexity. Such sensitivity may also exploited for the purpose of monitoring temperature for suitably temperature-dependant liquids. The permittivities of the alcohols used in this paper have a relatively high temperature-dependency, and changes of only a few degrees would be distinguishable for some liquids given the sensitivity shown by Fig. 6.

VI. Conclusion

An extremely low-cost sensor design has been presented, and shown to work for a range of liquids. The device is capable of measuring over a wide frequency range, covering dielectric constants of 1, air, to around 80 for distilled water. The sensor is very straightforwardly modified to adjust for high loss tangents by the simple addition of further sensors to increase the maximum amplitude of the response. Additionally, the rotational positioning of the slot around the pipe only minimally affects performance, and measurements can be taken at a reasonable distance, improving robustness. The single sensor level sensing method is highly sensitive to very small changes in liquid level. Further to this, the multiple sensor configuration lends itself well to a simple level-sensing system design, requiring only one frequency sample. The developed sensor is ideal for instances requiring robust, real-time, *in situ* monitoring at incredibly low-cost and complexity, low-power consumption and with simple fabrication techniques.

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