Capacitive and Inductive Hybrid (Inductive-Inductive and Capacitive, LLC) Touch Sensor for Large-Area Bottom-Emission OLED Displays

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Abstract

This paper introduces a novel in-cell capacitive and inductive hybrid (inductive-inductive and capacitive, LLC) sensor for large-area bottom-emission organic light-emitting diode (OLED) displays. The proposed LLC sensor consists of an LC sensor and a readout coil distributed across multiple layers in OLED structure. By leveraging inductive coupling between layers, the LLC sensor overcomes the electric field shielding effects caused by thick OLED cathode layers, enabling effective touch detection without compromising electrical stability. A 5×5 LLC sensor array was fabricated on a PCB, emulating the architecture of a bottom-emission OLED display. Experimental evaluations demonstrate robust touch state recognition, with root mean square (RMS) output voltage differences ranging from 0.805 mV to 0.481 mV between touched and untouched sensors. The proposed LLC sensor retains the cost efficiency and design benefits of bottom-emission OLEDs while addressing the limitations of conventional capacitive systems.

Author Keywords

Touch sensor; in-cell touch; bottom-emission OLED; LLC touch sensor; OLED; inductive coupling;

1. Introduction

The implementation of touch sensors in top-emission OLED displays can be broadly classified into three primary approaches: add-on [1], on-cell [2], and in-cell [3]. Each method presents distinct advantages and faces specific challenges. The add-on method shown in Figure 1(a), being the simplest to implement, involves attaching the touch sensor directly to the display panel. Its primary advantage is ease of implementation and low initial development costs. However, this method is associated with several drawbacks, such as degradation in display image quality (e.g., moiré and haze effect), increased panel thickness [4], and higher manufacturing costs [5]. The on-cell method in Figure 1(b) integrates the touch sensor between the cover glass and the display device, offering higher transmittance and enabling thinner panel designs than the add-on method [6]. However, the sensor's placement farther from the finger and closer to the display driving signal lines reduces the signal-to-noise ratio (SNR), negatively affecting touch sensitivity [5]. The in-cell method shown in Figure 1(c) integrates the touch sensor into the display panel, offering reduced manufacturing costs compared to the add-on and on-cell methods and enhancing optical transmittance [4]. However, the cathode patterning process during manufacturing may degrade the electrical characteristics of the OLED [5].

Compared to top-emission OLED displays, bottom-emission OLED displays offer several distinct advantages. One key benefit is their simpler fabrication process, which reduces the complexity of manufacturing steps and leads to lower manufacturing costs. Additionally, bottom-emission OLEDs allow for the implementation of thicker cathode layers, a design feature that minimizes IR drop and improves the electrical stability of the OLED panel [7].

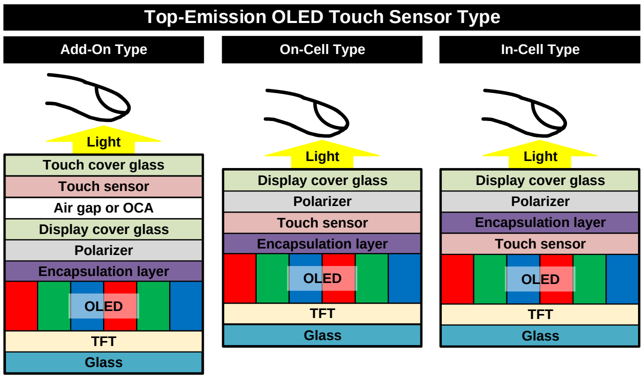

Figure 1. Types of touch sensors applicable to top-emission OLED structures and their cross-section views.

However, integrating conventional capacitive touch systems with bottom-emission OLEDs poses significant challenges. The thick cathode layers, essential for enhancing performance and electrical stability, inadvertently block the electric field signals required for touch detection. This shielding effect disrupts the functionality of capacitive touch systems, rendering them structurally incompatible with bottom-emission OLED displays. As a result, alternative touch technologies are necessary to overcome these limitations.

This study proposes a novel in-cell touch sensor that leverages a hybrid design combining capacitive and inductive sensing methods (inductive-inductive and capacitive, LLC) for application in bottom-emission OLED displays. The proposed LLC touch sensor combines the advantages of bottom-emission OLED technology and an in-cell touch sensor. The LLC touch sensor retains the cost-saving benefits of bottom-emission OLEDs while enabling the thick cathode layers to achieve reduced IR drop and improved electrical stability. Additionally, the LLC touch sensor effectively resolves the electric field shielding issues associated with conventional capacitive touch systems, offering a comprehensive solution to these challenges. To the best of our knowledge, the proposed LLC touch sensor is the first report on the in-cell touch sensor for bottom-emission OLED displays.

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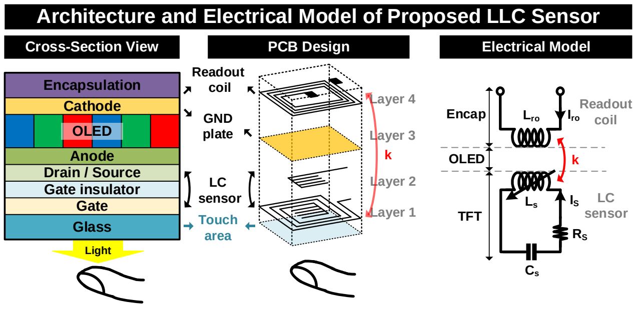


(a) (b) (c)

Figure 2. (a) Cross-section view of bottom emission OLED with the proposed LLC sensor, (b) PCB design for proposed LLC sensor, and (c) electrical model of LLC sensor.

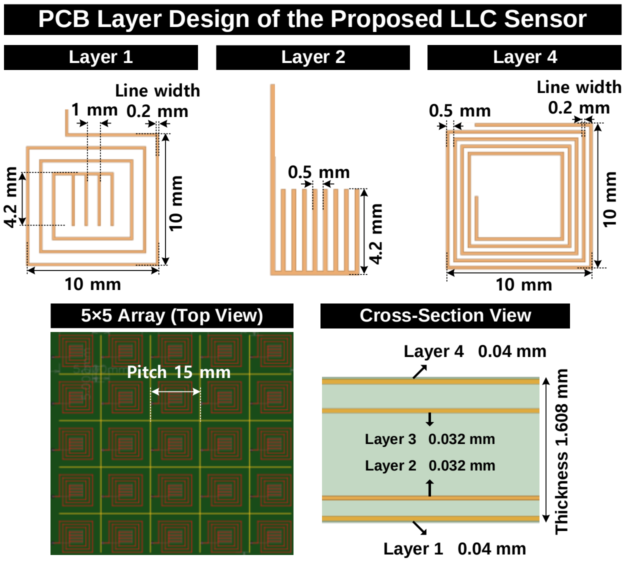


Figure 3. PCB layer design of the proposed LLC sensor.

2. Architecture of the Proposed LLC Touch Sensor

Figure 2 shows the architecture and electrical model of the proposed LLC sensor. Figure 2(a) shows the cross-sectional view of the bottom-emission OLED with the proposed LLC sensor. It consists of the display cover glass, which serves as the touch area, followed by the thin-film transistors (TFTs) layers, an anode layer, an OLED device, a cathode layer, and an encapsulation layer. The emitted light exits downward through the display cover glass while the finger touches the surface of the display cover glass from below. In the LC sensor, the capacitance (C_s) and inductance (L_s) components are modeled based on the parasitic inductance and capacitance generated by the gate, drain, and source layers of the TFT layers [4]. While L_s and L_{ro} are not physically connected due to the presence of the OLED cathode layer, they interact through inductive coupling, with the coupling coefficient (k) representing this interaction.

Figure 2(b) depicts the PCB design of the proposed LLC sensor, which emulates the structure of the bottom-emission OLED shown in Figure 2(a). The touch area on the PCB surface is treated with a solder mask. Layers 1 and 2 are used to model the LC components of the OLED TFT region. To implement the LLC sensor components (L_s and C_s), layer 1 is designed in a coil pattern, while Layer 2 adopts a comb pattern. These two layers are electrically connected through a via. Layer 3 represents the cathode layer of the bottom-emission OLED and is implemented as a ground (GND) plate. Layer 4 models the readout coil, patterned on the encapsulation layer of the OLED, incorporating a coil-shaped design to implement its inductance. Figure 2(c) shows the equivalent circuit model of the proposed LLC sensor.

Figure 3 shows the design of the proposed LLC sensor on PCB. All layer's metal widths were designed to be 0.2 mm. The cross-section shows the metal thickness and the overall thickness of the sensor. The metal thickness of layers 1 and 4 is 0.04 mm, while that of layers 2 and 3 is 0.032 mm. The proposed LLC sensor is designed with a 5 x 5 array, with each individual sensor having a pitch of 15 mm, which is considered suitable for large-scale touch sensor applications [8].

3. Operating Principle of the Proposed the LLC Touch Sensor

Figure 4 illustrates the operating principle of the LLC sensor, which is divided into two phases: the driving phase and the sensing phase. During the driving phase, the driving signal (V_{drv}) is transmitted to L_{ro} via the switching operation of the multiplexer (MUX). Through inductive coupling between L_{ro} and L_s, the signal is transferred from L_{ro} to the LC sensor. In the sensing phase, the MUX connects L_{ro} to an oscilloscope, enabling the measurement of the LC sensor's signal. The induced voltage of L_{ro} can be expressed as follows [9]:

$$V_1 = R_{ro}I_{ro} + sL_{ro}I_{ro} + sMI_s \tag{1}$$

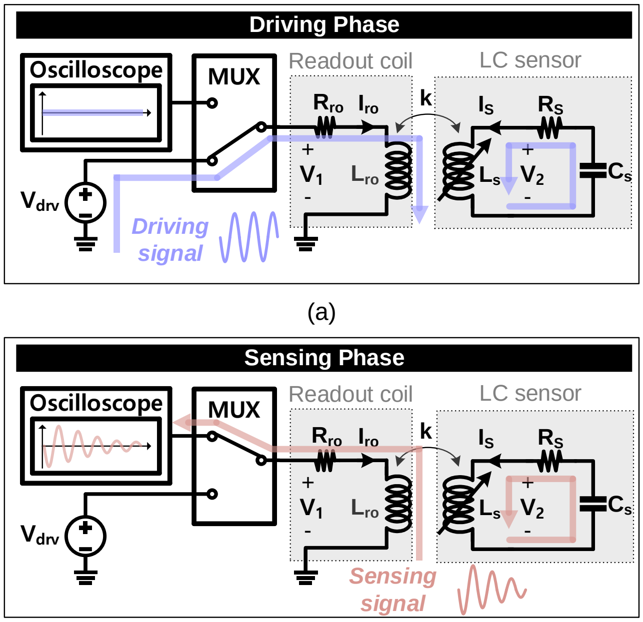
where V_1 and I_{ro} represent the voltage and current of L_{ro}, respectively, while R_{ro} represents the equivalent series resistance of L_{ro}, the variable s represents the complex frequency and is defined as $s = j\omega = j2\pi f$.

The mutual inductance M defines the inductive coupling between L_{ro} and L_s, as described in Equation (2) [9].

$$M = k\sqrt{L_{ro}L_s} \tag{2}$$

Here, k is the geometry-dependent coupling coefficient of M, which quantitatively defines the coupling strength between L_s and L_{ro} [9]. The proposed LLC sensor can transmit signals through the OLED cathode layer via inductive coupling. When a touch occurs, L_s decreases, reducing the signal amplitude. Consequently, the sensing signal's amplitude change depending on the touch status, enabling the proposed LLC sensor to distinguish between touched and untouched states.

Figure 5 illustrates how the electrical parameters of the proposed LLC sensor vary with the presence or absence of touch. When a touch occurs, the magnetic field generated by L_s induces eddy currents in the finger. These eddy currents reduce the total magnetic flux of L_s, leading to a reduction in its inductance [10]. Consequently, the magnitude of the sensing signal changes due to the decrease in L_s.



(a)

(b)

Figure 4. Operation of the proposed LLC sensor (a) driving phase and (b) sensing phase.

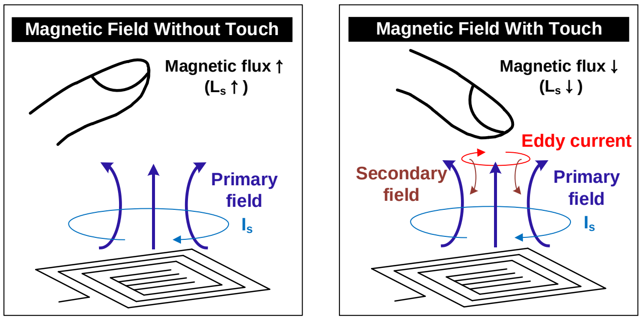


Figure 5. Inductance variation: (a) with touch (b) without touch [10].

4. Measurement Result

Figure 6 shows the design of the PCB for the proposed LLC sensor and experimental setup. The PCB features a 5×5 array of LLC touch sensors, each equipped with a MUX (TMUX7209 [11]) for driving and sensing operations.

Figure 7 presents the measured FFT results for a single touch sensor under touched and untouched conditions using a metal pillar with a diameter of 12 mm. The driving signal applied to the sensor is a 5 MHz sine wave with an amplitude of 10 V peak-to-peak. The FFT results in Figure 7 indicate that the amplitude decreases by 76.037 mV, from 658.28 mV in the untouched state to 582.24 mV in the touched state, providing a quantitative assessment.

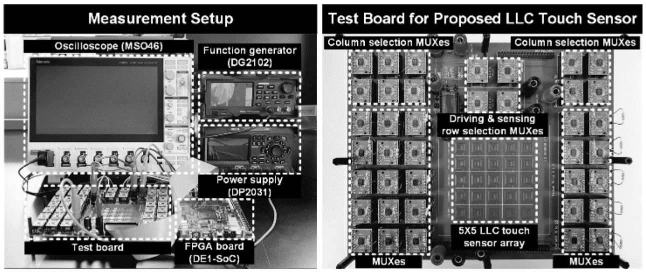


Figure 6. Measurement setup and top view of the PCB.

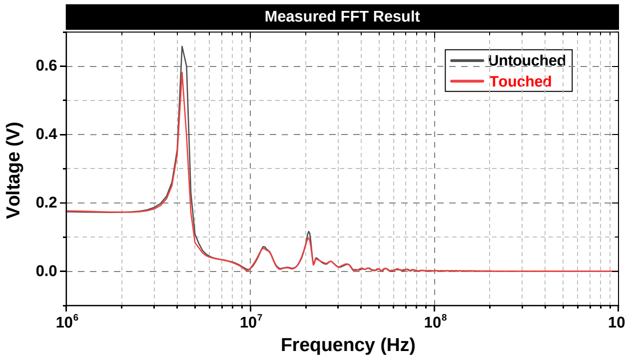


Figure 7. Measured FFT results for touched and untouched states with a single sensor.

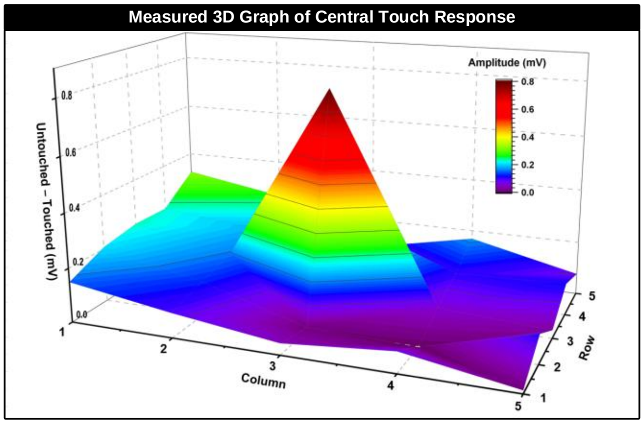


Figure 8. Coordinate extraction for the metal pillar.

Figure 8 shows the delta values between touched and untouched sensors, obtained from the FFT results after driving and sensing all 25 sensors sequentially. During the experiments, the sensor at the third column and third row was intentionally touched. This procedure was repeated 30 times, with offsets removed, and the results were accumulated and averaged. The results revealed that the root mean square (RMS) value of the output voltage difference between the touched and untouched sensors ranged from a maximum of 0.805 mV to a minimum of 0.481 mV. These findings confirm that touch signals can be effectively detected even in the presence of the OLED cathode layer, enabling precise recognition of the touch state.

5. Conclusion

This study introduced a novel in-cell hybrid touch sensor, the LLC (inductive-inductive and capacitive) sensor, designed for bottom-emission OLED displays. By combining capacitive and inductive sensing mechanisms, the proposed sensor effectively overcomes the shielding limitations of thick cathode layers, which hinder conventional capacitive touch detection. The LLC sensor leverages inductive coupling between layers, preserving bottom-emission OLED technology's cost-efficiency and electrical stability benefits. The fabricated 5×5 sensor array demonstrated reliable touch state detection, with RMS output voltage differences between the touched and untouched sensor ranged from 0.805 mV to 0.481 mV. These results confirm the sensor's ability to distinguish touch states despite OLED cathode shielding. Additionally, its scalable design makes it well-suited for large-area touch applications. Beyond touch sensing, the LLC sensor offers potential for flexible displays, wearable devices, and robotics. Future research will optimize its design and explore broader applications. This work provides a foundation for advancing touch sensors in next-generation OLED technologies.

6. Acknowledgements

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7. References

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