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Microwave ring resonator-based non-contact interface sensor for oil sands applications

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ABSTRACT

This paper presents the design, fabrication, and characterization of a non-contact microwave resonator sensor for liquid–liquid interface detection. The core of this sensor is a microwave planar ring resonator tuned at 5.25 GHz with a Q factor of 180. The geometry and materials of the designed sensor were optimized for higher sensitivity by finite element modeling and simulations. Here we demonstrate the detection of different liquid–liquid interfaces such as water–olive oil, water–olive oil–ethanol, and rag layer samples using microwave resonator method. In the proposed sensor, the resonance frequency demonstrated a maximum variation of 5.7% for water to rag layer interface. To increase the accuracy of the sensor in the interface detection, quality factor is also measured and demonstrated a maximum variation of 85% depending on the materials. The proposed sensor provides a non-contact real time, cost-effective, robust method for interface detection, which has potential applications in the oil sands industry.

1. Introduction

The rag layer is an undesirable mixture of water, fine solids and dispersed oil formed at the water–oil interface during the settling stages in the froth treatment of oil sands [1–3]. Detecting the exact location of rag layer is important for assuring the quality of produced oil as well as preventing bitumen loss to the tailings. Once entered into the oil stream, water and fine solids will contaminate the produced oil and may cause fouling and corrosion problems in the downstream processes. Therefore, developing a reliable non-contact sensor that can detect such interfaces is of great interest.

There are a few methods that have been proposed, and in some cases have been deployed in industry, in order to detect the interfaces of different liquids and their thicknesses. One of the most commonly used sensors in industry is based on the pressure difference between the two different liquids [4]. Although these sensors are inexpensive and can be easily installed, they are mainly suitable for crisp or level interfaces. Furthermore, their inability to deal with build-ups created on the surface of the sensor makes their application very limited in the oil sands industry. Another technique for interface detection uses displacer-based devices which requires operation at a fixed density which usually does not happen in the oil industry due to inherent temperature fluctuations during processing [4]. Vibrating switch-based devices are another family of interface detectors that suffer from disadvantages such as invasiveness and sensitivity to build-ups. [4]. Other sensing devices, such as fiber optics-based devices, are also sensitive to build-ups [5]. Nuclear radiation based sensors [6] are another alternative for interface detection, but they need regular inspection and approval due to the risk of radiation, and are estimated to be 2–4 times more expensive than other methods [4]. Capacitive sensors are also used for interface detection [7] but they suffer from sensitivity loss once water makes up more than 40% of the sample due to the absorption of the microwave energy by water [4,7].

Microwave resonator-based sensors [8–16], have been used for liquid sensing and have demonstrated many advantages over other methods. Waveguide cavity resonators are one of the most popular types due to their high quality factors and sensitivity. However, they are usually bulky and require direct contact with the sample. Planar resonators that have been also studied for mobile and satellite communications [17–22], are widely used as sensors. These sensors have recently demonstrated a huge potential in different applications in liquid and gas sensing [23–25]. They can be used for non-contact sensing and is placed at a fixed distance from a desired object [26]. The planar resonator based sensors have advantages such as low cost, easy implementation, long lifetime, and ability to

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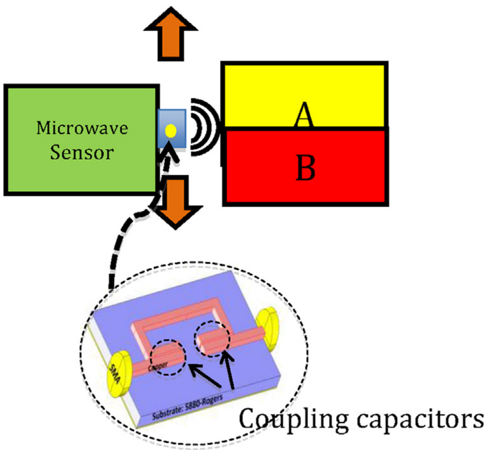

Fig. 1. Schematic of a non-invasive, non-contact interface sensor based on microwave ring resonator.

perform in non-contact fashion. These sensors are also small in size and have moderate sensitivity to variations of the ambient environment. Their planar structure with small form factors make them attractive for sensing applications [29–34].

Planar resonator based sensors, despite their advantages have not been studied for interface detection. In this work, we report on non-contact detection of liquid–liquid interfaces using a microwave resonator which has a potential in oil sands industry. We also discuss microstrip open loop ring resonator sensor design, simulation, and measurement of the interfaces of water–olive oil, water–olive oil–ethanol, and an industrial rag layer.

2. Principals of operation

Fig. 1 shows the overall sensing system. A microwave microstrip ring resonator forms the core structure of the sensor. This resonator structure consists of a half wavelength ring resonant coupled through the two coupling capacitors at the input and output ports. Three different parameters that play important roles in microwave resonators are resonance frequency, *Q*-factor and signal's amplitude. Variations in the coupling capacitance (shown in Fig. 1) affect all the above parameters, thus make them useful as indicators.

2.1. Resonant frequency

If the resonator is brought in the proximity of the material being sensed as shown in Fig. 2, the permittivity change affects the coupling capacitors. This capacitance is the summation of the three capacitors of C_{above}, C_{pp} and $C_{\text{dielectric}}$, which represents the capacitance through the material under test, the parallel plate capacitance, and the substrate capacitance, respectively:

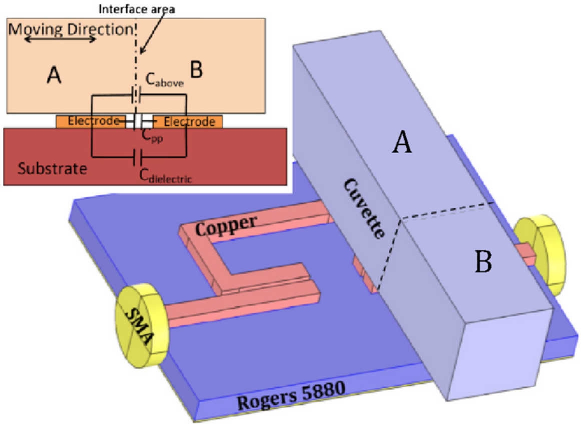

Fig. 2. Planar microstrip resonator and material above the sensor.

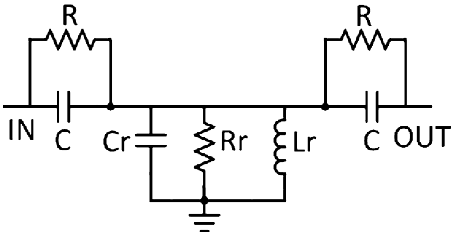

Fig. 3. Circuit model for the designed sensor.

$$C_{\text{above}} = \varepsilon_0 \varepsilon_{\text{above}} \frac{K'(m)}{K(m)} l \tag{1}$$

$$C_{\text{pp}} = \varepsilon_0 \frac{h \times w}{g} \tag{2}$$

$$C_{\text{dielectric}} = \varepsilon_0 \varepsilon_r \frac{K'(m)}{K(m)} l \tag{3}$$

where $K(m)$ and $K'(m)$ are the elliptic integrals of the first kind in terms of the parameter m and its complement [27], h is the thickness of the electrodes, w is the electrode length, g is the gap in between the electrodes, and m is a functional argument derived from the following equation:

$$m = \sqrt{\frac{\text{gap} \quad \text{width}}{(2 \times \text{strip} \quad \text{width} + \text{gap} \quad \text{width})}} \tag{4}$$

When the sensor is fully exposed to material *A* or *B*, the permittivity above the sensor ($\varepsilon_{\text{above}}$) is equal to ε_A or ε_B, respectively. Therefore, the overall capacitance would be C_A and C_B which have different values.

At the interface, the material is in the form of a multi-phase mixture that gradually changes from one material (ε_A) to another (ε_B). The Maxwell Garnett formula [28] determines the trend of permittivity variation from one liquid to another equation:

$$\varepsilon_{\text{int}} = \varepsilon_b + 3f\varepsilon_b \frac{\varepsilon_i - \varepsilon_b}{\varepsilon_i + 2\varepsilon_b - f(\varepsilon_i - \varepsilon_b)} \tag{5}$$

where ε_{int} is the permittivity of the mixture at the interface, ε_b is the permittivity of the bulk liquid, ε_i is the permittivity of the inclusion in the liquid (e.g. according to Fig. 2 and starting from liquid *A*, ε_b is the permittivity of material *A* and ε_i is the permittivity of material *B*) and *f* is the volume fraction of the inclusion. This equation governs the slope in the variation of the resonance response due to changes in the permittivity of the liquids and depends on the surface tensions of the two liquids. It is expected that ε_{int} has a value between ε_A and ε_B.

As was mentioned, variation in permittivity at the coupling capacitor changes the capacitance value and therefore the resonance frequency. Fig. 3 shows a circuit model for the designed sensor where the coupling capacitor *C* is sensitive to the physical characteristics of the sample. Variation in *C* results in a shift in resonance frequency which is used as a sensing parameter in this paper. Based on the theory described above, a detailed analysis is performed for two materials with permittivities of 80 and 4 while the interface is gradually moved vertically across the sensor. Fig. 4 shows the response as a function of distance. The observed step change due to the interface region is the main focus of the simulations.

However, it should be noted that for the best outcome the system should be initially set and calibrated for the two extreme values of material A and B to facilitate determination of the transition region.