Single-ended amplifier-based touch readout circuit with immunity to display noise

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JOURNAL OF INFORMATION DISPLAY
2023, VOL. 24, NO. 2, 127–135
https://doi.org/10.1080/15980316.2022.2154863

Single-ended amplifier-based touch readout circuit with immunity to display noise

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ABSTRACT
To suppress errors in a touch readout circuit due to display noise, differential sensing using fully differential amplifiers is widely used. However, conventional differential sensing methods require additional circuits or increase circuit complexity, thus increasing power consumption and circuit area or requiring additional dummy RX line on the touch panel. In this study, we propose a compact touch readout circuit composed of a single-ended amplifier while keeping the display noise suppression of differential sensing so as to minimize power consumption and circuit area increase and avoid the need for additional dummy RX line. The proposed touch readout circuit for is fabricated in circuit area of 0.4 mm^2 with 0.35 µm 3.3 V CMOS process and measured for 10.1-inch touch panel on top of a TFT-LCD panel. With the proposed touch readout circuit, the signal-to-noise ratio (SNR) is improved by up to 13.1 dB compared to the conventional touch readout circuit using single-ended amplifiers.

ARTICLE HISTORY
Received 26 October 2022
Accepted 27 November 2022

KEYWORDS
Readout circuit; mutual capacitive touch; display noise suppression

SUBJECT CLASSIFICATION CODES
LC; OLED; equipment

1. Introduction

The touch readout circuit, which reads out the touch signal from the capacitive touch panel, must be robust to display noise, because large display noise is injected from the operating display panel [1–7]. In particular, as the add-on type touch panel has advanced into an on-cell and further, an in-cell type touch panel, the gap between the display panel and the touch panel has been greatly decreased, and the display noise injected into the touch panel has become a more serious problem [3–10]. As shown in Figure 1, display noise is injected to the RX electrode of the touch panel through the common electrode located at the top of the display panel (for example, the cathode electrode in a top-emission OLED panel). Therefore, display noise is considered a common noise independent of the position in the panel [1,3–5,8,11,12]. Therefore, the display noise can be effectively suppressed by using a differential sensing method [1–3,6,11–13]. There are two common circuit implementations to realize the differential sensing method. One is to additionally use a fully differential amplifier that receives the outputs of the pair of readout amplifiers of two adjacent channels as differential inputs [6,12]. However, the added circuits increase the power consumption and the circuit area. The other is to design each channel's readout amplifier as a fully differential amplifier [1–3,11,13]. This circuit, however, can only detect the difference in capacitance between the adjacent two channels, then it is not sufficient for touch detection. To determine a touch, an additional dummy RX line is needed as the reference for the touch panel.

In this study, we propose a compact touch readout circuit that consists of a single-ended amplifiers instead of fully differential amplifiers, but at the same time effectively suppresses errors in a touch readout circuit due to display noise. The proposed compact touch readout circuit neither increases in circuit area or power consumption nor requires additional dummy RX lines.

The rest of this paper is organized as follows: Section 2 describes the principle of the proposed touch readout circuit. Section 3 shows the simulation and measurement results. This paper is concluded in Section 4.

2. Proposed touch readout circuit

2.1. Principle of the proposed touch readout circuit

Figure 2 shows the effect of display noise on the conventional touch readout circuit composed of single-ended amplifiers. In Figure 2, $C_M[N]$ represents the mutual capacitance between the RX line of the N-th channel and a TX line running perpendicular to the RX line. C_D is the parasitic capacitance between the RX line and the

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ISSN (print): 1598-0316; ISSN (online): 2158-1606

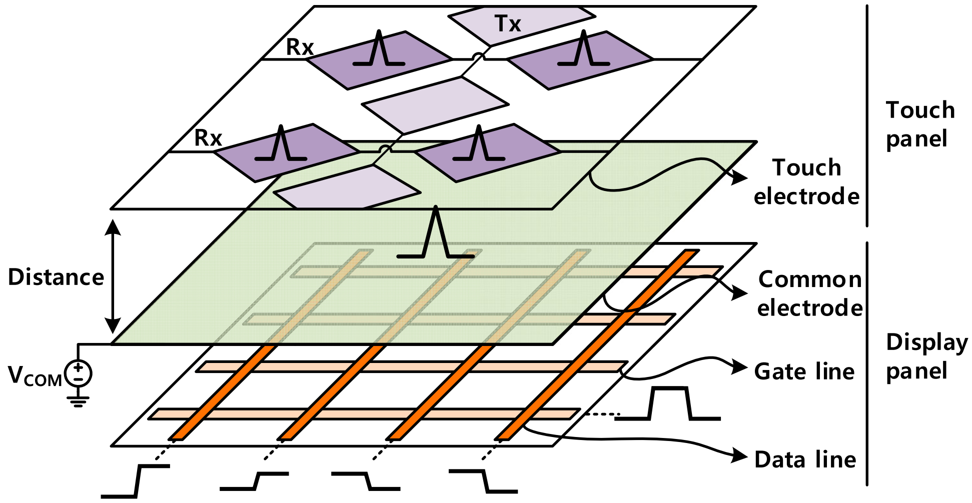


Figure 1. Display noise injection to the touch panel.

common electrode. C_P represents all the other parasitic capacitances between the RX line and the other electrodes. In the conventional single-ended amplifier-based touch readout circuit, the positive input of each amplifier is connected to the DC voltage, V_{REF}, so the display noise introduced through the common electrode appears at the output of the touch readout circuit, as shown in Figure 2.

To suppress the display noise, fully differential amplifiers are widely used to suppress the display noise, and the display noise is injected equally into both the positive and negative inputs so that it does not appear at the output of the touch readout circuit by common-mode rejection. In this study, we propose the use of compact single-ended amplifiers in which the display noise is still injected into both the positive and negative inputs of each single-ended amplifier. This allows a touch readout circuit to be constructed with single-ended amplifiers, which is relatively simple compared to fully differential amplifiers, while suppressing the display noise at the output of the touch readout circuit. The concept of the proposed touch readout circuit is shown in Figure 3, where the positive input of any amplifier except for the first channel's amplifier is connected to the RX line of the adjacent channel. The first channel's amplifier must have its positive input connected to a DC voltage. Otherwise, the positive input of any amplifier is undetermined because the voltage of the RX lines is undefined. In the proposed touch readout circuit configuration, two adjacent RX lines are connected to the positive and negative inputs of the amplifier, respectively, so the display noise is commonly injected into the two inputs. As mentioned above, because the display noise is independent of the position in the touch panel, the noise applied on the two RX lines are considered the same. Therefore, the display noise does not appear at the output of the touch readout circuit, because common-mode rejection is also possible even with a single-ended amplifier.

2.2. Analysis and design of the proposed touch readout circuit

The display noise suppression of the proposed touch readout circuit can be analyzed as follows: The voltage change of common electrode is denoted as ΔV_{COM}. And the voltage changes of OUT[i] and RX[i] ($1 \le i \le N$) due to the ΔV_{COM} are denoted as $\Delta V_{OUT[i]}$ and $\Delta V_{RX[i]}$, respectively. Even if ΔV_{COM} injects charges into RX[i], if the amplifier ideally has the infinite open-loop gain, the amplifier will make the voltage of the negative input equal to the voltage of the positive input. That is to say, ideally, the amplifier cancels out the injected charges and makes $\Delta V_{RX[i]}$ zero. However, since $\Delta V_{RX[i]}$ is non-zero due to the finite open-loop gain of the amplifier, charge change at RX[i] due to ΔV_{COM} can be expressed as in (1).

$$C_F(\Delta V_{OUT[i]} - \Delta V_{RX[i]}) + (C_M + C_P)(-\Delta V_{RX[i]}) + C_D(\Delta V_{COM} - \Delta V_{RX[i]}) = 0 \tag{1}$$

In (1), the display noise through TX lines is not considered because TX lines are driven by TX drivers. This assumption is found in many literatures, for example [2,4,11]. As shown in Figure 3, in the proposed touch readout circuit, the positive input of the amplifier in the first channel is fixed at a DC voltage, V_{REF}. If $V_{OUT}[1]_0$ and $V_{RX}[1]_0$ are defined as the voltages before ΔV_{COM} occurs, $\Delta V_{OUT}[1]$ and $\Delta V_{RX[N]}$ are defined as the voltage changes due to ΔV_{COM}, and the open-loop gain of

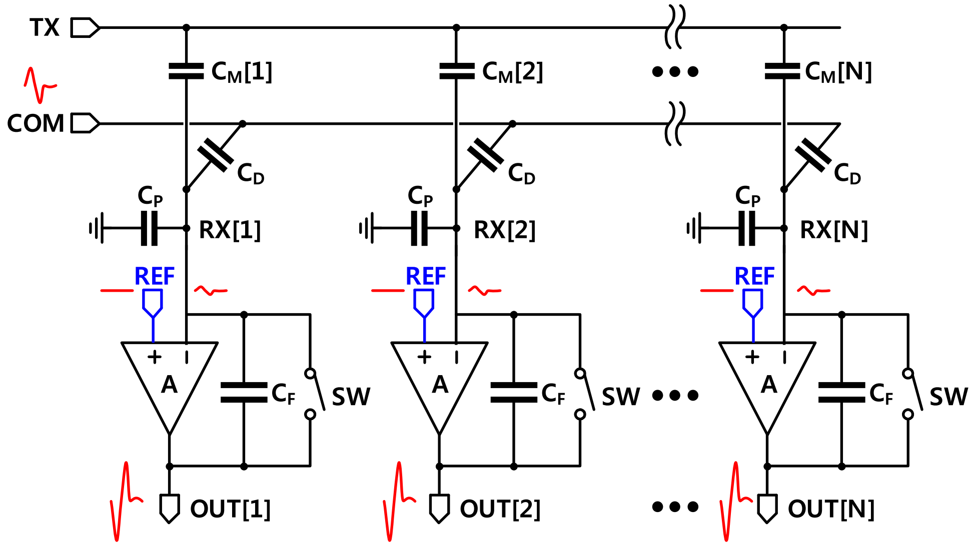


Figure 2. Display noise in the conventional single-ended amplifier-based touch readout circuit.

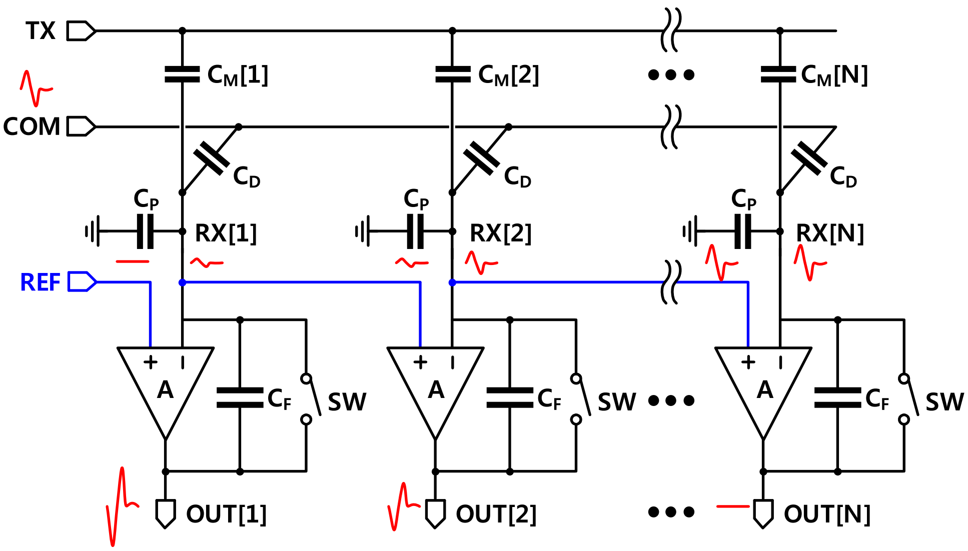


Figure 3. Proposed single-ended amplifier-based touch readout circuit.

the amplifiers are denoted as A, ΔV_{OUT} [1] is obtained as (2).

$$\begin{aligned}\Delta V_{OUT[1]} &= \mathrm{V}_{\mathrm{OUT}[1]} - \mathrm{V}_{\mathrm{OUT}[1]0}\\ &= \mathrm{A}(V_{REF} - V_{RX[1]}) - \mathrm{A}(V_{REF} - V_{RX[1]0})\\ &= -\mathrm{A}(V_{RX[1]} - V_{RX[1]0}) = -\mathrm{A}\Delta V_{RX[1]}\end{aligned} \tag{2}$$

If we put (2) into (1) and let $i = 1$, ΔV_{RX} [1] and ΔV_{OUT} [1] of the first channel are obtained as (3) and (4), respectively.

$$\Delta V_{RX[1]} = \frac{C_D}{(A+1)C_F + C_D + C_M + C_P}\Delta V_{COM} \tag{3}$$

$$\Delta V_{OUT[1]} = -\frac{AC_D}{(A+1)C_F + C_D + C_M + C_P}\Delta V_{COM} \tag{4}$$

On the other hand, the positive input of the amplifier in the second channel in Figure 3 is connected to RX[1], which is the RX line of the first channel. The output voltage of the second channel, $V_{\mathrm{OUT}}[2]$ and $\Delta V_{\mathrm{OUT}}[2]$ are obtained as (5) and (6), respectively.

$$V_{OUT[2]} = \mathrm{A}(V_{RX[1]} - V_{RX[2]}) \tag{5}$$

$$\begin{aligned}\Delta V_{OUT[2]} &= V_{OUT[2]} - V_{OUT[2]0}\\ &= A(V_{RX[1]} - V_{RX[2]})\\ &\quad - A(V_{RX[1]0} - V_{RX[2]0})\end{aligned}$$

$$= A[(V_{RX[1]} - V_{RX[1]0}) - (V_{RX[2]} - V_{RX[2]0})] = A(\Delta V_{RX[1]} - \Delta V_{RX[2]}) \quad (6)$$

If we put (6) into (1) and let $i = 2$, $\Delta V_{\text{RX}}[2]$ is obtained as (7), and if we put $\Delta V_{\text{RX}}[1]$ in (3) into (7), $\Delta V_{\text{RX}}[2]$ is simplified as (8).

$$\Delta V_{RX[2]} = \alpha \Delta V_{RX[1]} + \frac{C_D}{(A+1)C_F + C_D + C_M + C_P} \Delta V_{COM} \quad (7)$$

where $\alpha = \frac{AC_F}{(A+1)C_F+C_D+C_M+C_P}$.

$$\Delta V_{RX[2]} = (1+\alpha)\frac{C_D}{(A+1)C_F + C_D + C_M + C_P} \times \Delta V_{COM} \quad (8)$$

In the same way as in (7), $\Delta V_{\text{RX}}[3]$ in the third channel is obtained as (9), and if we put (8)into (9), $\Delta V_{\text{RX}}[3]$ is expressed as (10).

$$\Delta V_{RX[3]} = \alpha \Delta V_{RX[2]} + \frac{C_D}{(A+1)C_F + C_D + C_M + C_P} \times \Delta V_{COM} \quad (9)$$

$$\Delta V_{RX[3]} = (1+\alpha+\alpha^2)\frac{C_D}{(A+1)C_F + C_D + C_M + C_P} \times \Delta V_{COM} \quad (10)$$

In the same way, the $(N–1)$-th channel and the N-th channel, $\Delta V_{\text{RX[N}-1]}$ and $\Delta V_{\text{RX[N]}}$ are obtained as (11) and (12), respectively.

$$\Delta V_{RX[N-1]} = (1+\alpha+\alpha^2+\ldots+\alpha^{N-2}) \times \frac{C_D}{(A+1)C_F + C_D + C_M + C_P} \Delta V_{COM} \quad (11)$$

$$\Delta V_{RX[N]} = (1+\alpha+\alpha^2+\ldots+\alpha^{N-1}) \times \frac{C_D}{(A+1)C_F + C_D + C_M + C_P} \Delta V_{COM} \quad (12)$$

$\Delta V_{\text{OUT[N]}}$ of the N-th channel can be obtained as (13) in the same way as (6), and if we put $\Delta V_{\text{RX[N}-1]}$ in (11) and $\Delta V_{\text{RX[N]}}$ in (12) into (13), $\Delta V_{\text{OUT[N]}}$ is expressed as (14).

$$\Delta V_{OUT[N]} = A(\Delta V_{RX[N-1]} - \Delta V_{RX[N]}) \quad (13)$$

$$\Delta V_{OUT[N]} = -\alpha^{N-1}\frac{AC_D}{(A+1)C_F + C_D + C_M + C_P} \times \Delta V_{COM} = -\alpha^N \frac{C_D}{C_F}\Delta V_{COM} \quad (14)$$

If the open-loop gain of the amplifier (A) for ΔV_{COM} is not much high, α in (14) is smaller than one and is multiplied to the power of N, which suppresses the display noise. Whereas, in the case of conventional single-ended amplifier-based readout circuit, ΔV_{OUT} for all channels is the same as when $N = 1$ in (14), ΔV_{OUT} for ΔV_{COM} of the proposed circuit decreases with N. On the other hand, ΔV_{OUT} for ΔV_{TX} can be easily obtained from (14) by substituting the injected charge due to display noise ($C_D \Delta V_{\text{COM}}$) with the injected charge due to ΔV_{TX} ($C_M \Delta V_{\text{TX}}$). Since the frequency of the ΔV_{TX} is higher than ΔV_{COM}, the open-loop gain of the amplifier (A) for ΔV_{TX} is higher than the open-loop gain (A) for ΔV_{COM}. If A is sufficiently high, α for ΔV_{TX} is close to one, and the signal due to ΔV_{TX} is not suppressed. Meanwhile, ΔV_{OUT} for ΔV_{TX} of the proposed circuit which is the touch signal is similar to that of the conventional circuit, thus the output of the proposed circuit depends on the mutual-capacitance (C_M), not the difference of the mutual-capacitances of the adjacent RX lines.

Since ΔV_{OUT} for ΔV_{COM} of the proposed circuit decreases with N, this means that the display noise suppression is effective for channels far from the first channel but might be insufficient for channels close to the first channel. To address this problem, the proposed touch readout circuit uses a bidirectional scanning method, where a frame is divided into two subframes and reverses scanning direction between the subframes. More specifically, in the first subframe, V_{REF} is connected to the first channel (light-green in Figure 4), and the outputs of channels farther away from the first channel than the $(N/2)$-th channel are used as valid outputs of the touch readout circuit. Conversely, in the second subframe, V_{REF} is connected to the N-th channel which is the last channel (light-blue in Figure 4), and RX[$i+1$] is connected to the positive input of the amplifier in the i-th channel, so that the output of the $(N/2)$-th channel and the outputs of the channels closer to the first channel than the $(N/2)$-th channel are used as valid outputs of the touch readout circuit. Throughout the first and second subframes, all outputs of the touch readout circuits can be obtained with the display noise suppressed.

3. Simulation and measurement results

Display noise suppression of the proposed touch readout circuit was measured with Lenovo's 10.1-inch add-on type mutual capacitive touch panel. Also, for SPICE simulation, the circuit model of the touch panel is configured

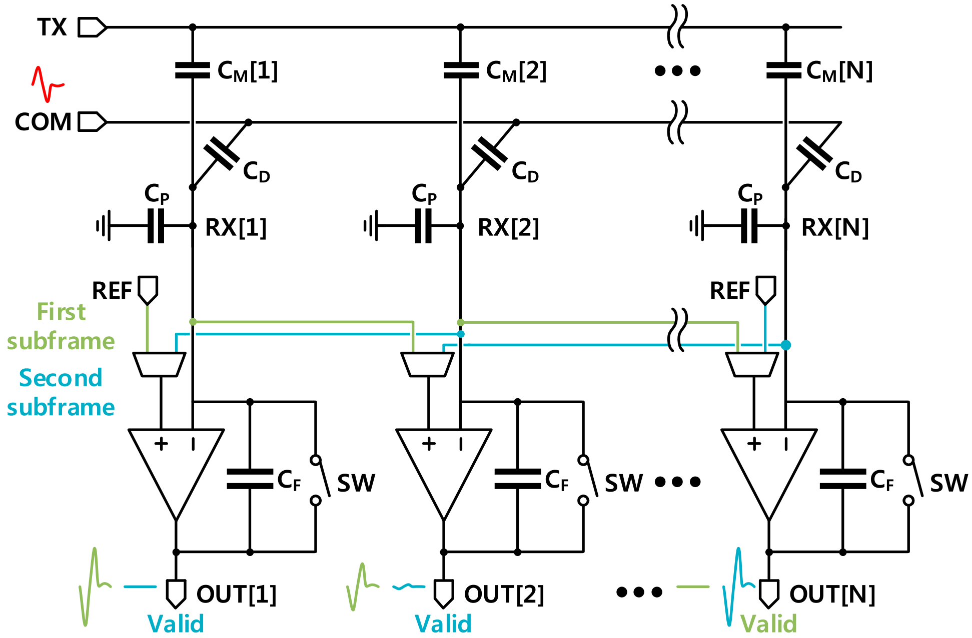


Figure 4. Proposed single-ended amplifier-based touch readout circuit with bidirectional scanning.

Table 1. Touch panel circuit parameters.

Item	Value	Item	Value
RX channel	27	TX channel	43
C_{RX}	100 fF	C_{TX}	100 fF
R_{RX}	50 Ω	R_{TX}	50 Ω
C_M (w/o touch)	1 pF	C_M (touch)	0.3 pF

as shown in Figure 5 [5,14], and the circuit parameters in Table 1 were obtained through the measurement of the touch panel. Therefore, C_D in (14), which is the capacitance between one RX line and the common electrode, is 4.3 pF because it is composed of as many numbers of C_{RX} (100 fF) as TX channels (43 channels).

The simulation results are shown in Figure 6. The display noise used in the simulation was collected from the LCD panel of a 13.1-inch laptop (ASUS, U35JC-RX006V) displaying a full-white screen. In Figure 6(a), the display noise is modeled as a 500 mV impulse with a frequency of 48 kHz and 160 mV impulse with a frequency of 96 kHz. In the first subframe in which the positive input of the first channel is fixed to V_{REF}, as described in sub-section 2.2, the display noise is not sufficiently suppressed at the output voltages of the close channels to the first channel. In Figure 6(b), it is clearly observed that the output of the first channel is affected by the display noise, while the display noise is sufficiently suppressed at the output voltage of the 14th, the last channel. Therefore, in the first subframe, the output voltages of the eighth to 14th channels, which belong to the half part far from V_{REF}, are accepted as valid touch information. Conversely, as shown in Figure 6(c), in the second subframe in which the positive input of the 14th channel is fixed to V_{REF}, the output voltages of the first to seventh channels, which belong to the half part far from V_{REF}, are accepted as valid touch information. The results of the simulated signal-to-noise ratio (SNR) will be presented and compared with the measured SNR in Figure 8.

Figure 7 is a micrograph of the proposed touch readout circuit of 14 channels fabricated in a 0.35 μm 3.3 V CMOS process. The main part of the fabricated readout circuit is the amplifier, and its specifications are presented in Table 2. To accurately read out the touch signal, the input-referred offset of the amplifier is tightly controlled with an average of 0.4 mV by applying the chopper stabilization technique. The TX drivers are constructed separately on the printed circuit board using discrete devices and generate 5 V TX signals. The proposed touch readout circuit is measured with the add-on type 10.1-inch touch panel mounted on top of the 13.1-inch LCD panel such that display noise is injected into the touch panel. If the output of each channel is measured 100 times each when touched and not touched, the SNR of each channel is calculated as (15) [9,11,15].

$$SNR = 20\log_{10}\left[\frac{\overline{V_{OUT\_TOUCH}} - \overline{V_{OUT\_w/oTOUCH}}}{\sqrt{\frac{1}{100}\sum_{i=1}^{100}(V_{OUT\_TOUCH}[i] - \overline{V_{OUT\_TOUCH}})^2}}\right] \tag{15}$$

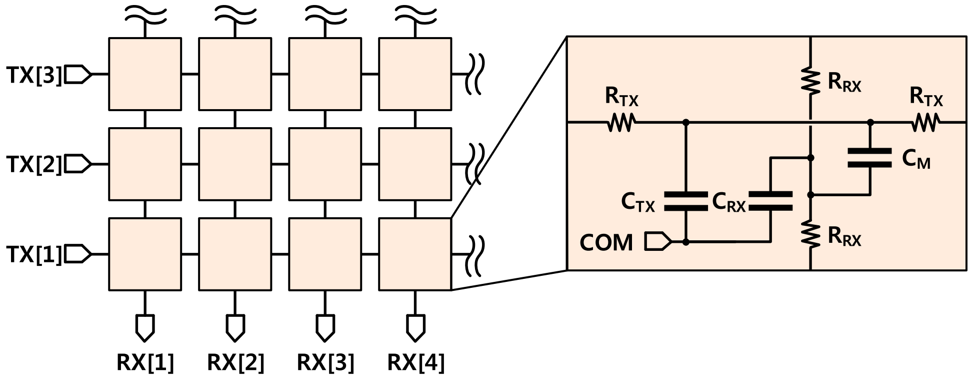


Figure 5. Touch panel circuit model for simulation [5,14].

Table 2. Designed single-ended two-stage amplifier specifications.

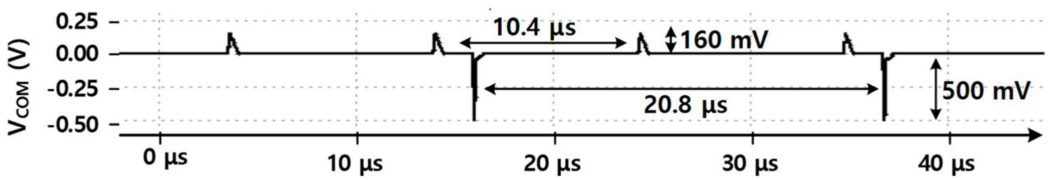
Item	Value	Item	Value
DC Gain	80 dB ∼	Bandwidth	5 MHz ∼
Phase Margin	60 ° ∼	Offset Voltage	∼ 0.4 mV
Quiescent current	42 μA	Area	3600 μm^2

where $V_{OUT\_TOUCH}[i]$ is the output voltage of i-th measurement when touched, and $\overline{V_{OUT\_TOUCH}}$ and $\overline{V_{OUT\_w/oTOUCH}}$ are the average of the output voltage of each channel for 100 measurements when touched and not touched, respectively.

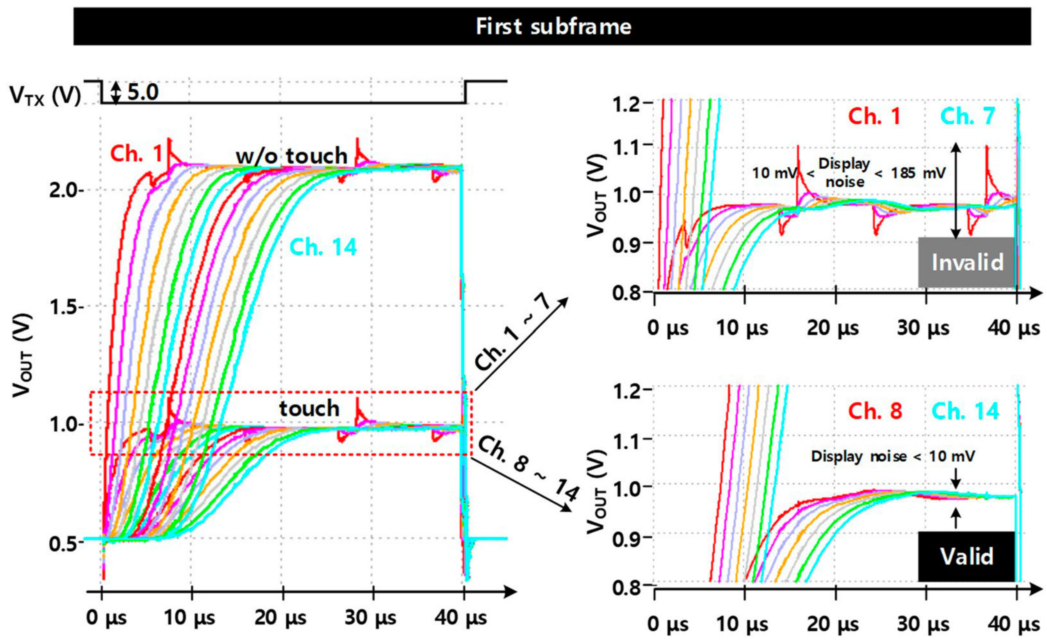
In Figures 8, the SNR of the proposed readout circuit for the full white and the zebra-pattern screens, both simulated and measured, are presented. Figure 8(a,b) shows the SNR in the first and second subframe, respectively. In the first subframe, V_{REF} is connected to the first channel, and in the second subframe, to the last channel (14th channel). In Figure 8(a), the first channel has the lowest SNR because it has a fixed positive input to V_{REF} in the same way as the conventional single-ended amplifier-based touch readout circuit, but the SNR increases as the channel becomes farther away from the first channel. The SNR for the full-white screen is measured to increase up to 13.1 dB at the last channel compared to the first channel and up to 12.6 dB for the zebra pattern screen. Therefore, in the first subframe, we only accept the outputs of the eighth to 14th channels as valid touch information. In Figure 8(b), on the same principle, the measured SNR increases up to 13.1 and 12.7 dB compared to the last channel for the full-white and the zebra pattern screens, respectively. This is because, in the second subframe, the amplifier of the 14th channel has its positive input fixed at V_{REF}. In the second subframe, we only accept the outputs of the first to seventh channels as valid touch information. Finally, by collecting the touch information from two subframes, the proposed touch readout circuit improves the SNR by a minimum of 6.3 dB to a maximum of 13.1 dB for the full-white screen and by a minimum of 7.2 dB to a maximum of 12.6 dB for the zebra pattern screen. The slightly lower SNR for the zebra pattern screen than that for the full-white screen is because the measured display noise for the zebra pattern screen is a maximum of 550 mV, while the measured display noise for the full-white screen is maximum of 500 mV. A 10% larger noise reduces the SNR by 0.8 dB in calculations, which is in good agreement with the measurement results. In addition, the measured SNRs in Figure 8 are lower than the simulated SNRs. This is because the simulations only include display noise, while the measurements also include internal circuit noise, power noise, jitter of the control signal, and other environmental noise. The SNR of the fabricated proposed touch readout circuit is compared with the previous works in Table 3. Given the fact that all the previous works in Table 3 use fully differential amplifiers to reject display noise, the proposed single-ended amplifier-based touch readout circuit exhibits good SNR, although not the best. Due to the simple circuit structure of the proposed touch readout circuit, the circuit area and power consumption are much lower than those of the previous works.

4. Conclusion

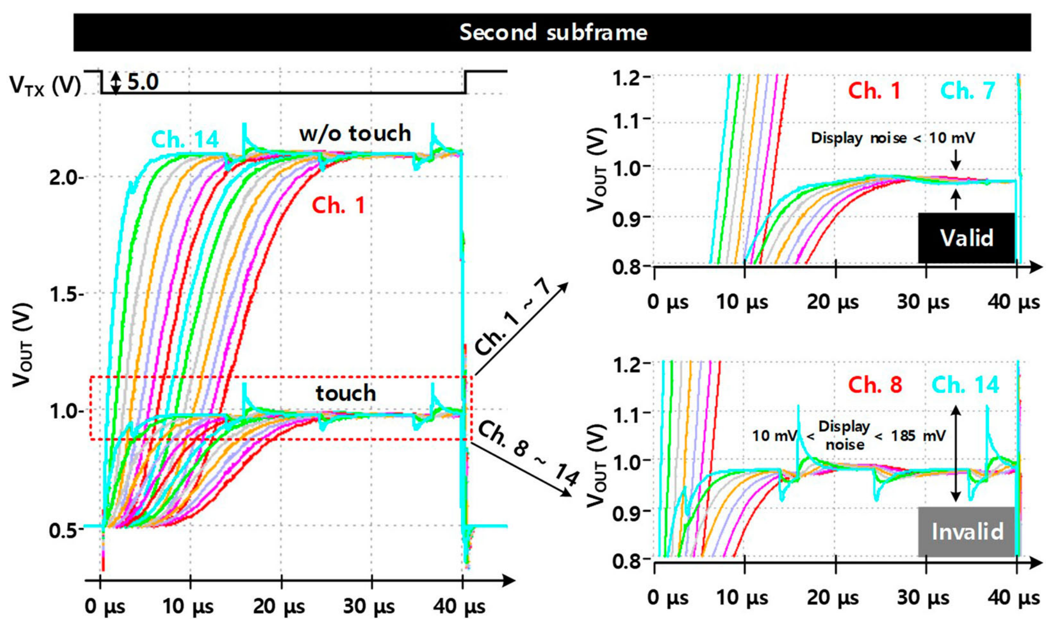
A touch readout circuit composed of single-ended amplifiers that effectively suppresses display noise is proposed, where the positive input of each amplifier is connected to the RX line of the adjacent channel instead of a fixed reference voltage and the negative input is connected to the RX line of its own channel. As a result, display noise is injected equally into both the positive and negative inputs of the amplifier and suppressed at the output of the touch readout circuit by common-mode rejection of the single-ended amplifier. Compared with fully differential amplifier-based touch readout circuits,



(a)



(b)



(c)

Figure 6. Simulation results of the proposed touch readout circuit. (a) Display noise. (b) First subframe. (c) Second subframe.

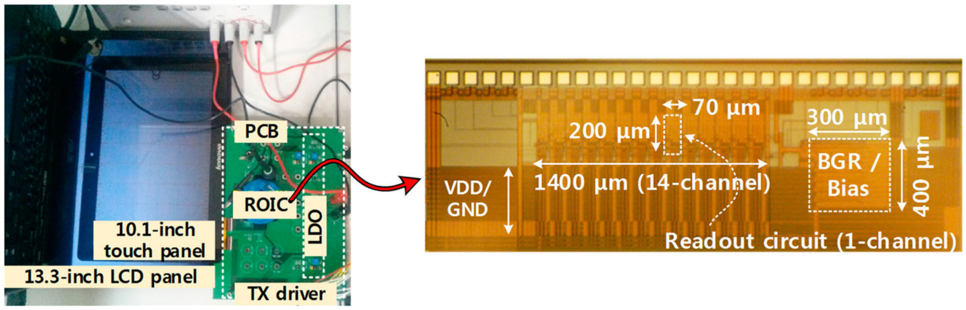


Figure 7. Micrograph of the fabricated touch readout circuit and measurement setup.

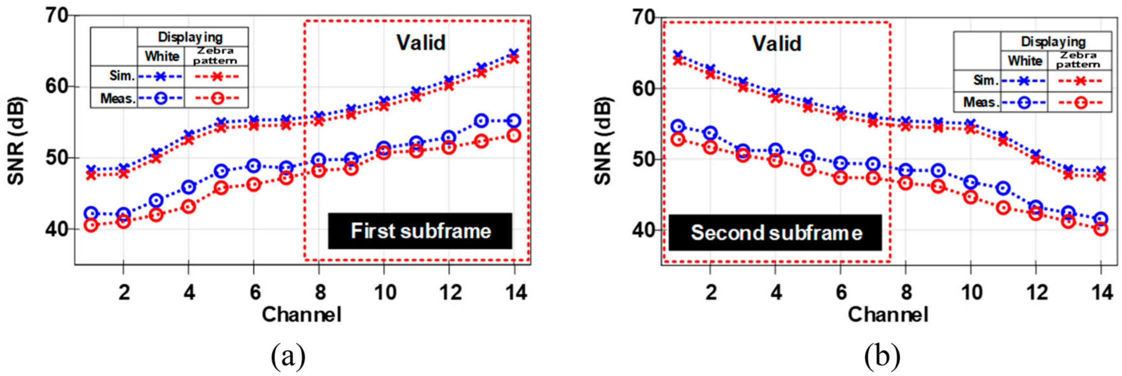


Figure 8. Simulated and measured results of the proposed touch readout circuit. (a) SNR of the first subframe. (b) SNR of the second subframe.

Table 3. Comparison with the previous works.

	This work	[16]	[13]	[2]	[3]	[6]
Readout structure	Single-ended	Fully differential	Fully differential	Fully differential	Fully differential	Additional fully differential
Touch panel	10.1-inch mutual	5.3-inch mutual	7.9-inch mutual	6.9-inch mutual	5-inch self/mutual	4.3-inch mutual
Channel	TX = 43 RX = 14	TX = 31 RX = 15	TX = 14 RX = 16	TX = 12 RX = 16	TX = 28 RX = 16	TX = 12 RX = 8
SNR (dB)	47.2 ~ 56.2	54.2	52.9	27.5	60 (mutual) 53 (self)	60
Framerate(Hz)	240	240	367	175	120	200
Power∗(μW/ch.)	450∗∗	766	825 (analog) 1,031 (digital)	4,750	638 (analog) 900 (digital)	788
Area∗ (mm^2/ch.)	0.029∗∗	0.099	0.353	0.314	0.994	0.275
Process	0.35 µm CMOS	0.13 µm CMOS	0.35 µm CMOS	0.35 µm CMOS	90 nm CMOS	0.18 µm CMOS

∗Total power and circuit area are divided by number of RX channels.
∗∗Only for analog front-end.

which are commonly used to reject display noise, the proposed touch readout circuit consumes much lower chip and power consumption due to its simple circuit structure.

The proposed touch readout circuit was fabricated in a 0.35 µm CMOS process and measured to have SNR of 47.2 to 56.2 dB, which is up to 13.1 dB improved compared to the conventional single-ended amplifier-based touch readout circuit. Even compared with the reported fully differential amplifier-based touch readout circuits, the SNR is comparable with much lower circuit area (0.029 mm^2 per RX channel) and power (450 µW per RX channel) consumed.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributors

Yongsang Yoo received the B.S. and M.S. degrees in electronic engineering from Hanyang University, Seoul, South Korea, in 2014 and 2016, respectively, where he is currently pursuing the Ph.D. degree. His research interests include sensor readout circuits, memory core, and peripheral circuits.

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References

[1] J.-E. Park, J. Park, Y.-H. Hwang, J. Oh, and D.-K. Jeong, IEEE J. Solid-State Circuits **54**, 1497 (2019).
[2] J.-S.S. Lee, D.-H.H. Yeo, H.-J.J. Kwon, B. Kim, J.-Y.Y. Sim, and H.-J.J. Park, IEEE Sens. J. **15**, 4595 (2015).
[3] K.D. Kim, S. Kang, Y.K. Choi, K.H. Lee, C.H. Lee, J.C. Lee, M. Choi, K. Ko, J. Jung, N. Park, H. Park, and G.C. Hwang, in *IEEE Symposium on VLSI Circuits, Digest of Technical Papers* (IEEE, 2014), Honolulu, HI, USA, pp. 1–2.
[4] O.-K. Kwon, J.-S. An, and S.-K. Hong, IEEE Sens. J. **18**, 4832 (2018).
[5] H.-S. Kim and K.-Y. Han, IEEE Sens. J. **16**, 859 (2016).
[6] J.E. Park, D.H. Lim, and D.K. Jeong, IEEE J. Solid-State Circuits **49**, 2305 (2014).
[7] J. Park, Y.-H. Hwang, J. Oh, Y. Song, J.-E. Park, and D.-K. Jeong, IEEE J. Solid-State Circuits **54**, 1694 (2019).
[8] K.D. Kim, S.H. Byun, Y.K. Choi, J.H. Baek, H.H. Cho, J.K. Park, H.Y. Ahn, C.J. Lee, M.S. Cho, J.H. Lee, S.W. Kim, H.D. Kwon, Y.Y. Choi, H. Na, J. Park, Y.J. Shin, K. Jang, G. Hwang, and M. Lee, Dig. Tech. Pap. IEEE Int. Solid-State Circuits Conf. **55**, 116 (2012).
[9] C.J. Lee, J.K. Park, C. Piao, H.E. Seo, J. Choi, and J.H. Chun, Sensors **18**, 1 (2018).
[10] J.H. Yang, S.C. Jung, Y.S. Son, S.T. Ryu, and G.H. Cho, IEEE Trans. Circuits Syst. I Regul. Pap. **60**, 1800 (2013).
[11] M. Miyamoto, M. Hamaguchi, and A. Nagao, IEEE J. Solid-State Circuits **50**, 335 (2015).
[12] J.H. Yang, S.H. Park, J.M. Choi, H.S. Kim, C.B. Park, S.T. Ryu, and G.H. Cho, in *Digest of Technical Papers, IEEE International Solid-State Circuits Conference* (IEEE, 2013), San Francisco, CA, USA, pp. 390–391.
[13] D.H. Yeo, S.H. Kim, H.K. Noh, B. Kim, J.Y. Sim, and H.J. Park, IEEE Sens. J. **16**, 6931 (2016).
[14] K. Byun, and B.-W. Min, J. Korean Inst. Electromagn. Eng. Sci. **25**, 47 (2014).
[15] ATMEL Corporation, *Touch Sensors Design Guide (10620D-AT42)*, Revision D (2009).
[16] S.H. Ko, IEEE Trans. Circuits Syst. I Regul. Pap. **67**, 1126 (2020).