A direct printed passive RF sensor for content aware drug bottles

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Abstract

Lack of compliance with regard to medical prescriptions has become a major cause of treatment failure, a problem particularly faced in the aging population. In order to aid patients in taking their medication properly, various products for solid drugs like electronic pill organizers have recently appeared on the market whereas there is a lack of effective solutions for liquid drugs. In this paper, a novel direct printed RF sensor for drug bottles is presented as a low-cost solution, which can be used for monitoring liquid medication. The fully-printed, single layer metal sensor has been realized on the top of a polyethylene bottle, acting as a resonant LC tank, which can be read remotely. Resonant frequency drifts proportionally to the liquid content, since the distributed capacitance value is affected by the permitivity of the liquid.

The demonstrator presented in this article shows an impressive sensitivity up to 316 kHz/mL, resulting in a cost-efficient and viable solution to detect content variation in the order of sub - milliliters.

Keywords: printed LC resonant tank, monitoring drug bottle, passive liquid sensor, syringe extrusion

1. Introduction

According to a recent study (Meera, 2012), more and more patients fail to comply with medical prescriptions resulting in a considerable performance gap between potential treatment success rate and actual results within a population. Different studies have clearly shown that 20 % to 30 % of medical prescriptions are never used and approximately 50 % of medications taken for chronic diseases are not taken as prescribed by the treating physician (Peterson, 2003) (Haynes, 2008). In the United States, this lack of compliance has dramatic effects on patient health, resulting in approximately 125 000 deaths annually and 10 % of hospitalizations as well as extra costs for the U.S. health care system, estimated between $ 100 and $ 289 billion.

One of the main reasons for medical non-compliance lies in the simple fact that patients forget to take the drugs as indicated (Tanke, 1993). Plenty of products, such as pill-organizers have recently appeared on the market, providing visual and/or auditory signals to remind the patient to take the prescribed drugs, with additional availability of online support centers and caregivers.

However, little has been done to verify that the patient has actually consumed the medication appropriately. Optical techniques, while providing good reliability, are not particularly effective for their use in transparent liquids or opaque drug bottles and are generally not low-cost and flexible enough for different applications.

In this paper, a novel concept of a printed sensor, remotely read from an RF system is proposed. The design of the capacitive sensing area is aided by numerical simulation. The functionality of the concept is verified by impedance measurements of printed RF sensors on medical bottles.

2. Methods

2.1 Sensor design

In an initial step, a co-planar capacitive sensing area for the RF sensor is chosen. Printed vertically on the side of the bottle, the resulting capacitance depends both on the dimensions of the capacitor itself and on the surrounding di-electric constant of the medium, according to the approximate formula:

$$C\left[\frac{pF}{cm}\right] = 0.12\frac{t}{w} + 0.18\,(1+\varepsilon_R)log_{10}\left(1+\frac{w}{s}\right) \qquad [1]$$

where t is the thickness of the metallic plates, w is the width, s the spacing between the plates and εR the di-electric constant. The above mentioned formula does not take into account the effect of a non-uniform di-electric medium, which is actually the case in this setting.

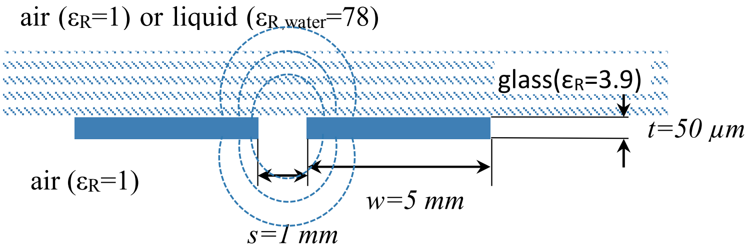


Figure 1: Co-planar micro strip capacitor principle scheme

For an estimation of the non-linear capacitive response, the co-planar micro strip on a glass bottle is modeled in COMSOL® Multiphysics and the electric potential distributions are simulated in full and empty bottles. As sketched in Figure 1, the dimensions of the simulated coplanar strips are 100 x 5 x 0.05 mm, with a separation of 1 mm. The diameter of the glass bottle is 60 mm and its average wall thickness approx. 2.2 mm. The simulated co-planar micro strip capacitor is then printed on the glass bottle and its capacitive response in various filling conditions measured.

The proposed design for the RF sensor consists of multiple co-planar strips which are connected by thinner traces to form an open coil. Figure 2 shows a schematic drawing of the sensor design and a picture of the RF sensor printed onto a 250 mL polyethylene (PE) bottle with an outer diameter of 63 mm.

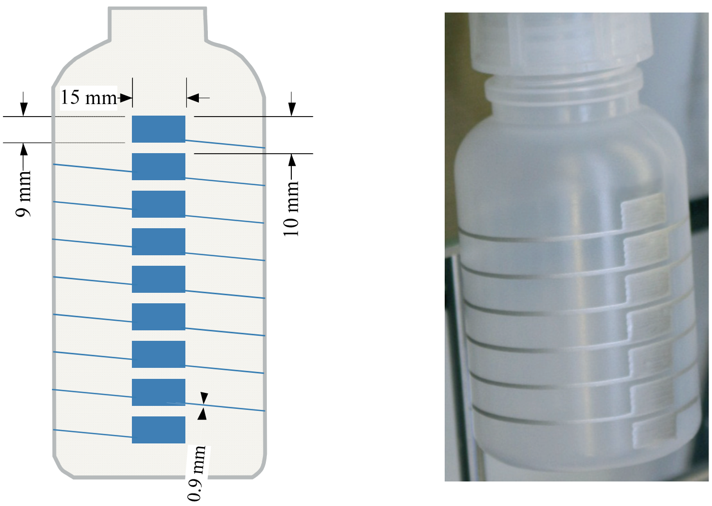


Figure 2: Schematic design of the RF sensor and picture of the RF sensor printed onto a PE bottle

As depicted in Figure 2, the chosen dimensions of the coplanar strips are 15x9 mm with a gap of 1 mm. The trace width of the connecting paths of the open coil is 0.9 mm.

2.2 Rapid prototyping of metallic sensors on bottles

In order to prove the concept and to be able to manufacture various sensor geometries in an efficient way, a digital syringe extrusion process was chosen to print a conductive micro particle ink (Chemtronics CW2200) directly onto medical PE bottles without any pretreatment. Polyethylene has been chosen for its optimal characteristics: (i) from a chemical point of view (especially for pharmaceutical applications) (ii) from an electrical point of view (very good performance in the RF domain) and (iii) ink adhesion. The printing platform is realized by a 3D printer (Velleman K8200), equipped with a simple rotational axis for bottles and a syringe extruder (New Era NE-511). All sensors are printed with a 5 mL syringe (B. Braun 8502350N) and a conic dosing needle with 0.41 mm extrusion diameter (OK International- 922125-DUV gauge 22).

In order to maintain a constant standoff between the dosing needle and the bottle surface, the geometries of the bottles are scanned with a touch probe and the Z - levels for the extrusion paths are calculated with linear 3D interpolation prior to printing. The layer thickness is adjusted by the rate of extrusion in relation to the inner diameter of the dosing needle, the print speed and the line density of the infill pattern.

The electrode geometries as well as printer control are programmed with the technical programming language Matlab®.

2.3 Characterization of printed sensors

For all measurements characterizing sensor responses in different filling conditions, an Agilent 4294A Precision Impedance Analyzer is used. The initial measurements of the capacitive response of the co-planar micro strip have been performed with direct metallic contact to the sensing probes at a frequency of 125 kHz. The chosen frequency matches one of the available ISM (Instrumentation Scientific Medical) frequencies.

For the measurements of the resonance frequencies of the printed RF sensor in different filling conditions, a copper coil wrapped around the bottle holder is connected to the Impedance analyzer. The equivalent electric circuit is depicted in Figure 3.

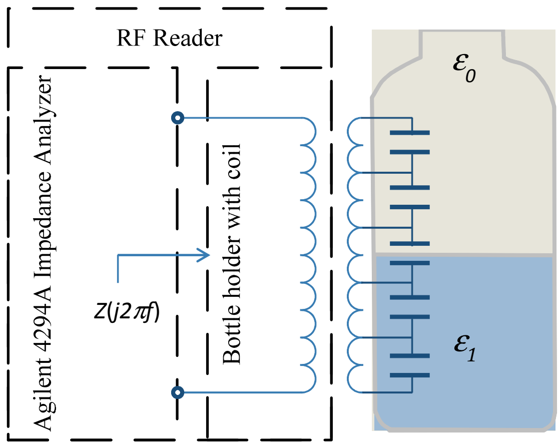


Figure 3: Equivalent electric circuit for the printed RF sensor and its reader

As indicated in Figure 3, the RF reader is realized by a coil connected to the impedance analyzer. The RF sensor is equivalent to a distributed LC network alongside the bottle; the capacitor value depends on the surrounding di-electric constant which will be modified by the presence of the liquid inside the bottle.

Due to the inductive coupling between the two coils, the impedance measured on the left hand side of the circuit, will depend both on the primary coil (integrated in the bottle holder) and on the resonating RF sensor.

The resulting LC circuit will then resonate at:

$$f_{res} = \frac{1}{2\pi\sqrt{L_{eq}C_{eq}}} \qquad [2]$$

where f_{res} is the resonating frequency of the passive RF tag, Leq and Ceq are the equivalent lumped inductance and capacitance of the distributed LC network (Figure 3).

Since the presence of a di-electric liquid inside the bottle will increase the di-electric constant and hence the equivalent capacitance, reducing the liquid content of the bottle results in a positive shift in the resonating frequency.

3. Results

3.1 Simulation and measurement of the capacitive micro strips

The geometry depicted in Figure 1 is modeled and simulated in COMSOL®, both in 2D and 3D electrostatic stationary analysis. In Figure 4, electric potential distributions are presented. The considerably different electrical potential distributions in the filled and empty case are due to the large difference between the electrostatic constants of air and water. This results in a change of the actual capacitance between the co-planar metallic strips.

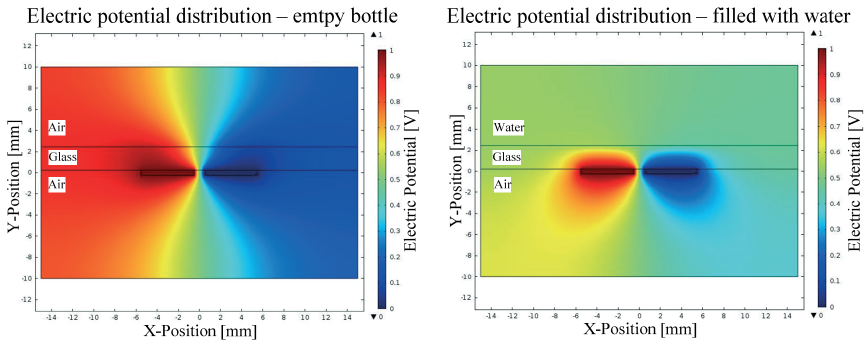


Figure 4: COMSOL FEM analysis of the electric potential distribution with air (left) or water (right) inside the bottle

The bottle has been filled with water and its capacity measured with a volume step of 5 mL. The results are presented in Figure 5.

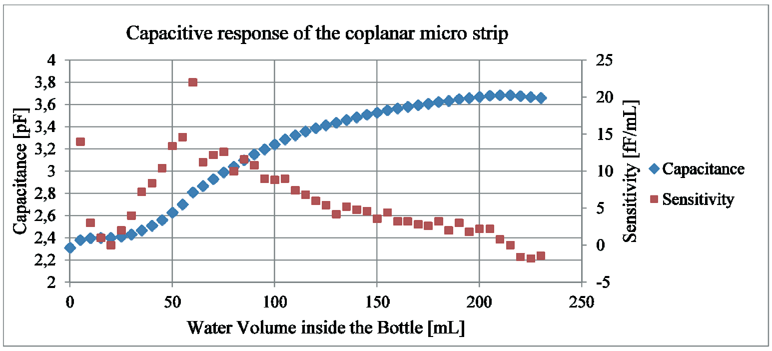


Figure 5: Capacitance measurements of the co-planar micro strip vs. water volume inside the glass bottle

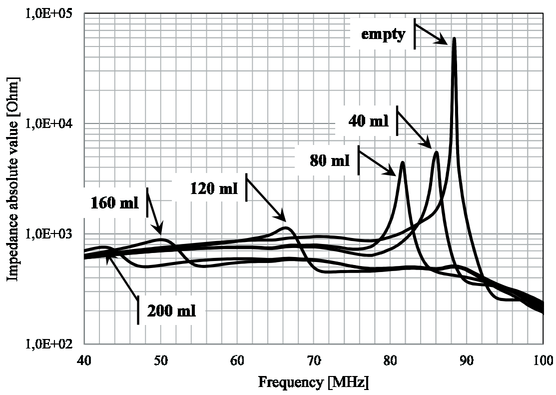
The capacitive response is flat up to approximately 40 ml. Up to this level the liquid does not face the printed electrodes and hence does not generate any significant change in the capacitance value. A similar behavior appears at fill volumes of more than approximately 200 ml, as in this case, the water level is higher than the printed strips and, for the same reason, gives no modification in the measurements.

From 40 ml up to 200 ml, the capacitance values clearly relate to the quantity of water poured into the bottle, from 2.3 up to 3.7 pF (in good accordance with simulations), albeit in a non-linear response. Ranging from 4 to 12 fF/mL, the system sensitivity is rather high, considering that in a bottle with a diameter of 60 mm, a variation of 1 ml results in a height variation of only 354 µm.

3.2 Measurements with the proposed RF sensor

Figure 6 shows impedance measurements, performed by sweeping the exciting frequency from 40 up to 100 MHz and modifying the water content in the bottle. As concluded at the end of chapter 2.3, the resonating frequency shifts downward while increasing the liquid level. In the central region of sensing, the RF sensor achieves an average sensitivity of approximately 316 kHz/ml.

Figure 6: Impedance measurements of the passive RF sensor detected by the RF reader as a function of the excitation frequency and the water content in the bottle



As expected, the quality factor of the equivalent circuit and hence the amplitude of the resonance decrease when increasing the liquid level, which is due to the increased losses induced by the presence of water near the distributed coil. It is worth noting that measurements proved to be highly reproducible and almost insensitive to the orientation of the bottle inside the cylinder-reading coil.

Figure 7 shows a plot looking at the resonance frequency vs. the bottle liquid content. In the response curve, two distinct regions with different sensitivity can be seen. The first region has a lower sensitivity of 88.6 kHz/ml and is followed by a second region with a higher sensitivity of 316 kHz/ml. When the bottle is nearly empty or filled beyond the sensor position, the sensitivity is close to zero, as would be expected, considering the capacitive response in Figure 5.

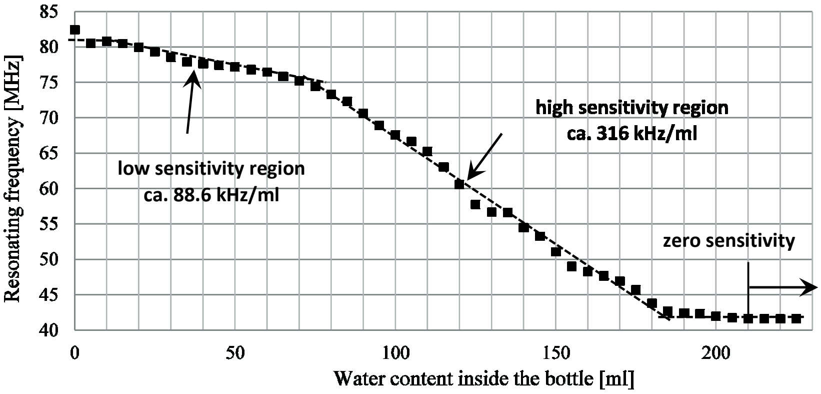


Figure 7: Resonating frequency response vs. liquid content in the content-aware bottle

4. Discussion

Even when taking into account the low sensitivity region, the performance of the proposed RF sensor is sufficient to allow for a simple and low cost tracking system for a bottle diameter of 63 mm. The sensor's peak detection capability allows to determine the quantity of liquid inside the bottle with a precision in the order of sub-milliliters. This can be used to monitor liquid content changes and may hence be useful in indirectly determining patient compliance.

As the function measuring liquid level changes per milliliter content is quadratic in relation to the bottle diameter, the precision of the RF sensor decreases quadratically when increasing the bottle diameter. Since drug bottles with diameters significantly larger than 63 mm are unusual for use in home medication - indeed, the majority of drug bottles for home use tend to be smaller in size-, this problem is not likely to be of clinical relevance.

As the rapid prototyping process used to manufacture the first generation sensors is unsuitable for a low cost production in an industrial scale, a different printing process is required. As the proposed sensor design depicted in Figure 2 can be printed in a single pass without any overlapping elements in need of an additional isolation layer, the sensor can be efficiently and effectively produced by various established printing processes such as screen printing or tampon printing. In addition to an increased resolution which enables smaller trace widths for connections, with industrial printing processes, the layer thickness of the printed sensor can be reduced dramatically, resulting in very low ink consumption per printed RF sensor.

5. Conclusion

In this paper, a novel direct printable RF sensor for passive measurements of the liquid volume inside drug bottles has been described. Due to its simple design, the sensor can be efficiently printed with established industrial printing processes in a single pass. Its high sensitivity in terms of resonance frequency vs. liquid content in the bottle, (88 kHz/mL - 316 kHz/mL, bottle diameter 63 mm) allows for a simple microcontroller based RF reader to measure the volume content of the bottle, meaning that the reader can be produced at a low costs too.

The precision of the sensor decreases in a quadratic fashion when increasing the bottle diameter. Since significantly larger drug bottles diameters - as used for home medication - are indeed very rare the proposed system may be regarded as a cost-effective solution to monitor the liquid content within sub-milliliter precision.

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