

Design and Verification of An Automated Non-contact Dielectric Sensor System

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Summary:

In biosensor research, it's important for the sensor to be non-invasive, label-free, and enable real-time sensing. Microwave dielectric sensors offer a promising solution. Our study proposed a dielectric sensor system integrating sensors and CMOS readout circuits. It measures substance permittivity by analyzing LC oscillator frequency and amplitude via an interdigit electrode antenna. Validation included measuring ethanol and methanol concentrations, showing strong correlation with VNA-measured permittivity. Real-time capabilities were verified by injecting air and DI water using a pump.

Keywords: dielectric constant, LC oscillator, interdigital electrode, permittivity, biosensor.

Introduction

When measuring biological samples, it's crucial for the sensor to be non-invasive, non-labeling, and capable of real-time sensing. Recently, antenna sensor architecture has emerged as a solution to meet these unmet needs. It utilizes electromagnetic waves to measure the permittivity of samples, which represents the relationship between electric displacement and applied electric fields. In a fundamental impedance experiment, we can calculate the complex permittivity as eq. (1) and (2). Admittance measurement reveals complex permittivity and distinguishes materials.

$$\epsilon^* = \epsilon' - j\epsilon'' \quad (1)$$

$$\epsilon' = \frac{Cd}{\epsilon_n A}, \epsilon'' = \frac{d}{RA\omega\epsilon_n} \quad (2)$$

Our study proposed a dielectric sensor system to measure the permittivity of materials under test. This sensor utilizes an interdigit antenna to generate an electric field. In addition, it employs an LC oscillator and incorporates digital readout circuits. Analysis of antenna resonance frequency and amplitude enables material permittivity inference and identification of biological substances.

Design of Dielectric Sensor System

Fig.1 shows the block diagram of the Dielectric Sensor System, which comprises a CMOS dielectric sensor [1], an amplitude readout circuit and a frequency readout circuit. The readout circuits help us digitalize the sensor's signal. The designed circuitry was fabricated by using the TSMC 0.18 μ m process. Besides, we have developed a digital microcontroller (STM32-L452REP) to interface with the readout circuits.

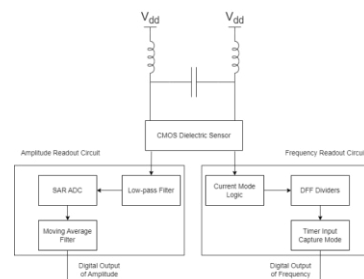


Fig.1 The block diagram of the Dielectric Sensor System.

The CMOS dielectric sensor uses interdigital electrodes as capacitors coupled with off-chip inductors to form an LC oscillator. Cross-coupled pair transistors cancel tank resistance (R_{eq}) for stable resonance.

Fig.2 depicts the schematic of the cross-coupled LC oscillator. At resonance, parallel inductance-capacitance admittance reaches zero, allowing the resonant frequency and amplitude to be derived from eq. (3) and (4) respectively [1].

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (3)$$

$$V = \frac{4}{\pi} I_{tail} R_{eq} \quad (4)$$

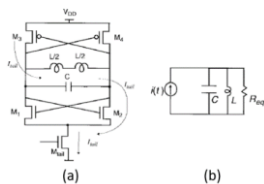


Fig. 2 The cross-coupled LC oscillator. (a) Schematic (b) Equivalent circuit [1]

By solving eq. (1), (2), (3), and (4), we can establish the relationship between the oscillating signal and permittivity. Eq. (5) and (6) show that f^{-2} is linear with ϵ' , and $\frac{1}{Vf}$ is linear with ϵ'' .

$$f^{-2} = 4\pi^2 L \frac{\epsilon_0 A}{d} \epsilon' \quad (5)$$

$$\frac{1}{Vf} = \frac{A\pi^2 L \epsilon_0}{2I_{tail} d} \epsilon'' \quad (6)$$

The frequency readout circuit comprises a current mode logic circuit (CML), frequency dividers, and a timer input capture circuit. The CML converts the oscillating signal to digital logic levels, allowing division by D flip-flop (DFF) dividers. Through 9-stage DFF division, the frequency becomes low enough for detection via the microcontroller's timer input capture mode. Positive edges of the sensor's signal trigger storing the counter value in the compare and capture register (CCR). Sensor frequency is calculated using eq. (7).

$$f_{sensor} = \frac{f_{ref}}{ACCR} \quad (7)$$

We measure the oscillating signal's amplitude by connecting one of the NMOS transistors from the cross-coupled pair to a low-pass filter. After filtering, it becomes a DC signal. The microcontroller reads this DC signal digitally through the embedded SAR SDC at 12-bit resolution, with VLSB at 0.439 mV. This digital output is further filtered using a moving average filter to minimize environmental interference.

Experiments and Results

Fig. 3 shows the device of our dielectric sensor system. We tested its performance by measuring 5 concentrations of ethanol and methanol samples. Parafilm was used to isolate the samples for non-invasive sensing. A 10 mL

sample, with a diameter of 55 mm, was placed directly over the electrode, covering it entirely, at a height of about 4.2 mm. After a one-minute settling time, the system recorded one minute of sensor signals, from which average and standard deviation were calculated.

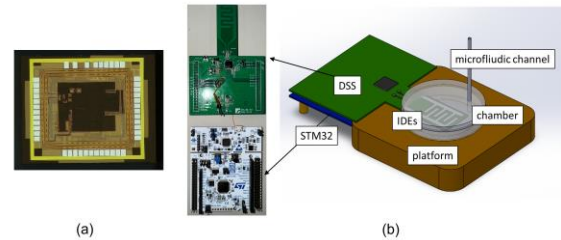


Fig. 3 The device of dielectric sensor system (a) The die photo of CMOS dielectric sensor. (b) The measurement setup.

Fig. 4 shows our sensor's signal correlation with substance permittivity from Vector Network Analyzer (VNA), following eq. (5) and (6). These results affirm high correlation, validating our dielectric sensor system's accuracy and reliability in permittivity measurement.

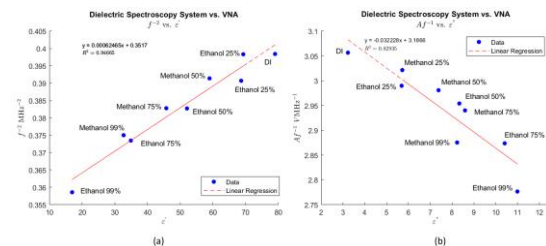


Fig. 4 Sensor output vs. substance's permittivity (a) f^{-2} vs. ϵ' (b) $\frac{1}{Vf}$ vs. ϵ''

To verify its real-time sensing capability, we use a pump to inject DI water and observe the sensor's response over time. Our assumption is that both frequency and amplitude will decrease as DI water has a higher permittivity than air. Once the DI water is fully injected, the pump switches to injecting air. The signal will increase but won't return to its initial level due to the remaining water. Fig. 5 depicts these results, showing a signal decrease at 25 seconds and an increase at 270 seconds, matching our pump settings. These results confirm the real-time sensing capability of our dielectric sensor system.

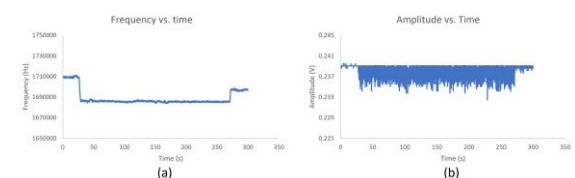


Fig. 5 Sensor output vs. time (a) Frequency vs. time (b) Amplitude vs. time.

References

[1] Wei-Liang Hsu (2022) . A CMOS Biosensor for Sensing Permittivity at Microwave Frequencies.