# Compact microwave based water-cut sensor suitable for downhole installation

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***Abstract* — Water is a by-product of oil extraction process whose amount needs to be determined accurately to optimize the oil production process. Almost 99.9% of the instruments used to determine water content in oil, are installed on the top surface outside an oil well. With the top surface water-fraction or water-cut (WC) meters, it is impossible to locate the water producing zones inside the well because oil (and water) is produced from multiple branches inside a well. Ideally, a downhole WC sensor needs to be installed with every branch of the well for better water management. This paper presents a compact microwave based WC sensor which is compatible with an existing downhole system. Sensor consists of a λ/4 open stub based spiral resonator. The stub is printed on a dielectric core residing in the center of a metallic pipe. The stub is fed with a microstrip feedline which has a dedicated ring-shaped ground plane. Mixture flowing between the central core and the metallic pipe changes the dielectric properties and the resonance frequency of this uniquely designed sensor. WC sensing phenomenon has been validated both in simulations as well as inside a flow loop with measured sensitivity of over 200%.**

***Keywords* — Microwave sensor, oil recovery, open stub, spiral resonator, water management, water-cut sensor.**

## I. INTRODUCTION

Water is typically present underground in the vicinity of oil reservoirs and is mixed with oil during production process. It is very critical to analyse the water content inside the oil in order to optimize the oil extraction process. For many years, drilling used to be performed vertically as shown in Fig. 1. It was much easier to analyze water content in production fluid for vertical wells because the fluid had a single path to rise to the surface and the instrumentation could be done on top-surface. There are many existing WC meters which are being used on the top surface to measure the water produced from a particular well. For example, water and oil can be distinguished based on the difference in their densities [1], infrared absorption coefficients [2] or dielectric properties [3] [4] [5] [6] [7] [8].

At present, oil companies prefer to drill horizontally in order to tap oil reservoir more effectively using multiple branches. Although, the oil production rates can significantly be enhanced by using multi-branched wells but fluid characterization becomes a challenge using conventional top-surface instruments. This is because, water can find its way to any of the oil producing branches and eventually gets mixed with the rest of the production of the well. WC meters on the top-surface can detect the overall rise in water content but the water producing branch cannot be located downhole. In order to do that, every oil producing branch must be equipped with a dedicated WC sensor so that the water producing zones can be abandoned as soon as they start mixing water with the oil. This will not only increase the oil production efficiency but will also help to minimize the amount of water produced with oil. It means that the water-handling cost can also be minimized and drinking water aquifers (near to the top surface) can also be protected from contaminated water produced during the oil production [9].

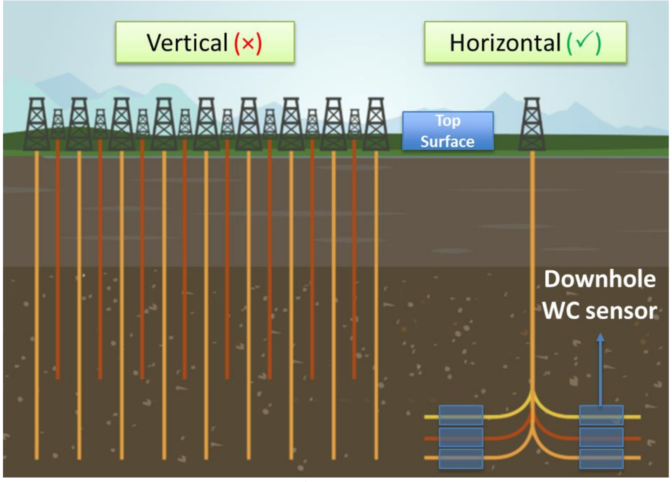

Fig. 1. Comparison of vertical vs horizontal drilling

Until now, very few downhole WC meters have been developed and installed in the field. In 2015, Schlumberger had launched Manara system to monitor downhole WC values using capacitive probes [10]. However this system is limited to work in low water (< 40-50%) conditions. Very recently, Weatherford has developed a downhole WC meter (Rheos 2P) which works on the optical principles [11]. However, a major drawback of this system is that it requires a continuous fiber optical cable from oil producing zones (many kilometres down the surface) to the top-surface. This is because, its readout electronics has not yet been minimized to fit in limited downhole space.

The objective of this paper is to present first of its kind, microwave based compact WC meter suitable for downhole installation. Microwave techniques (antennas or resonators) can be used to detect WC over full range (0-100%) by exploiting the difference in dielectric constant and dielectric loss of oil and water. Moreover, microwave resonators can easily be integrated with low-power and compact oscillators to form self-contained WC sensor. This is why, authors believe that the presented WC meter can potentially overcome the drawbacks of limited range of existing downhole WC sensors.

## II. DESIGN AND SIMULATIONS

Downhole sensors are usually installed during well completion process and are extremely difficult to retrieve back at a later stage. That is why, it is very important for the downhole design to be robust and be compatible with the existing downhole infrastructure. One of the major oil producing companies is developing a new retrievable downhole system, which allows downhole equipment to be retrieved back every 3–5 years. Compatible with that system, this paper presents a compact downhole microwave WC sensor. The production tubing of the well has a small diameter (50 to 75 mm) and is typically made of corrosion resistive metal such as INCONEL. Our WC sensor has to fit inside this metallic cylinder.

We started our sensor design with a hollow metallic tubing of 60 mm inner diameter, as shown in Fig. 2. We introduced a core (diameter 38.1 mm) of dielectric PEEK material in the center of the metallic tubing. There are 2 benefits of using a core in the middle of the sensor design. Firstly, the microwave resonator will be designed on the external surface of the dielectric core which will be used to measure the water content mixed with the oil. Secondly, the core causes a pressure drop and can be correlated with the flow rate of the fluid which is another desired fluid property to measure.

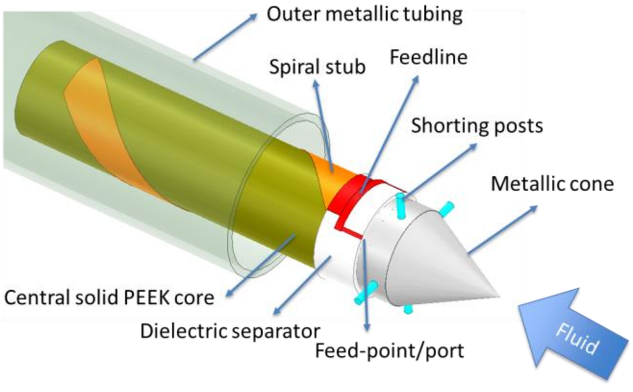

Fig. 2. Exploded view of the proposed downhole WC sensor

The production fluid enters the sensor from the right and the conical entrance of the sensor helps to minimize the flow disturbance. The cone is made of metallic material (silver colour in the figure) which extends to the bottom of the dielectric separator (shown in white colour). The sensor's feedline has a dedicated ring-shaped ground underneath the dielectric separator. Due to this arrangement, microstrip mode based feedline is matched with 50Ω impedance to avoid reflection losses. The feedline is then electrically connected with a λ/4 spiral stub which extends laterally on PEEK core. Outer metallic tubing acts as the ground plane for the spiral stub. Spiral stub forms the sensing region having its electrical fields between the signal (on PEEK core) and outer metallic tubing. As the fluid flows on top of the PEEK core, electric fields are perturbed and the impedance of the spiral resonator is changed.

At ambient conditions, water has a dielectric constant of 80 while oil has a value of 2.2. When the fluid mixture of different fractions of water inside the oil is passed through the microwave sensor, effective dielectric constant experienced by the resonator is changed. Higher water fraction (or higher effective dielectric constant) results into slowing down the microwaves as a result of which, the resonant frequency ($f_0$) is decreased as a function of water-fraction or water-cut (WC) and is evident from HFSS simulation results shown in Fig. 3.

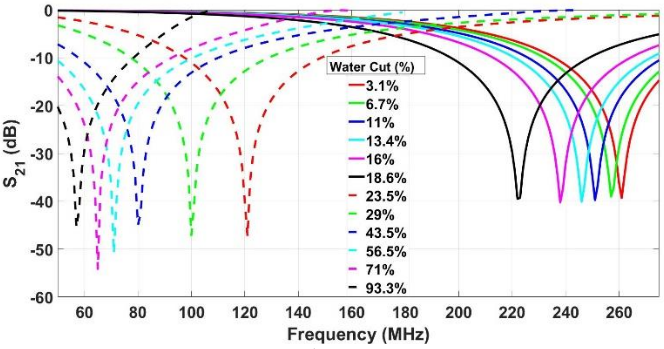

Fig. 3. Simulated $S_{21}$ response of downhole WC sensor in response to changing water-cut (WC) values of the fluid

Fig. 4 plots $f_0$ as a function of WC and inset of this figure shows water in light blue and crude oil in dark grey colour.

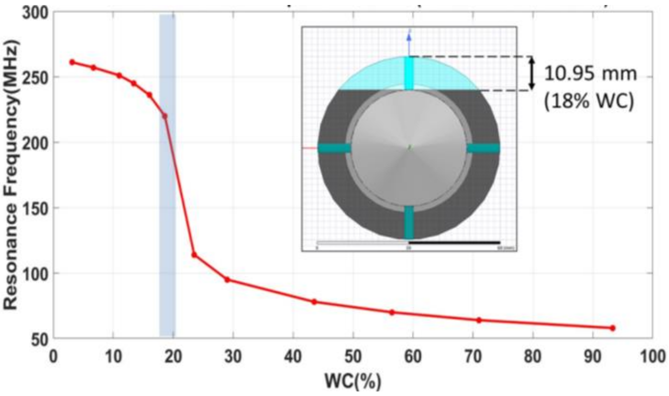

Fig. 4. Simulated resonance frequency of the resonator as a function of change in water-cut (WC). Inset shows the cross section of the simulation model

Fig. 4 shows another interesting phenomenon of this sensor which is a sharp dip in $f_0$ at WC value of 18%. This is because, at a WC value of 18% (scenario shown in inset of Fig. 4), water forms a continuous path between spiral signal (lying on central core) and ground plane (external metallic tube) of the resonator because of which most of the E-field tend to concentrate inside the water medium which has much higher dielectric constant than oil. It means that the resonator is dominantly affected by the water medium and causes a sharp dip in $f_0$ around WC value of 18%. However, the sharp dip does not affect sensor's sensitivity as the change in $f_0$ is distinguishable over full WC range and is evident from Fig. 3 and Fig. 4.

## III. PROTOTYPING AND CHARACTERIZATION

### A. *Fabrication*

We have fabricated a prototype of the compact (21cm long, 6 cm diameter) microwave based WC sensor by combining the techniques of conventional machining, 3D printing and screen printing. Firstly a core of 38.1 mm diameter has been machined from PEEK material as shown in Fig. 5(a). With the help of a 3D printed mask (not shown here), spiral resonator and ring ground plane dedicated for the feedline is printed on the outer surface of the PEEK core. A 3D printed dielectric separator has been fabricated on which feedline is printed, as shown in Fig. 5 (b). Placeholders to mount uFL connectors (shown in Fig. 5(c)) have been provided inside the dielectric separator. Four regular bolts (shown in Fig. 5(d)) have been fabricated with dual purpose. Firstly they provide mechanical strength to hold the central PEEK core in the middle of the metallic cylinder and secondly they help in electrically shorting the ring ground plane of the feedline with the ground plane of the spiral stub (i.e. outer metallic tubing). Two special bolts have been fabricated through which the test wires can be routed outside the sensor body. These wires have uFL connector at one end which connects on the sensor body while other end of the wire is terminated with SMA connector which is connected with the VNA to measure the $S_{21}$ response of the sensor. Fig. 5(e) shows the holes in the metallic cone which are used to route the wires such that they are not affected by the fluid flow.

### B. *Measurements*

Before characterizing the sensor in the flow loop, we protected the printed sensor and connectors with the help of cold-shrink tubing, as shown in Fig. 6(a). 3″ flanges have been used to connect the sensor in the flow loop and its front view is shown in Fig. 6(b). Epoxy has been installed on six bolts of the sensor assembly so that the leakage can be avoided. After that, the sensor has been pressure tested by closing both of its ends as shown in Fig. 6(c). After that the microwave meter has been installed inside the flow loop as shown in Fig. 6(d). 2-phase Coriolis meter has been used before the microwave meter in order to provide the reference WC measurements. It can be seen from Fig. 6(d) that microwave meter is extremely compact compared with the Coriolis meter, which makes our meter well suited candidate for downhole installation.

The flow loop has a big storage tank for oil and tap water which are pumped independently and are naturally mixed after passing through a $45^0$ Tee connection. We have characterized the response of our meter twice. Firstly, we ramped up the WC from 0% to 100% and then ramped down the WC from 100% to 0%. The measured resonant frequency ($f_0$) of the sensor over full WC range has been compared with the simulation data from Fig. 4.

It can be seen from Fig. 7 that measured data follows the similar trend as in simulation. For example, measured data confirms that $f_0$ decreases by increasing WC of the mixture. The change in $f_0$ is very consistent and repeatable in two independent set of measurements. Moreover, sensor shows a sharp dip in $f_0$ at around WC 18% just like in simulations, as explained above. The measured data point don't exactly overlap with the simulation points because of various factors such as fabrication imperfections and the dielectric loading effect of cold-shrink tubing which has been wrapped on top of the sensor for protection from the fluid. It must be noted here that we have achieved measured sensitivity of over 200% which is much more important than the absolute value of $f_0$. As long as the sensor gives repeatable data, it can reliably be related with the WC value using a lookup table.

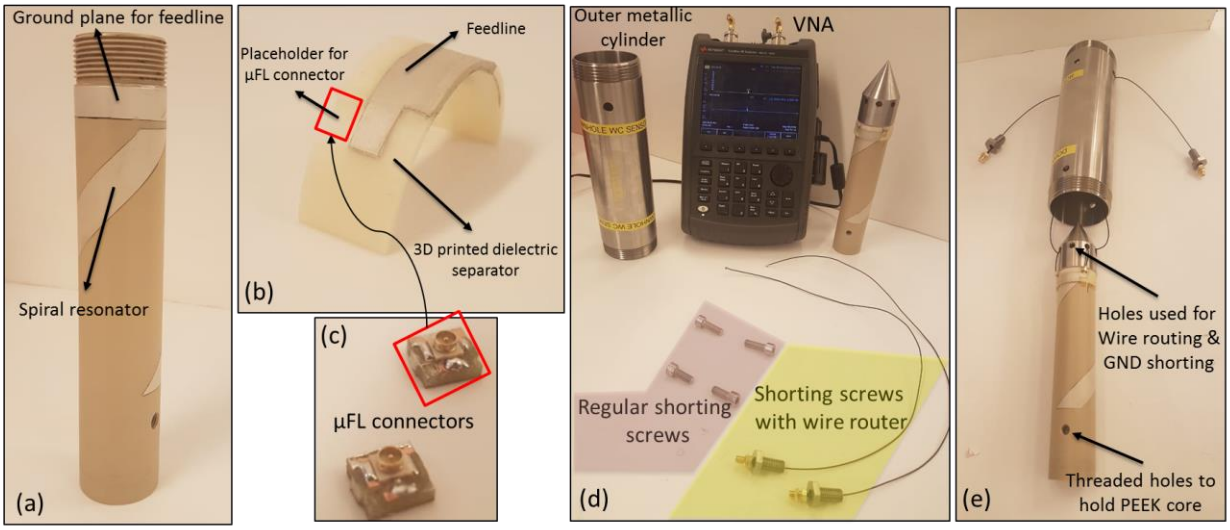

Fig. 5. Fabrication steps of proposed downhole water cut sensor (a) Spiral resonator and ground plane for feedline printed on PEEK core (b) 3D printed dielectric separator with printed feedline (c) uFL connectors (d) Different parts of downhole WC sensor prototype (e) Downhole WC sensor assembly before bolting it up

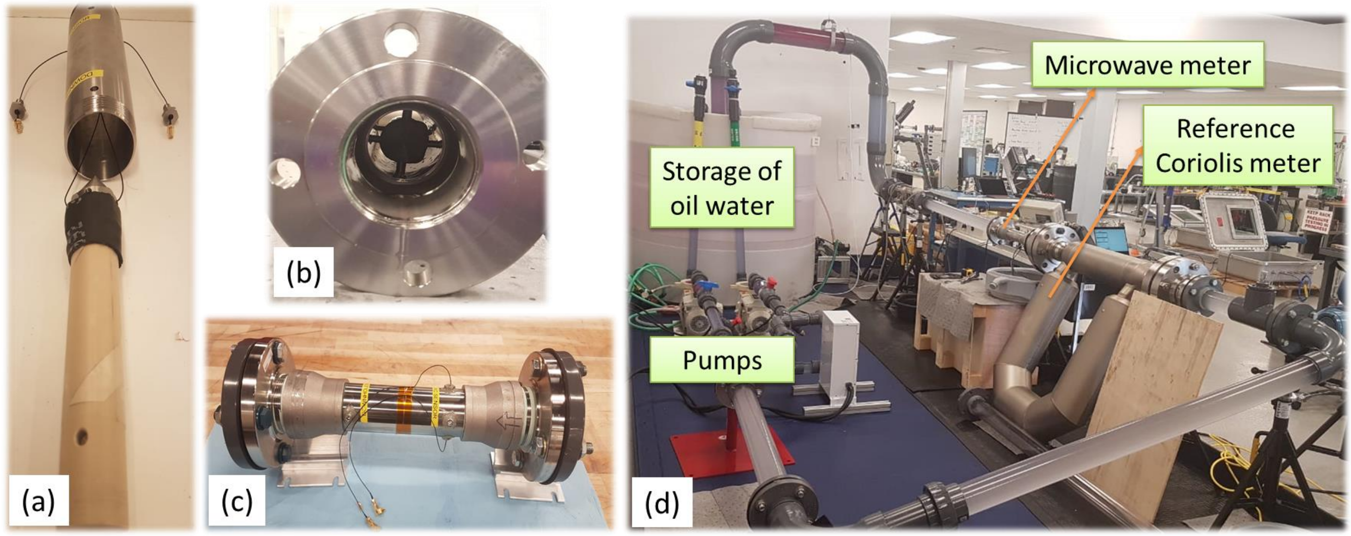

Fig. 6. Preparation of downhole WC sensor for flow loop testing (a) Cold-shrink tubing mounted on microwave resonator and test wires (b) Front view of the sensor after flanges are mounted (c) Pressure testing of the sensor (d) Flow loop test setup

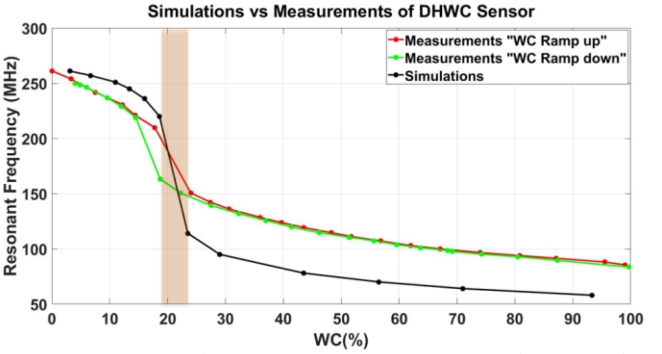

Fig. 7. Comparison of simulation and measurement performance of WC sensor

In future, the simulation model can be perfected by incorporating the effect of cold-shrink protection tubing and fabrication imperfections.

## IV. CONCLUSION

This paper presents a downhole compatible, compact and ultra-sensitive microwave based full range water cut sensor. In collaboration with leading oil producer, special attention has been paid for its compatibility with existing space restrictive downhole environment. Measured response follows the same trend as predicted by the simulation model and the repeatability of the sensor has been verified by two independent set of measurements. The measured sensitivity of over 200% is well suited to cover full range of WC with high accuracy. An interesting phenomenon of sharp resonance dip due to water continuity at WC 18% has been confirmed both in simulations and measurements. In future, microwave oscillator can be integrated with the resonator leading its way to, first of its kind, self-contained microwave based downhole WC sensor.

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