

Interdigitized capacitive humidity sensor using FR4 printed circuit board material without sensitive layer

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ABSTRACT

Humidity sensors are widely used across numerous applications, including agriculture, health, industry, environmental monitoring, and high-risk environments such as chip fabrication rooms. Interdigital capacitors (IDCs) are among several humidity-sensing designs that have been developed, and they are attractive due to simple fabrication and easy integration with electronic systems. We developed an IDC humidity sensor on a glass-epoxy substrate (FR4) using a standard commercial printed circuit board (PCB) production process. Without additional sensitive layer, the sensor production is simple. The sensor design was explored by varying electrode width. Calibration was performed in a self-constructed chamber over a relative humidity range from 15% to 90%. The IDC sensor was benchmarked against a standard humidity measurement instrument. The IDC capacitance showed a linear correlation with relative humidity, with a correlation coefficient of at least 0.98. With the finest track and spacing size of 0.254 mm achievable via commercial PCB manufacturing and a sensor footprint of 10×10 mm, the capacitance falls in the pF range, compatible with most available electronic devices. The sensitivity of the developed sensors is 2.361×10^{-4} , 2.361×10^{-4} , 2.361×10^{-4} picofarads for a track width of 0.254 mm, 0.3048 mm and 0.3556 mm respectively. These results indicate that mass production of IDC humidity sensors could be achieved at a low cost. The combination of small feature sizes and a compact sensor footprint support practical integration into existing electronic systems.

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1. INTRODUCTION

Humidity is a physical parameter that affects various aspects of life and is of particular concern in several fields. Hospitals, laboratories, museums, computer server rooms, electronic device storage areas, libraries, pharmaceutical storage areas, food industries, document storage areas, food warehouses, and many other facilities require humidity monitoring. Humidity is important because it affects both the stored objects and the processes. Humidity sensors have been developed using various approaches, including fiber-optic, resistive, capacitive, piezoresistive, and magnetoelastic approaches. Resistance-based sensors, such as humidity-resistive sensors, have been developed based on changes in the resistance of the sensitive layer of the sensor. The sensitive layer can be composed of polymers, salts, or other materials that are generally deposited as thin films [1], [2]. For example, layers containing polyaniline as a conductive material are often used in combination with other materials [3]. Materials with specific porosities, such as polymer micropores, have also

been developed as humidity-sensing layers [4]. Nanoparticles are also used as sensitive layers for humidity sensors based on resistive [5] and capacitive principles [6]. Conjugated microporous polymers have been developed as sensitive layers for gas and humidity sensing [7]. A composite polymer using polyvinylidene fluoride-polytetrafluoroethylene (PVDF-PTFE) was developed as a sensitive layer for an electrochemical humidity sensor [8].

Humidity sensors widely available in the market include digital humidity and temperature sensor model 11 (DHT-11) and model 21 (DHT-21), as well as a series of humidity sensors combined with temperature sensors. These sensors are widely used because of their low cost, small size, and ease of use. For example, humidity sensors are used in internet of things (IoT) systems for agriculture [9], environmental monitoring [10], and room humidity [11], and are widely used in the industry for various purposes, such as food processing, textile drying, and semiconductors [12].

Capacitive humidity sensors have been widely developed because of their high sensitivity, rapid response times, and accuracy. Furthermore, these sensors are relatively insensitive to temperature variations and exhibit good linearity and stability. Another advantage is the ease of miniaturization and integration with electronic devices.

The structure of the inter-digital capacitor (IDC) sensor is shown in Figure 1. Figure 1(a) shows a top view of the sensor, where L is the length of the adjacent electrode, a is the distance between the electrodes (electrode gap), and b is the distance between the electrode centers. Figure 1(b) shows a cross-sectional view of the sensor from the rear side, where h is the electrode thickness. A gas or liquid target was placed on the sensor surface. The total capacitance of the IDC is:

$$C_{IDC} = C_U(N - 1)L \quad (1)$$

where N is the number of electrodes and C_U the unit cell capacitance of the paired electrode.

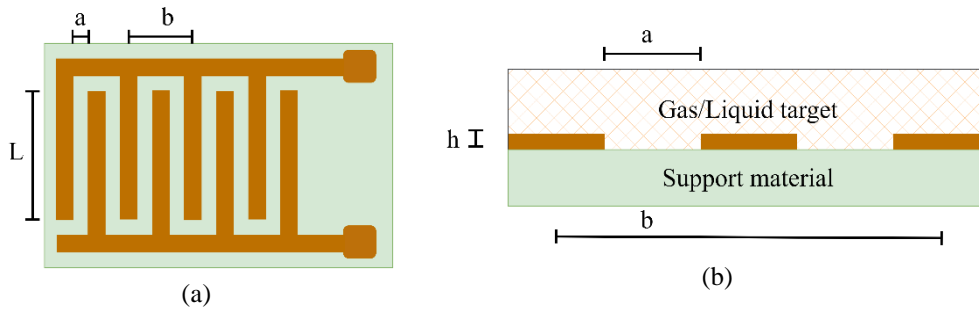


Figure 1. IDC structure: (a) top view and (b) cross section views of pair electrode

The capacitance of the unit cell per length is the sum of the capacitance caused by the gas/liquid target with a permittivity of ε_1 (C_1), capacitance formed by the support material with a permittivity of ε_2 (C_2), and permittivity of the parallel plate capacitor between adjacent electrodes (C_3), expressed as:

$$C_U = C_1 + C_2 + C_3 \quad (2)$$

The values are:

$$C_1 + C_2 = \frac{(\varepsilon_1 + \varepsilon_2)}{2} \varepsilon_0 \frac{K \left[\sqrt{1 - \left(\frac{a}{b}\right)^2} \right]}{K \left[\frac{a}{b} \right]} \quad (3)$$

$$C_3 = \varepsilon_1 \varepsilon_0 \frac{h}{a} \quad (4)$$

Where $K[x]$ is the complete elliptical integral of the first kind [13], [14]. Assuming that the dimensional values of the electrode are constant, the change in capacitance follows the change in the gas/liquid permittivity. The dimensional values of the electrode determine its sensitivity to the target analytes.

Sensitivity is a major concern in the development of capacitive sensors. One approach to increasing the sensitivity of capacitive humidity sensors is to use a mixture of titanium dioxide (TiO_2) and a polymer as the sensitive layer in an metal-insulator-metal (MIM) structure, thereby increasing the capacitance sensitivity per change in humidity [15]. However, this technique involves a multi-step fabrication process. The use of these composites is also advantageous for several reasons. The nanoporous PVDF-graphene (PVDFG)/lithium chloride (LiCl) composite improved the capacitance change of the interdigital capacitor (IDC) sensor with humidity. The hygroscopicity of LiCl and the porosity of PVDF amplify the capacitive effect by enhancing water adsorption. Graphene oxide doping into a P(VDF-trifluoroethylene (TrFE))/LiCl composite [16] improved the sensitivity and response time of the humidity capacitive sensor. The fabrication process is simple and uses drop casting. However, simple drop-casting methods lack surface homogeneity in the sensitive layer. Surface homogeneity and thickness are important as they significantly affect the sensor response. Therefore, careful preparation and fabrication are required.

Ceramics have also been used to improve the performance of capacitive humidity sensors. Copper oxide (CuO) ceramics exhibit large dielectric properties [17], which are interesting to investigate. Graphene is a sensitive material for humidity sensors. A large surface provides a large change in capacitance with humidity [18], [19]. Common substrates for IDCs include silicon [20], glass epoxy (flame retardant 4/FR4) [21], wood [22], and various polymers such as silicone rubbers (polydimethylsiloxane/PDMS, Ecoflex), polyimides, and epoxy resins [23]. The choice of substrate depends on the desired application and properties, such as flexibility, cost, and operating frequency. The IDC sensor is applicable to hard and flexible materials such as polyimide (PI), PDMS, polyester (polyethylene/PE), polyethylene naphthalate (PEN), PTFE, polyethylene terephthalate (PET), and paper [24]–[27]. This paper presents the development of a humidity sensor using standard printed circuit board (PCB) fabrication techniques. The surface of the PCB was masked using a common epoxy liquid used in PCB manufacturing. The sensitivity of the IDC humidity sensor was improved by coating the polymer on a PCB surface.

2. METHOD

The IDC sensor was fabricated using a PCB with a glass epoxy (FR4) substrate. The structure is shown in Figure 2. Figure 2(a) shows a top view of the sensor design. The IDC pattern with 16 electrodes (eight pairs) was coated with epoxy. The electrical lead was opened and gold plated to facilitate the connection and ensure durability. Figure 2(b) shows the rear view of the sensor, where the electrode thickness is significantly smaller than that of the FR4 substrate.

The PCB thickness was 1.6 mm, the used material was FR4-Standard TG 135-140, the copper thickness was 34.8 μm , and the Au surface plating was 25.4 nm. The relative permittivity of FR4 ranges from 3.9 to 4.7. Three different configurations were created with an electrode distance of 0.254 mm and electrode widths of 0.254, 0.305, and 0.357 mm (10, 12, and 14 mils, respectively). Three sensors were used to measure each electrode width. The surface of the IDC sensor was coated with a PCB mask ink material composed of epoxy resin.

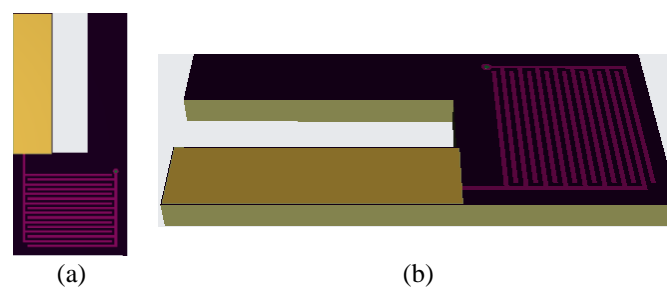


Figure 2. IDC sensor design: (a) top view of the IDC sensor and (b) 3D rear view of the IDC sensor

The humidity and temperature were measured using a PCE-HT 300 temperature-humidity measurement instrument with a humidity accuracy of $\pm 2\%$ for humidity below 80% and $\pm 2.5\%$ for humidity above 80%. The IDC capacitance was measured using a Bode 100 impedance analyzer at a maximum frequency of 50 MHz.

The sensor response to humidity was measured in a static chamber, as shown in Figure 3. The chamber was made of glass and had a volume of 4 L. In Figure 3, “A” shows the silica gel desiccator storage, “B” is the PCE-HT 300 probe, and C is the IDC sensor under test. The humidity in the chamber was controlled (reduced)

by adding a silica gel desiccator. The laboratory humidity during the measurement was approximately 70% and the temperature was 25 °C. The measurement procedure was as follows: first, the humidity sensor probe and IDC sensor were inserted into the chambers. The humidity and temperature of the chamber were measured using a PCE-HT 300 instrument. A small amount of water was injected through a pinhole to achieve a relative humidity of 90 %. The impedance and capacitance values of the IDC sensor were measured using a Bode 100 with a sweep frequency from 100 KHz to 50 MHz. The humidity of the chamber was reduced by filling it with a small amount of silica gel desiccator until the target humidity was reached. The impedance and capacitance of the IDC sensor were measured. The procedure was repeated until the relative humidity of the chamber decreased to 15%. It is difficult to further reduce humidity because of the absorbing capacity of silica gel. However, this is a problem for general-use sensors, except for sensors that measure in extremely dry conditions.

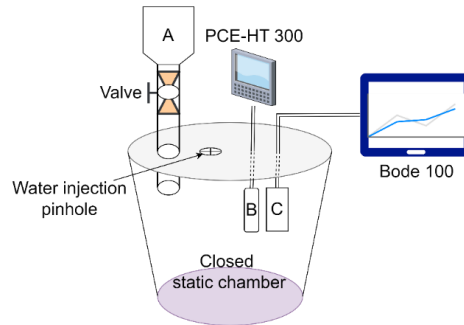


Figure 3. Static chamber for humidity test

3. RESULTS AND DISCUSSION

The epoxy was coated using dip coating of the epoxy liquid, followed by curing. Dip coating is a simple, fast, and cost-effective method. Commercial PCB manufacturers ensure the quality of epoxy coatings. The surface profile of the IDC sensor was measured using a Polytech Microsurf TMS-1200. Figure 4 shows the resulting profiles of the IDC electrodes.

The blue color indicates the sensor surface on top of the electrode, and the red surface indicates the surface of the non-electrode area. It can be seen that, on the same surface level, the coating is homogeneous and there is no uncoated surface. The electrode and non-electrode areas were flat; however, at the border between the electrode and non-electrode areas, the change was not a step change but a gradual change. This demonstrates the effect of epoxy dip coating on IDC surfaces. The electrode thickness was approximately 23 μm compared with 35 μm based on the manufacturing specifications and 43 μm from the work by Mansoor *et al.* [28]. This indicates that the epoxy coating was thicker than that on the top of the electrode.

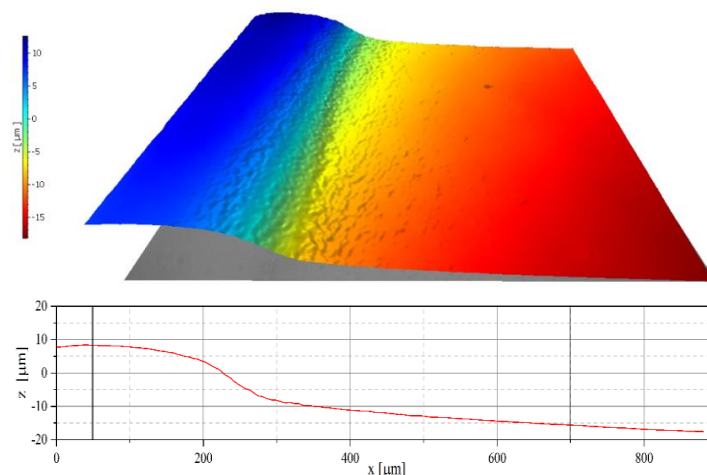


Figure 4. Cross section of finished IDC, electrode thickness is 23 micrometers

The surface profile of the sensor shows that the condition of a sharp-edge IDC surface is not fulfilled; therefore (3) and (4) cannot be directly applied. The measured capacitance of the IDC is expected to be higher than that of the model calculation, assuming that there is no epoxy coating on the IDC. The epoxy coating is assumed to have an electrical relative permittivity higher than 1.

The epoxy coating is an electrical insulator; therefore, when exposed to humidity, there is no electrical conduction between the electrodes. The complete electrical model of the IDC sensor is shown in Figure 5(a). In addition to the capacitance (C), the model has resistance (R) and inductance (L) values. The inductance is formed by the wired length and can usually be neglected, whereas the resistance arises from the electrical conductivity between the electrodes. As the inductance value is very small, it can be neglected, and the model becomes a parallel of capacitance (C) and resistance (R), as depicted in the simplified IDC sensor model in Figure 5(b). It is expected that the parallel resistance of the model will be high and that the IDC will act close to a pure capacitor. Based on the dimensions of the IDC sensor, the basic capacitances of the IDC sensors in dry air were 1.057, 1.049, and 1.076 pF for the IDC with electrode widths of 0.254, 0.3058, and 0.356 mm, respectively. Because the sensor electrode was deposited on the FR4 material, the resistance between the electrodes was very high.

The impedance measurement results of the IDC sensor using the Bode 100 impedance analyzer are shown in Figure 6. It can be seen that the impedance measurement, both in the magnitude and phase, has a smooth curve (less fluctuation) after the frequency of 2 MHz onward. It can be understood that the pure capacitance of the IDC has a high reactance value and hence impedance value at low frequency, as expressed by $X_C = \frac{1}{j\omega C}$, where X_C is the reactance, ω is the angular frequency, and C is the capacitance in farads.

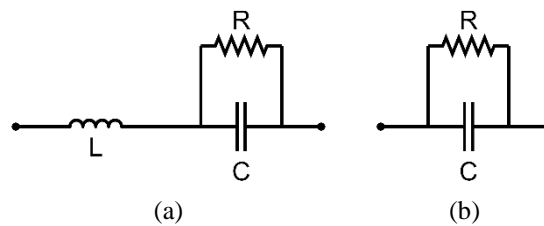


Figure 5. Electrical model of the sensor: (a) IDC sensor and (b) simplified IDC sensor

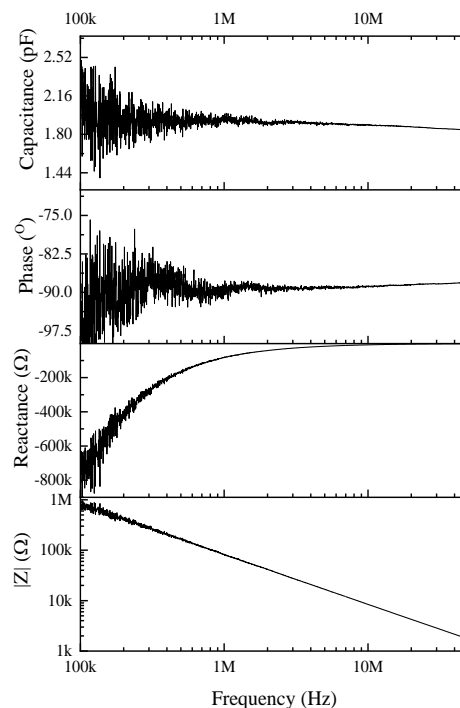


Figure 6. Impedance, reactance, phase and capacitance value of IDC

The reactance and phase of the measured signal were negative, indicating that the device under test using the Bode-100 was capacitive. At low frequencies (< 2 MHz), the phase value, reactance, and capacitance fluctuate considerably. This was caused by the measurement uncertainty of the Bode-100 because the device had a very high impedance value. The value of the impedance (capacitance reactance and resistance) was too high; therefore, the Bode-100 results had high uncertainty.

As the frequency exceeded 2 MHz, the measured reactance and phase exhibited a clear signal. Simultaneously, the impedance value fluctuated less as it decreased. The decreasing impedance value is due to the decreasing reactance of the capacitive part of the IDC. Although the resistance remained high, the reactance decreased as the frequency increased. The measured capacitance of the IDC sensor did not fluctuate significantly at frequencies above 3 MHz. Based on the obtained data, we used the IDC capacitance value at a frequency of 10 MHz for calculations. This frequency was taken as the phase of the sensor was close to -90° and the value of the capacitance was relatively constant, which indicates that the device was close to being purely capacitive.

The results suggest that if the sensor is used in the form of a simple oscillator circuit, the resonance frequency of the oscillator should be set to 3 MHz or higher to achieve a consistent response. This resonance frequency regime is different from that in other studies, which are in the low-frequency regime [29], [30]. The capacitance of the sensor as a function of humidity is shown in Figure 7. The graph shows that the capacitance of the IDC sensor changed linearly with the relative humidity. The linear correlation value was 0.98, indicating a very good relationship between the lowest and highest humidity. Based on (3), we can see that the capacitance value linearly dependent on the ϵ_1 , the permittivity of the air on the sensor surface, while the other parameter is constant. The sensitivities of the developed sensors were 2.361×10^{-4} , 2.361×10^{-4} , 2.361×10^{-4} for track widths of 0.254, 0.3048, and 0.3556 mm, respectively.

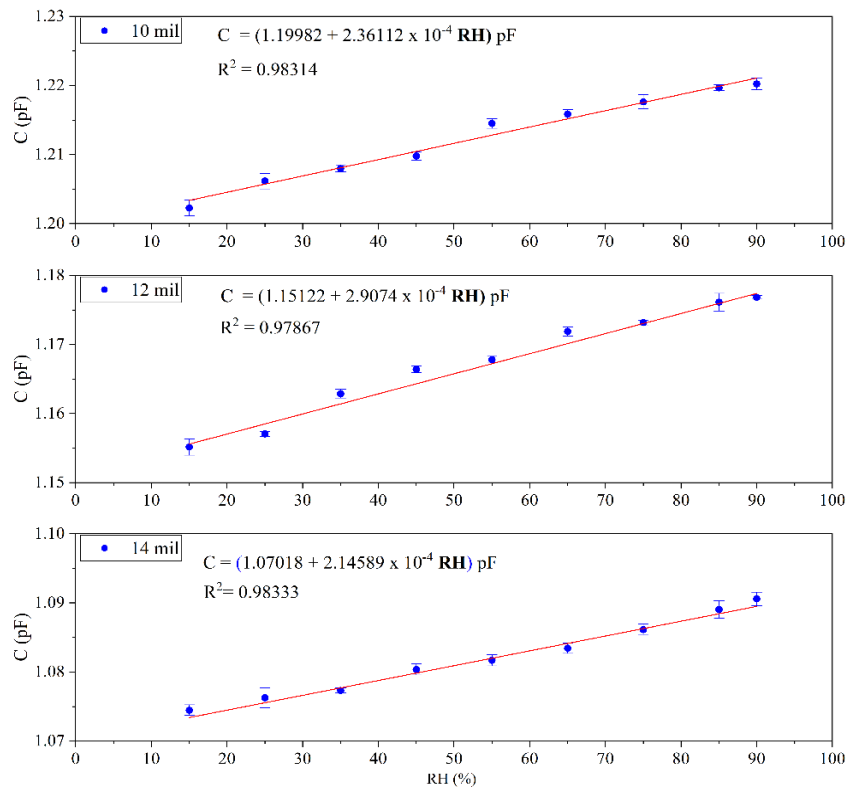


Figure 7. Capacitance change of IDC sensor to humidity

The linear response of the IDC capacitance value with a high correlation indicates that the sensor response can be extended to humidity levels below 15%. This indicates that the sensor can function at low humidity levels. There should be no limitation of the sensor for relative humidity below 15%. The linear change in capacitance with RH up to 90% suggests that the sensor can detect air humidity from dry to humid conditions. The range is comparable to other studies developing IDC using graphene as the electrode material without

additional sensitive material [22], using carbon nanotube composite material [31], polymer-based composite polyvinyl alcohol (PVA)/gelatin/chitin [32], and graphene microporous [7] materials. The uncertainty of detection was also very low for all RH conditions. The standard deviation among the sensors for each relative humidity (RH) detection was less than 0.1%.

The currently common commercial sensors (SHT31, DHT22, and HDC3021) used for comparison show that the sensor has a linear relationship for humidity below 80%, as shown in Figure 8. In our experiment, the commercial sensors were insensitive to relative humidity values > 80%. The RH measured by the sensor showed a small change and even a constant value at RH above 80%. As to SHT31 the datasheet, the best sensor performance is achieved at 20%–80% RH. The HDC3201 datasheet states that the accuracy of the sensor according to the RH range from 10% to 90% RH, and the typical accuracy was 1.5%. A report on calibrating the DHT22 [33] showed that the DHT22 is insensitive to relative humidity changes above 80% RH. The results demonstrate that a humidity sensor can be fabricated simply using an IDC made on a PCB with a standard masking the PCB. This opens the possibility of a very cheap humidity sensor that can be manufactured at a mass-production price from a PCB manufacturer.

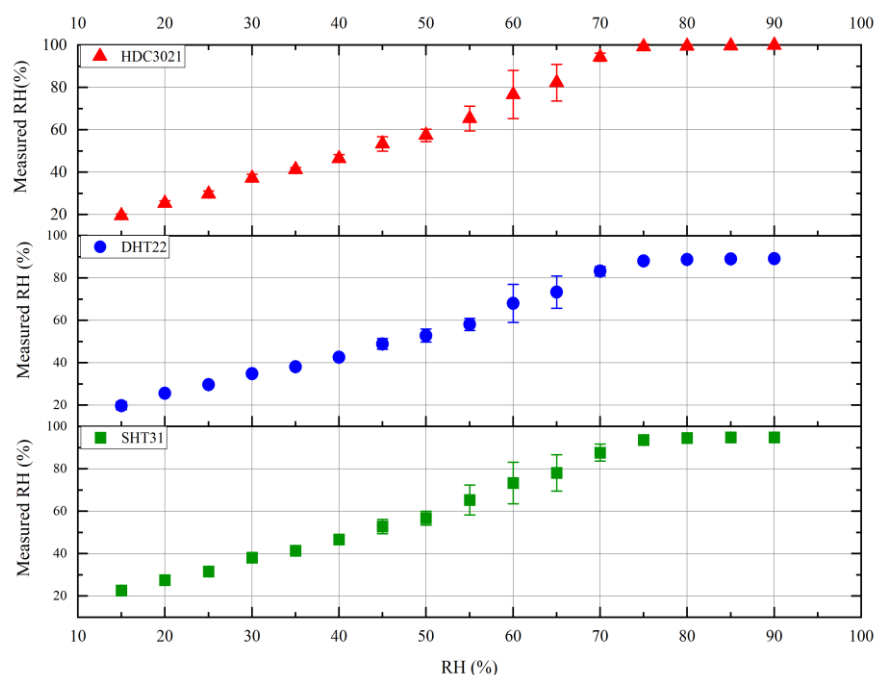


Figure 8. Measured relative humidity by SHT31, DHT 22 and HDC301

4. CONCLUSION

The developed IDC humidity sensor exhibited a good response to humidity. The capacitance value at 10 MHz has a strong linear correlation with air humidity. The IDC fabricated using a PCB with an epoxy coating resulted in shallower areas between the electrodes, resulting in a smaller volume of air. This resulted in a smaller capacitance value for the IDC sensor than that of the theoretical model. However, the capacitance of the IDC sensor with FR4 was highly linear with respect to the humidity. The correlation between the capacitance and relative humidity was 0.98. The sensors linearly responded to relative humidity ranging from 15% to 90% RH. The sensitivity of the developed sensor to RH was very low. Further development is required to enhance the sensor sensitivity and other sensor performance. The measured capacitance range of the IDC using the finest resolution of a commercial PCB maker is a few pF, which is easy to handle with commonly available electronic devices. These results demonstrate the potential of a low-cost IDC humidity sensor using PCB materials and a PCB manufacturing process.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available in this article.




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