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Liquid sensing in aquatic environment using high quality planar microwave resonator

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ABSTRACT

This paper describes a non-contact liquid sensor operating in an aquatic environment using an active, feedback loop assisted, planar, micro strip microwave resonator. The proposed sensor has the ability to operate in noncontact fashion within a distance of 0 to 8 cm. The active loop technique is shown to increase the primary quality factor from 210 to 500,000 in air when measured at a resonant frequency of 1.52 GHz. The quality factor of the proposed resonator is adjustable with the direct current (DC) bias voltage and is set to 450,000 in the presence of an aquatic medium. The ability to adjust the quality factor of the reported microwave sensor allows for larger dynamic range and permittivity variation monitoring. Different shifts in resonant frequency are reported in the presence of various liquid samples in tubes which are submerged in deionized (DI) water. The proposed device is used to distinguish between Water, Ethanol, Methanol, Isopropanol, and Acetone in a submerged tube inside a water filled container.

1. Introduction

Microwave planar ring resonators are being used in various sensing applications ranging from solid material identification to liquid and gas sensing and detection [1,2]. They have a planar structure with a simple, low-cost fabrication process and operational form factor. They have the tremendous advantages of both their noncontact sensing ability and their easy integration and compatibility with complementary metal oxide semiconductor (CMOS) technologies. The miniaturization of these resonators is simpler than that of other microwave components such as cavity waveguides. Split-ring resonators have been widely used in microfluidic devices for the label-free detection of biomolecules and the detection of various concentrations of a target material within solution [3–7]. Ring resonators detect variations in nearby mediums through variations in the electric field around the device. Though planar resonator sensor has all of these advantages, it suffers from low resolution due to its low quality factor, on the order of 100 to 300. In most previous works the distance between the sample target and the resonator had to be minimized so as to optimize the effects of the electric field. Microfluidic structures have also been proposed so as to increase the accuracy and minimum detectable limit in the liquid medium [8,9].

Water is one of the two major environments in which the life cycle occurs, therefore the ability to detect changes through and within water can have significant impact on our understanding of everyday life. Biomedical applications such as monitoring cellular activity or bacterial growth rates are forced to take place within an aquatic environment. In many applications, the direct heating or cooling of a cell or substance is not possible and water is therefore used to heat or cool the environment indirectly for live tissues. Microfluidic circuits are playing an increasing role in biomedical sensing applications. These circuits pass liquids through simple cylindrical tubes which facilitate the external sensing method. In addition, these sensors can benefit environmental applications. There are several pipes that travel through lakes to transport crude oil. Any oil leakage into the water must be monitored closely. Considering the fact that oil tends to separate from static water, detecting separated liquids in aquatic media can be highly beneficial for detecting oil leakage in ponds. Moreover, there are several industrial mechanical machines or oil processing instruments that use water for heating and cooling. Monitoring the chemical processes through the surrounding water is one of the challenges for the sensor community.

To increase the quality factor and sensitivity of the microwave resonator sensor, several techniques have been proposed, such as the use of metamaterials in resonator structures [10,11], precise matching of the resonator [12], or employing regenerative active feedback resonance (RFR) [13–16]. Also using 3D structures such as rectangular waveguides cavity has also been reported to

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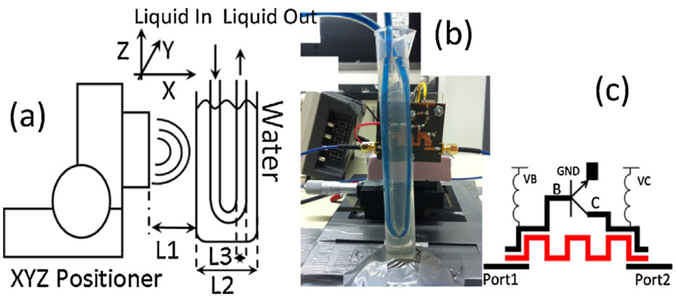

Fig. 1. (a) Schematic of the proposed sensing structure with a 3D high precision positioner. A water-filled tube is placed in a distance of $L1$ with the diameter of $L2$ and another smaller tube with the diameter of $L3$ is placed inside that. (b) The experimental setup and the fabricated sensor, (c) schematic of the microwave sensor.

increase the quality factor and resolution of the sensor device [17]. Among these techniques RFR is a very promising technique that can increase the quality factor by several orders of magnitude. RFR devices are lower in cost and complexity than highly sensitive, high-resolution micro electro-mechanical (MEMS) devices, and are very simple in terms of their operation and establishment. These devices has also demonstrated high potential in liquid material sensing and classification while a carrier tube is mounted on the sensor plane [18].

This work reports the operation of a robust, state of the art microwave microstrip RFR resonator within the unique application of underwater media. The aquatic medium is normally harmful for microwave devices since water has such a high loss factor and reduces the quality factor of the device. This, in consequence, reduces the minimum detectable permittivity of the resonator. In this work, an active feedback loop is employed to boost the quality factor of a conventional microwave microstrip resonator, which in turn also increases the penetration depth of the electric field from the reported device and assists the resonator to detect liquid variations in water [12]. It has previously demonstrated that such sensors can be utilized for very high resolution and small permittivity change detection [16]. Here, similar sensor is utilized and illustrated that by using regenerative feedback loop, the produced loss by aquatic sensing medium can be compensated maintaining sensor's high resolution read out capability.

2. Theory of operation and implementation

The schematic of the proposed sensing system is shown in Fig. 1(a). The core of the sensor is a passive meander-shaped resonator which is assisted by a feedback loop employing a low noise, high gain transistor from California Eastern Laboratories (CEL) as an amplifier.

For passive resonators the length of the microstrip line plays a critical role in determining the resonant frequency of the system. This resonator is a half-wavelength resonator, thus the total length can be calculated from the following equation [12]:

$$l = \frac{c}{2\sqrt{\varepsilon_{eff}}} \times \frac{1}{f_r} \quad (1)$$

where l is the total length of the resonant microstrip line, ε_{eff} is the effective permittivity of the materials in the sensor ambiant environment, c is the velocity of light and f_r is the resonant frequency. The device is fabricated on a printed circuit board (PCB) from Rogers corporation (5880) with a thickness of 0.79 mm and a dielectric constant of 2.2 ± 0.2. Substrate surfaces are covered with a thin layer of copper with conductivity of 5.8×10^7 Sm^{-1} and thickness of 37 μm. The loss factor of the substrate is quite low 0.0004 and 0.0009 at 1 MHz and 10 GHz, respectively which is thus suitable for our range of operation frequency.

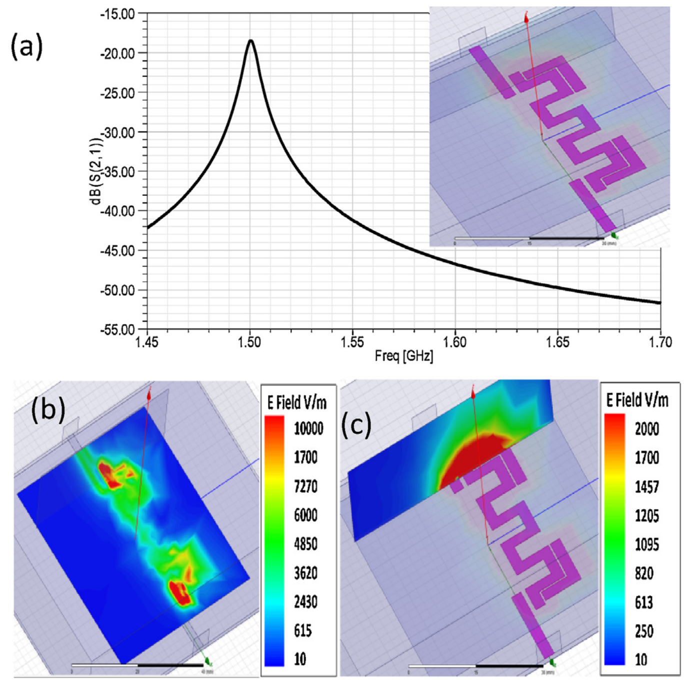

Fig. 2. (a) Passive resonator structure and $S21$ simulation result in HFSS. (b) Electric field distribution of the resonator at 1 mm distance from the surface. (c) Electric field distribution around the hot spot of the resonator perpendicular to the resonator surface.

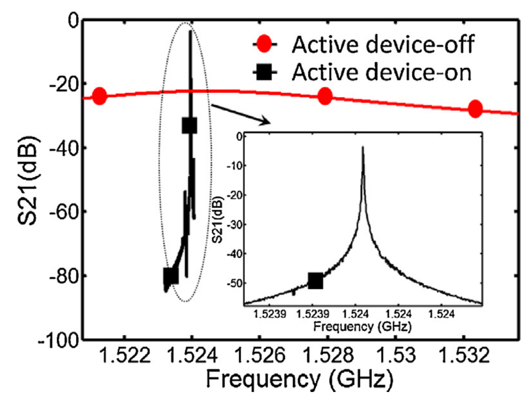

Fig. 3. Comparison of the measured resonance profiles for the on/off states of the active loop. A tremendous enhancement in the quality factor is shown, the resonant frequency remains almost fixed and the amplitude is increased since the active device introduces extra power to the system. A two-port high precision measurement is performed to achieve $S21$ vs. frequency while foam electromagnetic absorbers are used to reduce the external noise and scattering radiation effects.

The passive sensor structure and $S21$ parameter simulation is shown in Fig. 2(a). The electric field distribution around the resonator from a distance of 1 mm from its surface is described in Fig. 2(b). Fig. 2(c) presents the field distribution in a plane perpendicular to the resonator surface around the coupling gap while operating at resonant frequency.

In the active loop section, two 18 μH inductors are used as the direct current (DC) feed to the transistor. The collector voltage of the RF transistor is set to 8 V and the base voltage is kept variable to optimize the Q-factor for various conditions. The active feedback loop around the main resonator cancels the power loss of the resonator by introducing a negative resistance which increases the Q-factor by 3 to 4 orders of magnitude. The fabricated resonator in the test structure, as well as the schematic of the resonator, is shown in Fig. 1(b) and (c). Fig. 3 shows a comparison between the