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Design, Fabrication, and Characterization of an Interdigitated Micro-Capacitive Level Sensor Coupled with Signal Conditioning Circuit

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Abstract. Capacitance-based fluid level switches are extensively used to control cryogen flow in cryogenic storage systems. Despite their popularity, these switches typically require expensive fabrication techniques and complex read-out circuitry; they often have the disadvantages of being heavy and having a large thermal mass. This paper introduces a novel cryogenic liquid point level sensor based on an interdigitated capacitor (IDC) integrated with a signal conditioning circuit on a PCB. The design leverages PCB manufacturing techniques to optimize the sensor's electrode configuration, resulting in a compact and efficient solution. The signal conditioning circuit utilizes matched monostable multivibrators and an Exclusive OR (XOR) gate to convert capacitance changes into stable DC voltage signals. This device can precisely sense cryogen levels and provide fast, reliable switching signals for external control valves. The dynamic response of the sensor in liquid nitrogen (LN_2) is analyzed and presented, demonstrating its potential to improve the accuracy and efficiency of cryogenic liquid-level measurement systems.

1 Introduction

The precise measurement of liquid levels in cryogenic environments is a critical requirement in various scientific and industrial applications. Cryogenic liquids, such as liquid nitrogen (LN_2), are extensively used in fields ranging from medical and biological research to aerospace and energy storage systems. Accurate and reliable sensing of liquid levels in these extreme conditions is essential to ensure the safety, efficiency, and effectiveness of the processes involved.

Capacitive point level sensors are a widely adopted technology for liquid level measurement due to their simplicity, robustness, and relatively low cost. These sensors operate on the principle of capacitance variation, which occurs when the dielectric medium surrounding the sensor changes, such as when a liquid level rises or falls. Interdigitated capacitors (IDCs) are a specific type of capacitive sensor that offers enhanced sensitivity and miniaturization, making them suitable for high-precision applications in constrained environments [1, 2, 3].

The importance of accurate liquid level sensing in cryogenics cannot be overstated. Cryogenic point level sensors must withstand extreme temperatures and maintain high accuracy over a wide range of conditions. Traditional capacitive point level sensors face challenges such as thermal drift, dielectric constant variations, and sensitivity to environmental conditions, which can affect their performance in cryogenic applications.[2, 3]

Despite these challenges, recent advancements in IDC-based sensors have shown promise in addressing these limitations. The IDC sensor's design, characterized by interleaved electrodes, provides a large surface area for capacitance measurement, enhancing sensitivity and stability. Additionally, the integration of signal conditioning circuits can further improve the sensor's performance by filtering noise and compensating for environmental variations. [4]

In this paper, we present a novel cryogenic liquid point level sensor based on an IDC and a detailed design of its signal conditioning circuit. The proposed circuit employs matched monostable multivibrators and an Exclusive OR (XOR) operation to measure capacitance changes in the fractions of picofarads accurately. This approach ensures high precision and reliability, making it suitable for cryogenic applications. An in-depth analysis of the sensor's working principle, the design considerations for the signal conditioning circuit, and experimental results demonstrating the sensor's performance in cryogenic conditions are presented here.

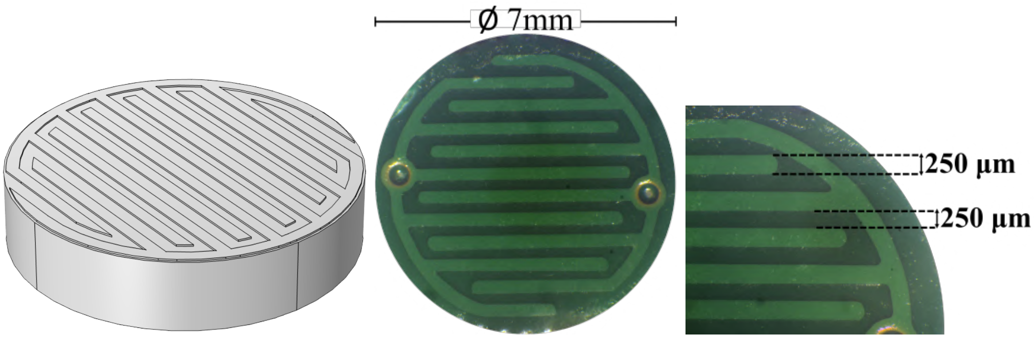
By addressing the current limitations of capacitive point level sensors and leveraging the advantages of IDC technology, this work contributes to the advancement of cryogenic liquid level sensing, with potential applications in various scientific and industrial domains.

2 Inter Digitated Capacitive Sensor

The design of the interdigitated capacitor (IDC) sensor was conducted using finite element method (FEM) simulations in COMSOL Multiphysics, adhering to stringent dimensional constraints. The sensor's diameter was fixed at 7 mm, and the design needed to comply with the limitations inherent in printed circuit board (PCB) manufacturing techniques. These constraints included the minimum width, thickness, and gap between electrodes, which collectively dictated the number of fingers in each electrode.

To optimize the sensor's capacitance, it was essential to maximize the number of interdigitated fingers within the given dimensions. Simulation results indicated that increasing the number of fingers directly enhances the capacitance. The design achieved the maximum number of fingers by employing the smallest possible gap and trace width for the electrodes, as specified by the PCB manufacturer, which in this case were both set to 0.254 mm (10 mils).

Under these parameters, the COMSOL simulation yielded a capacitance of approximately 1.77 pF for the IDC at a frequency of 30 kHz. Figure 1(a) illustrates the COMSOL model of the IDC sensor. Subsequently, the IDC was fabricated using PCB manufacturing techniques, resulting in a measured capacitance of approximately 2.52 pF, as shown in Figure 1(b) and 1(c). The discrepancy between the simulated and measured capacitance values highlights the need for careful consideration of manufacturing tolerances and material properties in practical applications.



((a)) ((b)) ((c))

Figure 1: (a) FEM model of IDC designed in COMSOL Multiphysics. (b) IDC sensor fabricated using PCB manufacturing technique. (c) Interdigitated electrodes width and gap as 0.250 mm or 10 mils

3 Signal Conditioning Unit

The digital electronic circuit designed to measure capacitance changes in the fractions of picofarads is illustrated in the simplified block diagram in Figure 2(a). The circuit comprises two matched monostable multivibrators (MM1 and MM2) that are triggered by a 30 kHz pulse signal [5, 6]. These multivibrators are connected to two RC differentiator, where the duty cycle of each multivibrator is determined by the time constant τ of its corresponding RC circuit.

The RC circuit in the reference path contains a standard capacitor with a capacitance approximately equal to that of the Interdigitated Capacitor (IDC) sensor when immersed in liquid nitrogen (LN_2), which is around 2.16 pF. The IDC sensor is connected to the second RC circuit. Any change in the capacitance of the IDC sensor results in a change in the time constant τ , described by the equation $\tau = RC$. Here, R represents a variable resistor used for the sensor's initial calibration.

The signals generated by the two RC oscillators are then fed into an Exclusive OR (XOR) gate. The XOR operation produces a digital signal with a duty cycle proportional to the difference between the time constants of the two input signals. This resulting signal undergoes inversion to ensure the output voltage is within the 5-volt range before being passed through a low-pass filter. The low-pass filter converts the digital signal into a corresponding DC voltage, which is used to quantify the capacitance change.

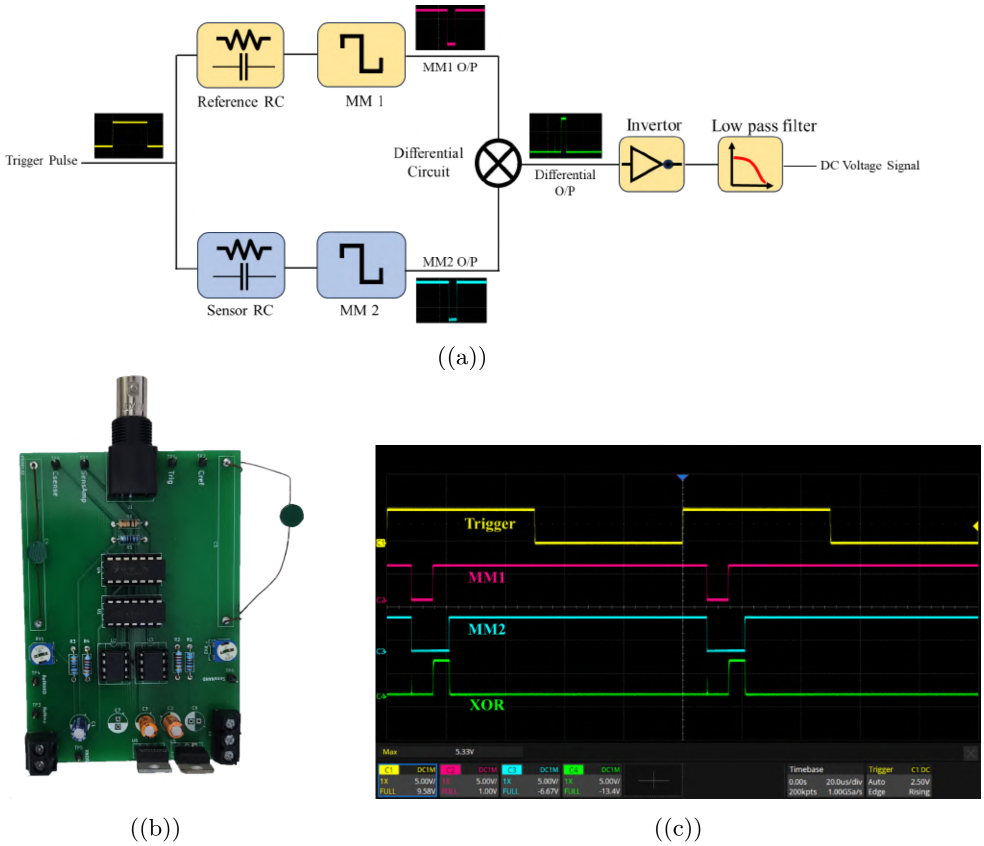
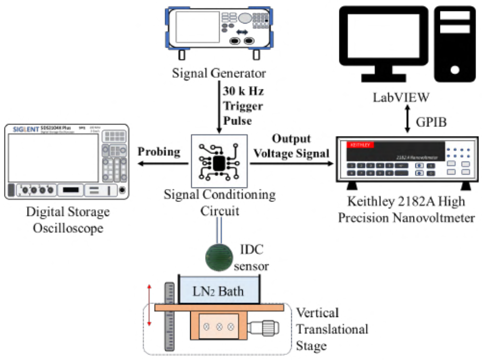


Figure 2: (a) Block diagram of the driving and signal conditioning circuit showing waveforms in each stage. (b) PCB for the signal conditioning unit with IDC sensor. (c) Signal waveform probing each stage of the circuit (waveform obtained when sensor is immersed in LN_2).

4 Experimental Setup and Procedure

The experimental setup was designed to evaluate the performance of a sensor and its signal conditioning circuit. This setup included several key components: a 4-channel oscilloscope, function generator, nanovoltmeter, and data acquisition unit, as shown in Figure 3(a). The sensor and its signal conditioning circuit were mounted above a vertical translational stage, capable of holding an LN_2 in a polystyrene container and designed to move in 1 mm increments to precisely vary the sensor-to-LN_2 surface distance.

The signal generator was used to provide a 30 kHz square wave trigger signal to the sensor and circuit. The oscilloscope was employed to probe different sections of the circuit, while the nanovoltmeter measured the output voltage of the signal conditioning circuit. Prior to conducting the experiments,



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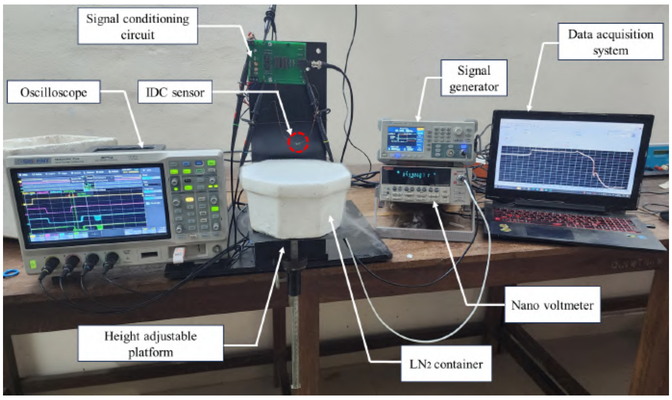

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Figure 3: (a) Block diagram of the experimental setup for characterising IDC sensor in LN_2. (b) Experimental setup for characterising IDC and signal conditioning circuit in LN_2.

the signal generator and nanovoltmeter were calibrated to ensure accurate and reliable measurements. The oscilloscope was also calibrated to correctly display signal waveforms. The adjustable platform was positioned so that the distance between the sensor and the LN_2 surface could be varied with high precision. All components were interconnected, and the LabVIEW software was configured to capture and record data from the nanovoltmeter.

The initial setup for experimental procedure is as shown in Figure 3(b), where the sensor and signal conditioning circuit were securely mounted above the vertical translational stage, and a polystyrene container filled with LN_2 was placed on the platform. The signal generator was then set to output a 30 kHz square wave, which was applied to the sensor. The platform was adjusted in 1 mm steps to vary the distance between the sensor and the LN_2 surface, and at each step, the sensor's response and the conditioned signal were recorded. The oscilloscope captured waveforms from different points in the circuit, and the nanovoltmeter recorded the output voltage. All data were logged into the LabVIEW software for subsequent analysis.

5 Results and Discussions

The response characteristics and sensitivity of the designed IDC sensor were evaluated under cryogenic conditions, specifically with liquid nitrogen (LN_2). The sensor demonstrated a response time of 14.5 mV/s, indicating its capability to quickly detect changes in capacitance as the distance between the sensor and LN_2 varies.

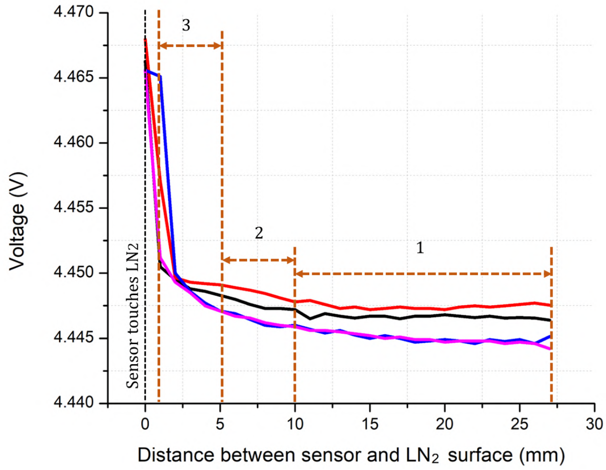
The sensor starts detecting changes in capacitance at a distance of approximately 5 mm from the LN_2 surface. It is observed that the sensitivity measured was nonlinear with respect to the distance of the dielectric medium above the sensor, which is in good agreement with similar other experiments on planar capacitive sensors [7, 8]. The sensitivity measured ranged from 0.5 mV/mm to 1.2 mV/mm as the distance between the sensor and the LN_2 surface varied from 5 mm to 1 mm. This nonlinearity is partly attributed to the temperature-induced changes in the dielectric properties of the FR4 substrate, which become more pronounced at lower temperatures.

Figure 4(a) illustrates the changes in output voltage as a function of the distance between the sensor and LN_2. As the sensor gets closer to the LN_2 surface, the output voltage increases due to the cooling of the sensor and the associated changes in the dielectric constant of the FR4 substrate. The voltage continues to rise more significantly as the sensor approaches the LN_2 surface, reaching a maximum when the sensor touches the LN_2.

Figure 4(b) presents the output voltage plotted against time, with distinct sections corresponding to different distances of the sensor from the LN_2 surface:

1. Sensor in nitrogen vapor/gas: When the sensor is in the nitrogen vapor, far from the LN_2 surface, the vapor is near room temperature. The sensor is unaffected by LN_2 temperatures in this region, and the output voltage remains relatively stable.

2. Approaching LN_2 Surface: As the sensor gets closer to the LN_2 surface, the temperature of the



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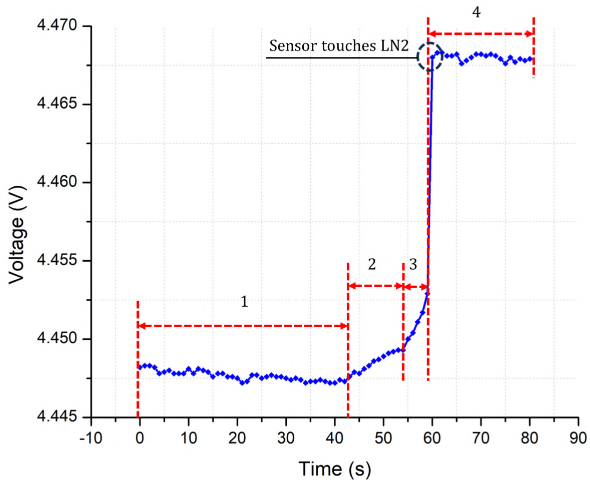

((b))

Figure 4: (a) Variation of output voltage with varying distance between the IDC sensor and the LN_2 surface. (b) The voltage vs time plot of sensor showing different regions corresponding to different distances of sensor from LN_2 surface.

sensor environment decreases, causing an increase in output voltage. This increase is due to the cooling of the sensor and the associated changes in the dielectric constant of the FR4 substrate [7].

3. Sensitive Region (Around 5 mm): At approximately 5 mm from the LN_2 surface, the sensor starts to detect significant dielectric changes, marking the region where the sensor becomes sensitive to the presence of LN_2. This sensitivity continues to increase as the sensor approaches the LN_2 surface.
4. Contact with LN_2 Surface: Upon touching the LN_2 surface, there is an almost instantaneous rise in output voltage, demonstrating the sensor's rapid response. The total change in output voltage (ΔV) is observed to be 25 mV, representing the voltage difference between the sensor in air/nitrogen and the sensor in contact with LN_2.

These results highlight the IDC sensor's high sensitivity and rapid response in cryogenic environments, making it a valuable tool for precise liquid level measurement in various scientific and industrial applications.

6 Conclusion

This study presents the design and evaluation of an interdigitated capacitor (IDC) sensor for cryogenic liquid level measurement using liquid nitrogen (LN_2). Optimized through FEM simulations, the sensor maximizes capacitance within PCB manufacturing constraints. Integration of signal conditioning with matched monostable multivibrators and an XOR gate ensures high precision. The sensor demonstrated a response time of 14.5 mV/s and sensitivity from 0.5 mV/mm to 1.2 mV/mm for varying distances. Experimental results confirm rapid response and high sensitivity, with a total voltage change of 25 mV. The IDC sensor offers a reliable solution for cryogenic applications in scientific research and industry.

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