Design of a Noncontact Passive *LC*-Based Level Sensor With a Readout System

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***Abstract*— In this article, a noncontact-type wireless and passive level sensor has been presented based on *LC* sensing technique. A novel low-cost and handy readout mechanism has also been proposed here. In the proposed method, LDC1000 has been used to measure the sensing parameter remotely. The designed level sensor consists of a coplanar capacitor which varies with the changing level inside any container. A planar spiral inductor has been used as the reader coil. The change in level varies the fringing field around the capacitor, which changes the capacitance value. The change in capacitance, indicating the changing in level, is measured with impedance analyzer in terms of resonating frequency and real part of the input impedance. The experiment of the level sensor has also been performed with LDC1000-based readout system, which validates the concept of the proposed system. The proposed technique has also been evaluated analytically to deduce the measuring component as a function of the sensing parameter.**

***Index Terms*— Coplanar capacitor, *LC* sensing, level measurement, noncontact sensor, readout circuit.**

I. Introduction

LEVEL measurement plays a crucial role in industrial applications such as chemical processing, food industry, pharmaceutical, fuel storage, water treatment plants, and power generation industries. For level detection in storage tanks, a variety of measuring techniques have been used such as mechanical, electromechanical, electrical, optical, and microwave methods, as per appropriate suitability and ease of installation [1]–[4]. All the methods can be generally categorized into contact–noncontact, invasive–noninvasive, intrusive–nonintrusive, and wired–wireless types. Most of the mechanical, electromechanical, and electrical measurement methods are contact and invasive types.

Capacitive-sensing-based level measurement systems are one of the most popular and basic ones. Three parallel plate capacitors have been designed to eliminate the dielectric effect of air on the measuring level column, where two reference capacitors are present along with the liquid level capacitor [5]. Interdigital capacitive structures are also hugely mentioned in the literature and used to measure the liquid level. The capacitance of it changes with the liquid level between two comb electrodes [6]. The conventional probe-type capacitive level sensors are affected by the excitation frequency of the applied ac voltage. To eliminate this effect, a constant phase impedance sensor has been designed and the changing phase angle has been measured to get the equivalent level [7].

Different noncontact and wireless level sensors are also profusely used for various applications, mostly based on optical and wave-based technologies. Ultrasonic and radar-based level measurements are the most popular ones among these categories. A microwave-based technique has also been designed using a microwave generator and measuring the microwave reflection coefficient [8]. To detect the level inside any storage tank, an acoustic resonance system has been used [9] and the corresponding level has been calculated in terms of resonance frequency. Level measurement has also been performed using optical level sensors. A silica-based fiber Bragg grating (FBG) has been embedded with a diaphragm [10] and the shift in wavelength has been measured, related to the change in liquid level. A noncontact-type liquid level measurement technique has been proposed in [11], where a millimeter-wave-based Doppler sensor has been used to measure the absorption of millimeter wave by the liquid.

Different inductive sensors have also been discussed in literature to measure the level inside any tank. An inductive sensor, comprised two coils of different sizes, has been used for simultaneous measurement of level and conductivity of any liquid [12]. Electromagnetic induction technique based on high-frequency ac signal has been described for liquid level measurement [13], [14], where the phase of mutual inductance and resonating frequency has been measured. In both the cases, the measurement is done with a wired connection which is unsuitable for nonaccessible measurement applications. A nonintrusive inductive-type sensor has been proposed to measure liquid level inside any sealed container [15], using a wire-wound coil and a set of planar coils, stacked on the outside wall of the container by measuring the mutual inductance. Due to its invasive nature, this cannot be useful to measure any corrosive or reactive liquid or for solid materials.

In this present work, a noninvasive and wireless level sensor has been proposed, designed, and experimentally validated based on the *LC* sensing technique. The sensor consists of a coplanar capacitive sensor, integrated with a planar coil and placed on the outer wall of the container. It can also be modified and installed on the inner wall of the measuring tank with proper waterproof coatings. The measurement of the level has been performed using a readout coil positioned near the inductive coil mounted to the container when the measuring data are required without any wired connection. The proposed design can be easily used in industrial applica-

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tions for level measurement in multiple tanks or containers, where only the sensor would be installed on the outside wall of the tank. Instead of using individual signal conditioning circuits for each tank, the measuring level can be detected using a single readout circuit for all the systems. Generally, the readout coil is excited with a high-frequency ac signal during measurement, using costly equipment like spectrum analyzers [16], impedance analyzers [17], or vector network analyzers (VNAs) [16] to get the sensing parameter in terms of frequency spectra or impedance. Other readout methods have also been presented in the literature for *LC*-sensing-based technologies for different applications [18]–[21].

A readout circuit based on LDC1000 has been presented for *LC*-sensing-based measurement to achieve an easier, low-cost, and useful alternative. LDC1000 has been used previously in literature for other applications such as force sensors [22] and hand tremor detectors for Parkinson's disease [23] to measure the equivalent inductances. Here, LDC1000 has been used to wirelessly measure a variable capacitance value, with which a fixed inductor is connected parallel. The readout scheme can be used universally for any *LC* sensor. Till now, LDC has not been explored for the readout purpose of *LC* sensors, and no commercial documents are available on it. In this work, experiments have been performed with the conventional method using impedance analyzer and the proposed method using LDC1000EVM for the same *LC* level sensor.

II. Level Sensing Principle

A. Capacitive Sensing Theory With Liquid Level

The conventional capacitive level sensor is contact-type, invasive, coaxial cylindrical, mostly unsuitable for various applications. It works with the concept of parallel plate capacitors, where the electric field is distributed uniformly without considering the fringing field effect. Capacitive-sensing-based level measurement can also be done noninvasively inside any nonmetallic container, using the concept of coplanar capacitor [24]. But for the coplanar capacitor, the two plates lie on the same plane, and the fringing field becomes the dominant electric field.

To perform coplanar capacitor-based level measurement, two electrodes or metal strips are mounted on the outer wall of the container. Due to the planar structure of the capacitor, it can be easily mounted on most surfaces. The length of electrodes must be greater than or equal to the height of level to be measured, as shown in Fig. 1. Due to the fringing effect, any variation in the dielectric of the surrounding substances changes the value of coplanar capacitance. The sensing performance of coplanar capacitive sensor depends on various parameters such as shape and size of electrodes, spacing between electrodes, and width of electrodes. It also affects the electric field strength, penetration depth of the field lines, and sensor's sensitivity. To eliminate stray capacitance and undesired EMIs, shielding and guarding is very important.

The capacitance of a coplanar capacitor, due to the presence of the dielectric material on one side of it, can be expressed as [25]

$$C = \varepsilon l_c \frac{K(\kappa')}{2K(\kappa)} \tag{1}$$

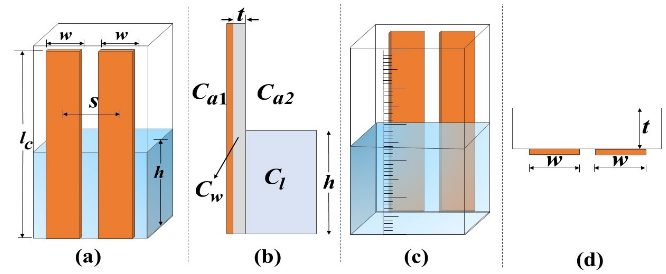


Fig. 1. Design and arrangement of coplanar capacitor for liquid level measurement. (a) Front view. (b) Side view. (c) Backside view. (d) Top view.

where ε is the dielectric constant of the present dielectric material, l_c is the length of the coplanar electrode pair, $K(\kappa)$ and $K(\kappa')$ are the complete elliptic integrals of first kind, and κ and κ' are the coefficients depending on the geometric parameters of the capacitor, which can also be related by the following equations:

$$\kappa = \frac{\tanh\left(\frac{\pi s}{4t}\right)}{\tanh\left(\frac{\pi(w+s/2)}{2t}\right)} \tag{2}$$

$$\kappa' = \sqrt{1-\kappa^2}. \tag{3}$$

Here, s is the separation between the two electrodes, t is the thickness of the electrodes, and w is the width of the electrodes, as shown in Fig. 1(a).

Equation (1) can also be written in a simplified manner as following:

$$C = l_c \cdot \varepsilon \cdot f(s, w, t). \tag{4}$$

From (4), it can be observed that the function $f(s, w, t)$ of the coplanar sensor is independent of the length of the electrodes.

When the level inside any container is measured using coplanar capacitive sensor, the arrangement of the sensor would be as per Fig. 1(b), surrounded with different dielectrics around it. At the outer side of the container, the dielectric is air throughout the length of the sensor. On the opposite side, different dielectric layers are present, such as the dielectric of the container wall, the dielectric of the material present inside the container, and the dielectric of the air. So, the total capacitance of coplanar capacitor for this arrangement is formed by four capacitive elements due to different dielectrics and can be expressed as [26]

$$C = C_{a1} + C_l + C_w + C_{a2} \tag{5}$$

where C_{a1} is the capacitance outside the container due to air, C_w is the capacitance due to the dielectric of the container's wall, C_l presents the capacitance due to the height of the material column inside the container, and C_{a2} is the capacitance for air in the upper portion of the container. All the capacitive elements can be calculated as per (4) and written as

$$\begin{aligned} C = {} & l_c \cdot \varepsilon_a \cdot f(s, w, \alpha) + l_c \cdot \varepsilon_w \cdot f(s, w, t_w) \\ & + h \cdot \varepsilon_l \cdot f(s, w, \alpha) + (l_c - h) \cdot \varepsilon_a \cdot f(s, w, \alpha) \end{aligned} \tag{6}$$

where h is the height of the material column inside any container and l_c is the length of the coplanar electrode pair. ε_a, ε_w, and ε_l are the respective dielectric constant of air, container wall, and the material inside the container. For

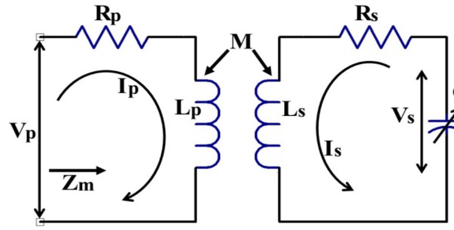


Fig. 2. Basic conceptual circuit diagram of the *LC* sensor.

level measurement using coplanar capacitive sensors, it is not needed to calculate the entire capacitive elements separately and individually. For the calculation of C_{a1}, C_l, and C_{a2}, the thickness of the respective dielectric material has been considered infinite. As per (6), all the parameters have constant value and only h varies due to level changing level of the measuring material. So, (6) can be represented as

$$C = h \cdot (\varepsilon_l - \varepsilon_a) \cdot f(s, w, \alpha) + C_0 \tag{7}$$

where

$$C_0 = 2l_c \cdot \varepsilon_a \cdot f(s, w, \alpha) + l_c \cdot \varepsilon_w \cdot f(s, w, t_w). \tag{8}$$

Actually, C_0 is the capacitance of the coplanar sensor when the container is empty. Now, (7) can be rewritten as

$$C = K_1 h + K_2 \tag{9}$$

where K_1 and K_2 are constants and can be written as

$$K_1 = h \cdot \left(\varepsilon_{liq} - \varepsilon_{air}\right) \cdot f(s, w, \alpha) \tag{10}$$

$$K_2 = C_0. \tag{11}$$

So from (9), it can be concluded that the capacitance change in the coplanar capacitor has a linear relationship with the level.

B. LC Sensing Using Coplanar Capacitor

The noncontact-type coplanar capacitive sensor is modified to an *LC*-based measurement to get a passive wireless level sensor. For *LC*-sensing-based systems, two coupled coils are needed, which are inductively coupled via mutual inductance. The basic principle of the *LC* sensing has been shown using a circuit diagram in Fig. 2. The primary side or reader side consists of an inductor L_p which is supplied with a high-frequency ac sweeping voltage V_i. The secondary or sensor side is formed by inductor L_s and a variable capacitance C_s. R_p and R_s are the respective equivalent series resistance of inductors L_p and L_s. I_p and I_s are the currents through primary and secondary coils, respectively.

The variable capacitor here is actually the sensing capacitor, changes with level. In this design, the capacitance of the sensing coplanar capacitor changes linearly with the level inside the container as per (9). The designed inductors on both sides are square planar spiral coils. The variation in the capacitance value changes the mutual coupling M between two coils, which is further translated into a shift in resonance frequency and also changes the maximum real part of the magnitude of impedance in the reader side. Thus, the measuring parameter level can be measured wirelessly and passively.

The change in the resonance frequency and the impedance characteristics can be detected using impedance analyzer which is connected to the reader coil. It also acts as the ac voltage source to the antenna. The impedance, seen from the reader side Z_m, is given by [17]

$$Z_m = R_p + j2\pi f L_p + \frac{(2\pi f M)^2}{R_s + j\left(2\pi f L_s - \frac{1}{2\pi f C_s}\right)^2} \tag{12}$$

where f is the sweep frequency of the ac signal. The above equation can also be represented as [17]

$$Z_m = R_p + j2\pi f L_p \left(1 + \frac{\left(k \cdot \frac{f}{f_r}\right)}{1 + j\frac{1}{Q}\frac{f}{f_r} - \left(\frac{f}{f_r}\right)^2}\right) \tag{13}$$

where k is the coupling coefficient between the inductors, f_r is the resonant frequency, and Q is the quality factor of the *LC* tank circuit; f_r and Q can be written in the form of

$$f_r = \frac{1}{2\pi\sqrt{L_s C_2}} \quad \text{and} \quad Q = \frac{1}{R_s}\sqrt{\frac{L_s}{C_2}}.$$

Now, the real part of impedance Z_m can be given by

$$Re(Z_m) = R_p + 2\pi f L_p k^2 Q \cdot \frac{\frac{f}{f_r}}{1 + Q^2\frac{f}{f_r} - \left(\frac{f}{f_r}\right)^2}. \tag{14}$$

The real part of Z_m becomes the maximum at the resonant frequency f_r. If the maximum of the real part of Z_m is presented as $Z_{\max}$, it can be written as

$$Z_{\max} = R_p + 2\pi f_r L_p k^2 Q = R_p + L_p k^2 \cdot \frac{1}{R_s C_s}. \tag{15}$$

So from (13) and (15), the shift in resonance frequency and the maximum value of the real part of the impedance can be measured, which gives the changes in level in the sensor side.

III. Readout System

A. Conventional Method

The basic and most important characteristics of *LC* sensing technology are its noncontact and passive-type characteristics. When the measuring data are required, only then the primary or readout circuit is used to get the change in measuring parameter in the sensing side. The readout circuit is supplied with a high-frequency ac signal to induce voltage in the sensing side. Generally, impedance analyzers or VNAs are used to provide the ac voltage and to measure the changing parameter. Here, the experiment has been first performed using an impedance analyzer to measure the designed *LC*-based level sensor and verify its sensing principle. From the impedance analyzer, the change in resonance frequency and the impedance value have been measured with the change in liquid level according to (13) and (15).

B. Proposed Method

To get a low-cost and handy technique for the measurement of *LC* sensors, an LDC1000-based alternative measurement procedure has been proposed here. As impedance analyzers, spectrum analyzers, or VNAs are very costly and bulky, those are not always suitable for on-site measurements and industrial applications. On other contrast, LDC1000-based readout circuit can be easily used on-site, due to the small form factor, low power consumption, and digital output.

LDC1000 is an inductance-to-digital converter, designed by Texas Instruments for applications of inductive sensing. It can measure the resonance frequency and the parallel impedance of an *LC* tank circuit, connected to it. The basic working principle of LDC1000 is shown in Fig. 3(a). Its primary application is to sense any metal target and detect location and movement between two surfaces. According to Fig. 3(a), LDC1000 is connected to an *LC* resonator. An ac current flows through the inductor, producing an ac magnetic field. The produced magnetic field creates an eddy current and induced voltage to any nearby conductive material. The induced voltage in conductive material generates its own magnetic field, opposite to the original field in the LDC side. As a result, a change occurs in inductance and parasitic resistance values, connected to the LDC. The eddy current produced in the conductive material depends on the distance between the two coils, composition, size, etc.

Fig. 3(b) shows the Norton-equivalent circuit or the equivalent parallel model of the diagram presented in Fig. 3(a). As mentioned earlier, LDC1000 is designed to measure the parallel impedance. Hence, to use LDC1000 for the readout purpose, the parallel equivalent or Norton-equivalent circuit has been used and analyzed here. Generally, $R_{p\text{Sensor}}$ is measured as a function of distance in various applications of LDC. If Figs. 2 and 3(a) are analyzed and compared, it can be realized that both the circuits follow the same working principle. So, instead of measuring distance, the change in capacitance can also be measured using LDC1000. For any *LC* sensing, measurement is generally performed by maintaining a constant distance. To measure the change in capacitance and to use LDC1000EVM for readout purpose, the *LC* tank circuit is needed to be placed with a changing capacitor as per Fig. 3(a). With a fixed distance between two inductors, any change in capacitance value further affects the current induced in the tank circuit. The changing current further alters the original magnetic field and $R_{p\text{Sensor}}$ value. According to Fig. 2, the voltages V_p in the reading side and the sensing side are

$$V_p = R_p I_p + j \cdot 2\pi f L_p I_p + j \cdot 2\pi f M I_s \tag{16}$$
$$V_s = R_s I_s + j \cdot 2\pi f L_s I_s + j \cdot 2\pi f M I_p. \tag{17}$$

As V_s is the voltage across capacitor C_s, it can also be expressed as

$$V_s = j \cdot \frac{1}{2\pi f C_s} I_s. \tag{18}$$

Equation (18) can also be expressed as

$$I_s = -j \cdot 2\pi f C_s V_s. \tag{19}$$

As the current I_s changes with the changing C_s value according to (19), it can be written as

$$I_s = f(C_s). \tag{20}$$

If Fig. 3(b) is considered, then it can be written as [28]

$$V_{pL} = L_{pL}\frac{dI_{pL}}{dt} - M(d) \cdot \frac{dI_{sL}}{dt} \tag{21}$$

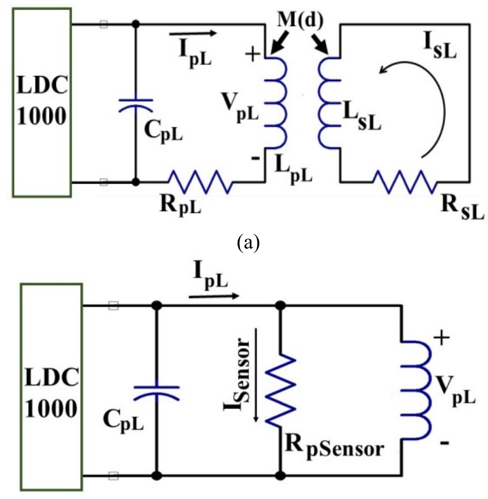


Fig. 3. (a) Basic principle of LDC1000 [28]. (b) Norton-equivalent circuit.

where V_{pL} is the voltage across the L_{pL} inductor connected to the LDC and L_{sL} is the inductor of the conductive target material. I_{pL} and I_{sL} are the currents through the inductors L_{pL} and L_{sL}, respectively, and R_{pL} and R_{sL} are the respective parasitic resistances of the inductor L_{pL} and L_{sL}. $M(d)$ is the distance-dependent mutual coupling between the two inductors in LDC applications. In the Norton-equivalent circuit in Fig. 3(b), if the equivalent parallel resistance is $R_{p\text{Sensor}}$ and the current through it is I_{Sensor}, then the voltage across the inductor is written as [28]

$$V_{pL} \approx I_{\text{Sensor}} \cdot R_{p\text{Sensor}} \tag{22}$$

and

$$R_{p\text{Sensor}} = \frac{1}{R_{sL}} \cdot \frac{L_{pL}}{C_{pL}}. \tag{23}$$

If the changing capacitor C_s is connected to the secondary side of Fig. 3(a), the system will be compatible as per the *LC*-sensing-based measurement system. The change in capacitance in C_s can be detected and measured. So, from (21), it can be stated as follows:

$$V_{pL} = f(I_{sL}) = f(C_s) \tag{24}$$

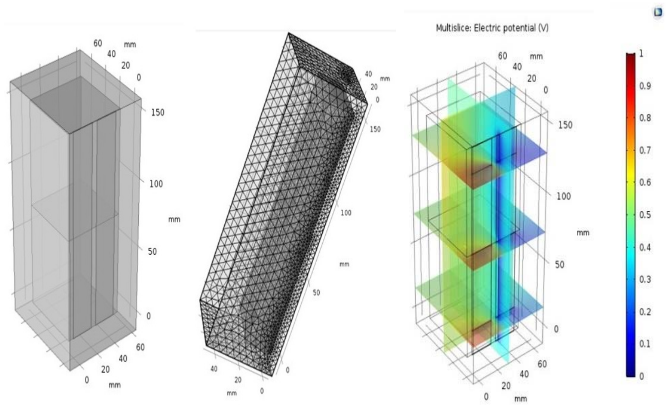
and

$$R_{p\text{Sensor}} = f\left(V_{pL}\right) = f(C_s). \tag{25}$$

So, any change in C_s value will change the value of $R_{p\text{Sensor}}$, which can be easily monitored using LDC1000.

IV. Simulation-Based Analysis for Capacitive Sensing

To verify the coplanar capacitive sensing principle for the proposed level sensor, finite element analysis (FEA)-based simulation has been done using COMSOL Multiphysics. It has also helped to design the sensor coil and the reader coil for the experimental setup design of *LC* sensing. For the simulation, an electrode pair has been designed as per the actual design parameters of the prototype. The modeled electrode pair is adjacent to a cuboid column to represent the liquid level inside



(a) (b) (c)

Fig. 4. Simulated results of coplanar capacitor with varying level. (a) Designed model. (b) Meshing of designed system. (c) Electric field across design.

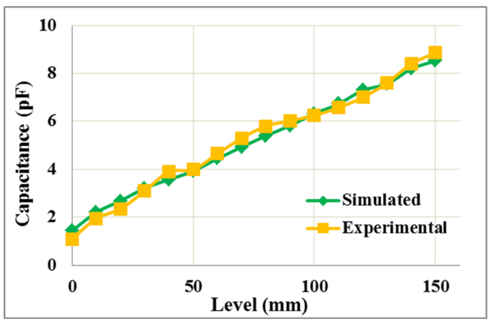


Fig. 5. Characteristics between level and capacitance of coplanar capacitor.

any container, as shown in Fig. 4(a) and (b). The dielectric constant inside the column has been changed gradually from 1 (dielectric constant of air) to 80 (dielectric constant of water) to observe the change in capacitance when the liquid level increases. In this simulation, to get the capacitance change, a dc voltage of 1 V has been applied to one electrode, and the other one has been grounded to generate an electric field between the two electrodes. At first, the total column length has been applied with the dielectric of air to indicate the empty container. Then, to show the change in water level, the dielectric constant has been changed gradually inside the cuboid.

Finally, the full length of the cuboid has been assigned with the dielectric constant of water. The electric potential across the electrodes has been changed too with the changing dielectric, as shown in Fig. 4(c). From the recorded electrical energy values across the electrodes, the capacitance between the two has been computed. The capacitance has also been measured with the changing liquid level using Hioki LCR meter. Both the simulated and the measured values of the capacitance are presented in Fig. 5.

V. Sensor Fabrication and Experimental Setup

The proposed *LC*-sensing-based level measurement scheme has been demonstrated experimentally using a basic prototype sensor. For the experiment, a 150-mm-long coplanar capacitive sensor has been designed and fabricated as a flexible one on a transparent 100-μm polyester film. One side of the film has been covered fully with copper tape of 35-μm thickness. At the other side of the film, two copper strips with 25-mm width have been attached, with a separation of 5 mm in between to form the electrode pair as presented in Fig. 6.

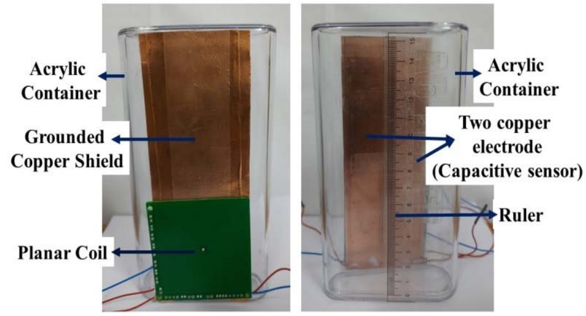


Fig. 6. Designed coplanar capacitor and spiral sensor coil.

TABLE I
Designing Parameters of Capacitor and Inductors

Component	Parameter	Details
Coplanar Capacitor	Length	150 mm
	Total width	60 mm
	Width of single electrode	25 mm
	Thickness	0.125 mm
	Separation	5 mm
	Substrate	Polyester film, 100 µm
Sensor Coil & Reader Coil	Track width	0.254mm
	Track thickness	35 µm
	Spacing	0.254mm
	Number of turns	50
	Outer diameter	60 mm
	Inner diameter	5 mm
	Substrate	Glass epoxy, 1.6mm

The backside of the sensor, which is entirely covered by the copper layer, is grounded as a guard electrode. The sensor and the reader coils have been designed identically. Two square planar spiral coils have been fabricated on double-sided glass epoxy PCB with a size of 60 mm $\times$ 60 mm. The width of the copper tracks is 0.254 mm and the separation between the two tracks is also 0.254 mm. Both the ends of the spiral coil have been connected to the pads so that the header pins can be soldered for connections. All the detailed specifications of the coplanar capacitor and the planar coils are mentioned in Table I.

To conduct the experiment, an acrylic container has been taken to measure the water level inside it. The height and width of the container are 160 mm and 95 mm, respectively. The thickness of the container wall is 1 mm. The designed coplanar capacitor and the sensor coil have been connected to form an *LC* tank circuit. The flexible planar capacitor has been placed on the outside wall of the container using double-sided tissue tape. A copper strip of size 150 mm $\times$ 60 mm has been placed as the grounded guard electrode, as shown in Fig. 7.

To place the reader coil, one platform cum stand has been designed in such a way that the distance between the sensor coil and the reader coil can be easily varied. During the experiment, the container has been gradually filled with distilled water (dielectric constant of 80) to measure its level. The measurement has been done in steps of 1 cm. So, totally 16 data have been taken with the changing water level for a 150-mm-long coplanar capacitive sensor. The capacitance of the coplanar capacitor has been measured using Hioki LCR

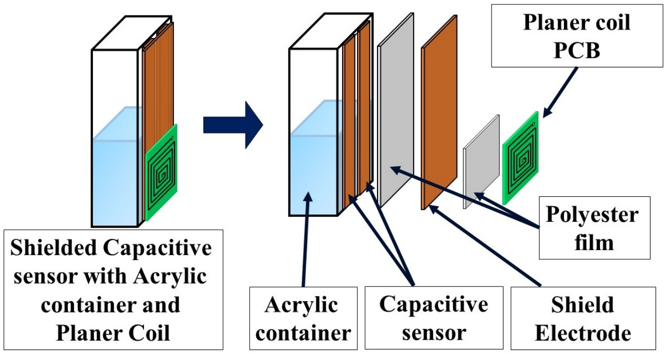


Fig. 7. Placement and arrangement of coplanar capacitor and spiral sensor coil.

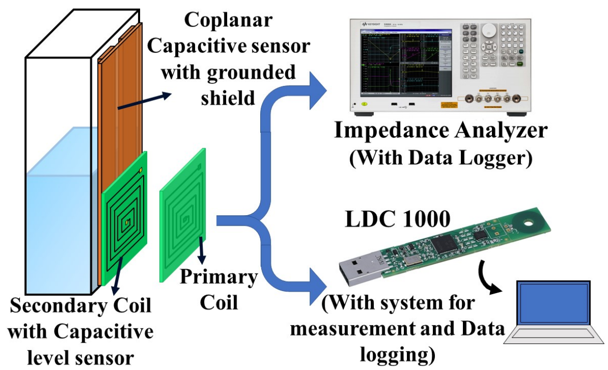


Fig. 8. Graphical representation of the proposed LC-based level measurement.

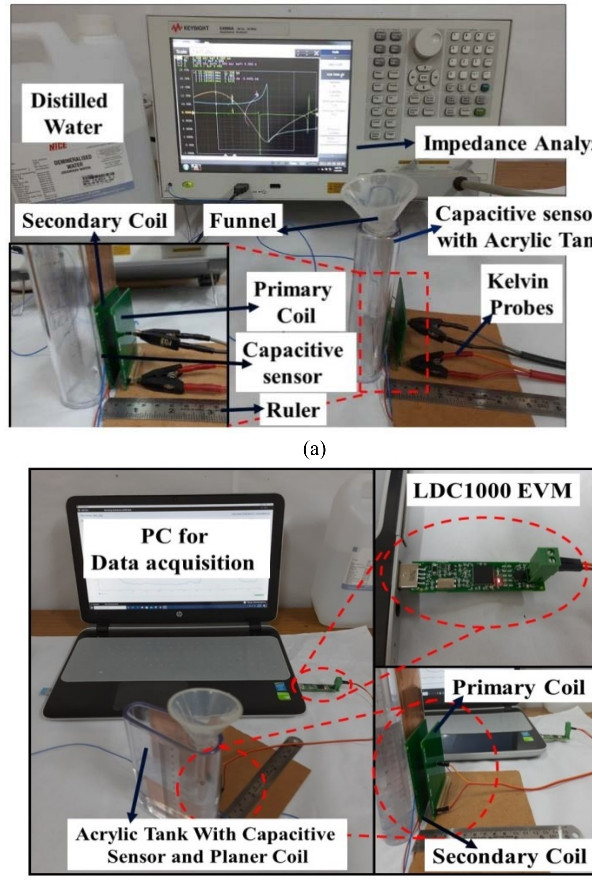
meter with the changing water level and the measured data are presented in Fig. 5. The experiment has been carried out both with the impedance analyzer and LDC1000 for readout purposes. First, the reader coil has been connected to an Agilent E4990A impedance analyzer using Kelvin probe. Four-port measurement has been performed with an ac sweeping frequency around 1–5 MHz to get the equivalent impedance value.

The experiment has then been repeated using LDC1000 and the reader coil has been connected to a terminal port, mounted on the edge of LDC1000EVM. LDC1000 has an operating resonating frequency range of 5 kHz–5 MHz. The designed reader coil has a higher value of self-resonating frequency than the particular range. So, during the measurement, a capacitor of 47 pF has been connected in parallel to the reader coil to bring down the resonating frequency into that particular range. To fetch the measured data, LDC1000EVM has been connected with a dedicated GUI on the computer. The measurement has been started with an empty container and the corresponding data have been measured. The experiment has been repeated for ten times to get the average data and for two different coupling distances of 4 mm and 6 mm between the sensor and the reader coil, using both impedance analyzer and LDC1000. The graphical representation of the proposed *LC*-based level measurement is presented in Fig. 8.

VI. Results and Discussions

The experiment has been performed in two steps. First, the measurement has been done using an impedance analyzer, as shown in Fig. 9(a). An ac sweeping voltage has been applied to the reader coil connected to it. The sweeping frequency ranges from 1–5 MHz for liquid levels of 0–150 mm. The distance between the two coils has been precisely maintained for a constant coupling factor as the coupling coefficient has a vital role for measurement. The sensor coil and the reader coil have been kept separated by two different distances of 4 mm and 6 mm, and measurement has been done in both the cases individually to observe the effect of coupling distance. The measured resonance frequency f_r and the real part of the input impedance Z_m have been obtained from the impedance analyzer for all the 16 different liquid levels. Fig. 10(a) and (b) shows resonating frequency characterization with the real part of the input impedance Z_m for 4-mm and 6-mm coupling distances, respectively. In both the figures, it can be seen that the resonance frequency and the real part of the input impedance decrease monotonically to the lower range with the increase in liquid level inside the container, as per (13) and (14). From Fig. 10(a) and (b), it can be observed that the range of the real part of the impedance differs due to different coupling distances. In Fig. 10(a), the measured impedance with 4-mm coupling distance possesses higher values compared with Fig. 10(b) with 6-mm coupling distance.

The measurement has been repeated for ten times for each coupling distance. Fig. 11 shows the characteristics curves between the sensor's resonating frequency and the liquid level for the average data obtained from the measurements. The characteristic curves between $Z_{\max}$ and liquid level are



(a)

(b)

Fig. 9. Photographic view of the experimental setup. (a) With impedance analyzer. (b) With LDC1000.

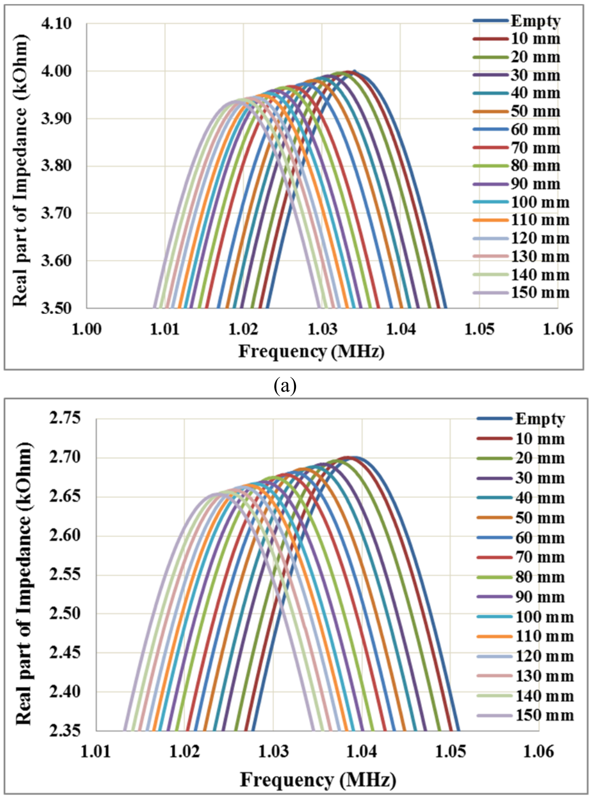


Fig. 10. Measured resonant frequency and real part of the impedance with different liquid levels (a) with 4-mm coupling distance and (b) with 6-mm coupling distance.

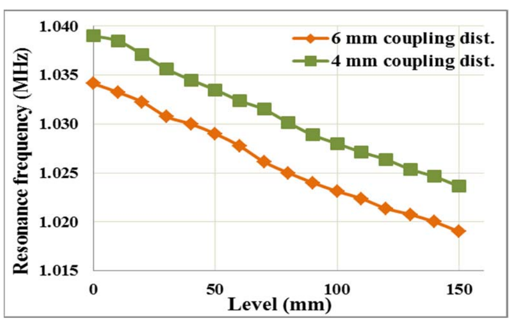


Fig. 11. Characteristics curve between level and resonating frequency.

presented in Fig. 12(a) and (b) for 4-mm and 6-mm coupling distances, respectively. Fig. 11 shows a linear relationship between the resonating frequency and liquid level. $Z_{\max}$ also changes with a linearly changing level of water. The sensitivity of the designed level sensor is 112.5 Hz/mm and 93.75 Hz/mm in terms of resonating frequency for coupling distances of 4 mm and 6 mm, respectively. The change in the real part of impedance with changing liquid level is relatively small. In terms of impedance, the respective sensitivities for coupling distances of 4 mm and 6 mm are 0.375 Ω/mm and 0.315 Ω/mm. The sensitivity in both the cases is better for lower coupling distance due to stronger mutual coupling.

In the second stage, the measurement has been repeated with LDC1000 for the readout purpose. The experimental setup of the designed level sensor with LDC1000 is presented in Fig. 9(b). In this case also, the container has been gradually filled with water, and the data have been noted down

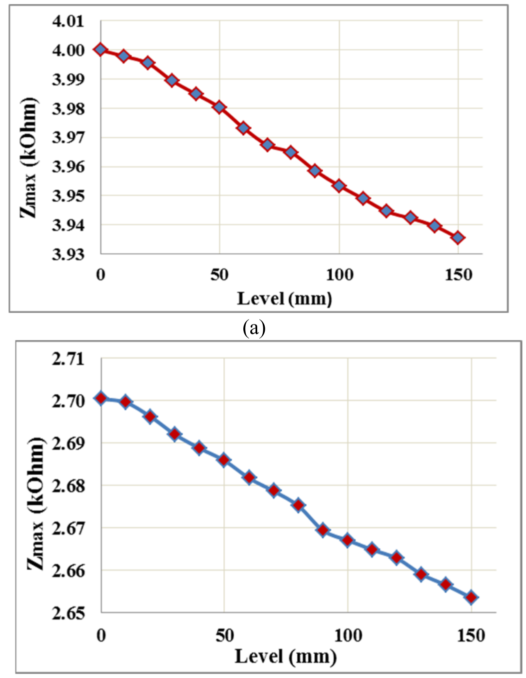


Fig. 12. Characteristics curve between level and maximum real part of impedance (a) with 4-mm coupling distance and (b) with 6-mm coupling distance.

for $R_{p\text{Sensor}}$ using the dedicated GUI for LDC1000EVM in each step. The experiment has also been conducted for ten times in this setup. The average value of $R_{p\text{Sensor}}$ of all the measurements has been presented with respect to the liquid level in Fig. 13 for both 4-mm and 6-mm coupling distances. The characteristic between $R_{p\text{Sensor}}$ and the liquid level presents a linear relationship for both the distances, though the ranges are different. The sensitivities of the designed level sensor with this proposed readout system are 1.29 Ω/mm and 1.21 Ω/mm for coupling distances of 4 mm and 6 mm, respectively. As LDC1000 can measure the change in $R_{p\text{Sensor}}$ with 16-bit resolution, nominal changes in resistance value can be detectable and measured too. While using the impedance analyzer, it has been observed in Fig. 12(a) and (b) that the measured impedance range is higher for lower coupling distance as it depends on mutual coupling. But in Fig. 13, it is just the opposite with the measurement of LDC1000. Because with LDC1000-based readout mechanism, the parallel impedance has been measured, and it changes inversely to series resistance and impedance value as per (23). So, by measuring $R_{p\text{Sensor}}$ value, it can be possible to measure the changing parameter, and LDC1000 can be used for readout purposes for any *LC*-sensing-based measurement.

The experiment has been performed for a water level from 0 to 150 mm. The same concept can be used to increase the range of water level sensor by increasing the length of electrode pairs. The experiment has been repeated for ten times in the span of one week to analyze the measurement errors and reproducibility of the designed system. In Fig. 14, standard deviation and reproducibility have been plotted to analyze the measurement error and preciseness of the experimental system in terms of resonance frequency, real part of the maximum amplitude (measurement with impedance analyzer), and equiv-

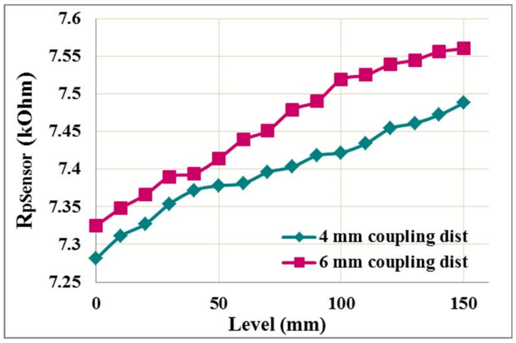
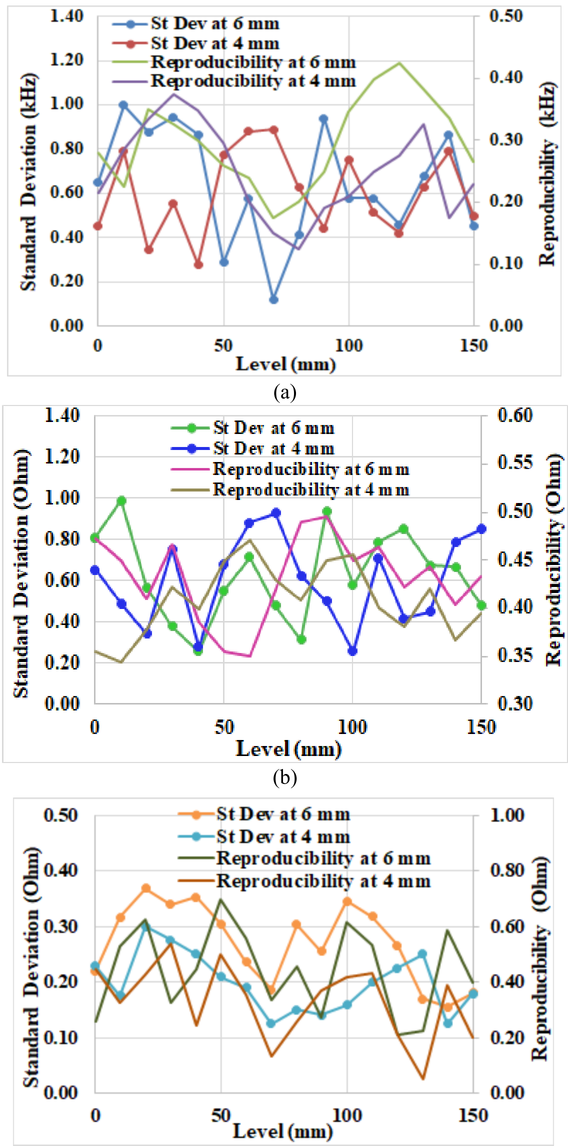


Fig. 13. Change in $R_{p\text{Sensor}}$ with changing liquid level.



(c)

Fig. 14. Characteristics curves of standard deviation and reproducibility of output responses with different coupling distances. (a) For resonance frequency. (b) For maximum real part of impedance. (c) For equivalent parallel resistance of LDC1000 ($R_{p\text{Sensor}}$).

alent parallel resistance (measurement with LDC1000). From Figs. 11 and 12, it can be seen that the output characteristics show almost linear curves. The percentage nonlinearity has been calculated for each output and is given in Table II. Only the outputs of LDC show percentage nonlinearity greater than 1%. The designed sensor also gives measurement errors and reproducibility within a limit, which is comparable to the other designed level measurement systems [12], [15] and commercially available level sensor [28]–[30].

TABLE II

PERCENTAGE NONLINEARITY OF DIFFERENT CHARACTERISTICS

Measuring Parameter	Percentage Nonlinearity	
	4 mm Coupling Distance	6 mm Coupling Distance
Resonance Frequency	0.099	0.097
Real part of maximum impedance	0.13	0.21
Equivalent parallel resistance of LDC	2.32	2.8

The proposed design is a wireless level measurement technique and it gives a lot of advantages over a wired measurement system that directly measures the changing capacitance. If the designed sensor is used in industrial applications for the same multiple units, no individual signal conditioning circuit is required for every system. Only the sensor is needed to be installed on the outside wall of the container or tank. The designed LC-based level sensor is also very useful for different applications due to its noncontact, passive, and wireless properties. The level sensor is not only capable of measuring the level of any liquid but also the level of any solid material inside any non-metallic container can be measured using it. The design can be used multiple ways; it can be installed both inside and outside the container.

If the sensor is attached to the inner wall, the same wireless measurement procedure can be used using the reader coil from outside of the container. In that case, some extra modifications and recalibration have to be done as per the particular application. In this work, the container of the liquid is of cuboid shape. But the sensor can be easily placed on any cylindrical container too, as the designed coplanar capacitor has been fabricated on a flexible substrate. In this case, the sensor coil is also needed to be designed and manufactured on a flexible PCB. In this work, a square spiral planar coil has been chosen as a reader coil. Any modification in the type and design can be opted out as per the ease of application. The sensor part can also be designed as a tag-like structure, where both coplanar capacitor and planar inductor are fabricated together using a multilayer PCB. The installation procedure will be much simpler as the tag would just be attached to the wall of the container. The overall cost, including the sensor's maintenance cost, will be comparatively less than the other wired sensor as it is free from wear and tear problems due to its wireless property. Coupling coefficient plays a crucial role here as the proposed readout system is distance-dependent. If the measurement system is designed as an automated system, the robustness and repeatability of the sensor will improve hugely.

VII. CONCLUSION

In this work, a contactless passive LC-sensing-based level sensor and a novel readout system for LC tags have been proposed, described, and experimentally validated. The sensing method for the proposed level sensor is based on the fringing field effect of the coplanar capacitor. A planar spiral inductor has been used as the sensor coil, with the coplanar capacitor to form the *LC* tank circuit. The measuring parameter has been detected with a planar reader coil. The designed level sensor is suitable for different applications such as solid materials, corrosive, and reactive materials. The proposed readout method is based on LDC1000. It has also been applied to designed level sensor and obtained satisfying results, which proves the concept. So, the proposed system and methodology can be adapted as a low-cost, compact, and easier alternative to bulky and costly equipment like impedance analyzer or VNA, for any *LC*-sensing-based wireless measurement systems.

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