10.4 A Noise-Immune Stylus Analog Front-End Using Adjustable Frequency Modulation and Linear-Interpolating Data Reconstruction for Both Electrically Coupled Resonance and Active Styluses

Kyung-Hoon Lee[1], Sang-Pil Nam[1], Jung-Ho Lee[1], Michael Choi[1], Hyung-Jong Ko[1], San-Ho Byun[1], Jin-Chul Lee[1], Yong-Hoon Lee[1], Yeong-Cheol Rhee[1], Yoon-Kyung Choi[1], Byung-Hoon Kang[2], Chang-Byung Park[2], Sungsoo Park[2], Taesung Kim[2]

[1]Samsung Electronics, Hwaseong, Korea
[2]Samsung Electronics, Suwon, Korea

As the demand for intuitive and interactive displays is increasing in mobile devices such as smartphones and tablets, a pressure-sensitive stylus pen solution is needed for advanced user experiences [1-5]. Figure 10.4.1 compares electromagnetic resonance (EMR), active, and electrically coupled resonance (ECR) stylus systems, and shows cross-sectional views of sensor panels. EMR stylus systems have been successfully commercialized for high-end devices due to their battery-less, light, and pressure-sensing features [1-2]. However, EMR stylus systems require an extra sensing panel for electro-magnetic coupling. The active stylus system does not require the additional sensing panel but needs a battery located inside the stylus. On the other hand, ECR stylus systems are cost-effective without needing either the additional sensing panel or a built-in battery. Furthermore, ECR stylus systems measure pen pressure by sensing a stylus' resonant frequency change upon pressure without additional circuitry [3]. Due to the external noise injection to the stylus system being more than ten times larger than the pen signal as shown in Fig. 10.4.1, noise immunity is a key performance factor for commercialization. This paper proposes an analog front-end (AFE) for both ECR and active stylus systems with high noise immunity that results in improved signal-to-noise ratio (SNR) by applying a fully differential architecture, adjustable frequency modulation (AFM), and linear-interpolating data reconstruction (LIDR).

Figure 10.4.2 shows the AFE architecture, comprising 2 groups of a 7-channel receiver, two groups of a reference-channel receiver, and channel-selecting multiplexer. A single receiver channel consists of a charge-to-voltage converting amplifier (CA), a down-conversion mixer, a 4th-order low-pass filter (LPF), a programmable gain amplifier (PGA), and an analog-to-digital converter (ADC), while a reference-channel receiver amplifies the external noise with CA only for common-mode noise rejection. In global scan mode, the overall 14-channel receiver scans all the column and row panel electrodes sequentially to sense the pen's approximate position. In local scan mode, the 2 groups of the 7-channel receiver are dedicated to the 7 column and the 7 row electrodes respectively, positioned near the pen's coarse location for sensing the pen's accurate coordinate.

The AFE supports 3 signal-sensing modes (single-ended, pseudo-differential, and fully differential modes) to support various application and system requirements. Figure 10.4.3 shows the single-channel receiver with its 3 sensing mode configurations. In the pseudo-differential mode, touch screen panel's common noise is suppressed by partially canceling the panel noise, using the reference channel. The physically remote location between the signal and reference-sensing electrodes prevents extensive suppression of the panel noise. In the fully differential mode, the receiver utilizes the 2 adjacent panel electrodes as the differential input signals and cancels the panel's common noise for the AFE's SNR improvement.

Figure 10.4.4 shows the frequency-domain analysis of the noise-suppressing adjustable frequency modulation (AFM) scheme. The AFE senses the pen pressure by detecting the varying ECR pen's LC resonant frequency upon applied pressure. A noise-efficient filter adjusts its cut-off frequency to track the ECR pen's frequency change for maximum out-of-band noise suppression and better SNR. Most external noise sources such as fluorescent lamps, chargers, and hum are located in the low-frequency band (20 to 250kHz), and their harmonic components are positioned in the higher-frequency band (>700kHz) than the pen frequency (f_{pen}). A simple way to suppress the external noises, located in both sides of the pen signal band, is to add a band-pass filter (BPF) in the signal path. However, BPF with narrow (~30kHz) transition band is disadvantageous in circuit implementation to adjust the filter's cut-off frequency. To eliminate the need for the filter's cut-off frequency change, an AFM scheme is proposed. In this stylus receiver, a frequency down-conversion mixer modulates the pen signal to a low-frequency band while external noise is modulated to a high-frequency band. Regardless of the pen signal's frequency change upon pressure, the modulated pen signal is always fixed at 30kHz ($\Delta kHz = f_{PEN} - f_{MOD}$ in Fig. 10.4.4) by adjusting the modulation frequency according to the pen signal frequency, detected in the global scan mode. A 4th-order switched-capacitor Butterworth low-pass filter with fixed 50kHz 3-dB cut-off frequency sufficiently suppresses out-of-band noise regardless of the signal frequency variation, and a switched-capacitor PGA amplifies the low-pass filtered pen signal for further SNR enhancement. The AFE architecture can be easily employed to various kinds of ECR and active stylus pen systems without hardware modifications.

A display panel's periodic pixel updates generate noise spikes that are transferred to the touch screen panel via coupling capacitance and cause stylus AFE's performance degradation. Although the fully differential sensing suppresses the display noise, the noise inevitably remains. The linear-interpolating data reconstruction (LIDR) scheme suppresses this remaining display noise further. LIDR comprises two operations: 1) resetting the charge-to-voltage converting amplifier (CA), and 2) the linear interpolation of the AFE output. The horizontal synchronized clock signal (H_{SYNC}) from display panel contains timing information for the periodically coupled display noise. While H_{SYNC} is active, CA is reset to avoid the AFE saturation, and the whole AFE channels go to a null state. However, the nulling information during H_{SYNC} timing can be restored by the linear interpolation of digital processing. Figure 10.4.4 illustrates time-domain analysis of the LIDR with AFM. Without LIDR and AFM, the output of PGA is saturated during the H_{SYNC} timing due to the injected display noise that contaminates the signal frequency information. When the frequency of the pen signal is higher than that of H_{SYNC}, the PGA output is not restored by the interpolation properly with LIDR only, as shown in the middle of Fig. 10.4.4. However, the pen signal can be most effectively restored with both LIDR and AFM because the frequency of the modulated pen signal (30kHz) is sufficiently lower than that of H_{SYNC} (250kHz), as shown in the right-side of Fig. 10.4.4.

The AFE is fabricated in a 100nm CMOS process, and its performance is measured on a 10.1-inch commercial tablet as shown in Fig. 10.4.5. The touch screen panel for AFE evaluation contains a 4mm-channel-pitch mesh structure with 54×35-metal-mesh. The AFE achieves up to 56dB SNR in ECR stylus, applying the noise-suppressing AFM and LIDR schemes in the fully differential mode. The active stylus is also implemented and evaluated with the same AFE that performs with 2dB higher (58dB) SNR than ECR stylus. The extracted column- and row-axis coordinates of the ECR stylus are shown in Fig. 10.4.5 (bottom). The performances of the AFE and previous works for styli are summarized in a table in Fig. 10.4.6. Based on the table, the AFE achieves the highest SNR (56dB), compared to the previously reported best performance (49dB), even with injected display and charger noises. The AFE supports pressure sensing at an active stylus as well as a passive stylus, and the 10b resolution is superior to the recent previous works (6b). Figure 10.4.7 shows a die photograph of the stylus AFE, embedded in one-chip stylus and finger-touch controller. The total size of the IC is 39.2mm^2, while the stylus AFE occupies 5.49mm^2.

References:

[1] Samsung. Galaxy Note8 [Online]. Accessed on Nov. 9, 2017. Available: http://www.samsung.com/global/galaxy/galaxy-note8/

[2] Wacom. What is the EMR [Online]. Accessed on Nov. 9, 2017. Available: http://www.wacom.com/en-in/support/faqs/scope-of-business/electro-magnetic-resonance-information

[3] C. Park, et al., "A Pen-Pressure-Sensitive Capacitive Touch System Using Electrically Coupled Resonance Pen," *ISSCC Dig. Tech. Papers*, pp. 124-125, Feb. 2015.

[4] M. Hamaguchi, et al., "A 240Hz-Reporting-Rate Mutual-Capacitance Touch-Sensing Analog Front-End Enabling Multiple Active/Passive styluses with 41dB/32dB SNR for 0.5mm Diameter, *ISSCC Dig. Tech. Papers*, pp. 120–121, Feb. 2015.

[5] J. An, et al., "A 3.9kHz-Frame-Rate Capacitive Touch System with Pressure/Tilt Angle Expressions of Active Stylus Using Multiple-Frequency Driving Method for 65," *ISSCC Dig. Tech. Papers*, pp. 168-169, Feb. 2017.

 978-1-5090-4940-0/18/$31.00

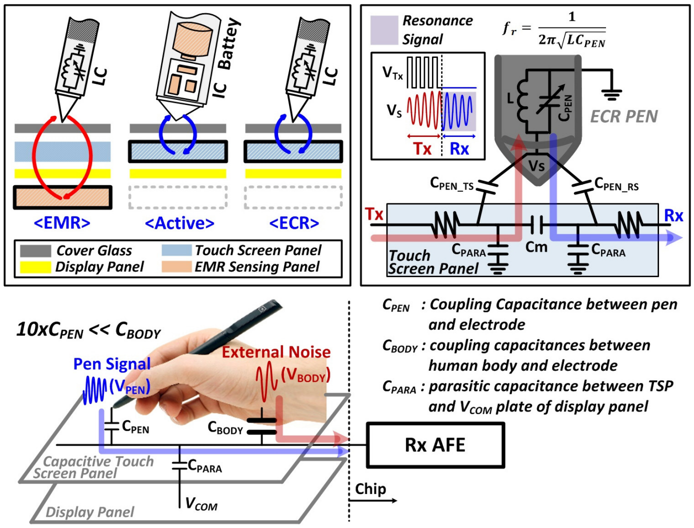

Figure 10.4.1: Comparison of stylus systems, and circuit model for a pen signal and external noise coupling mechanism.

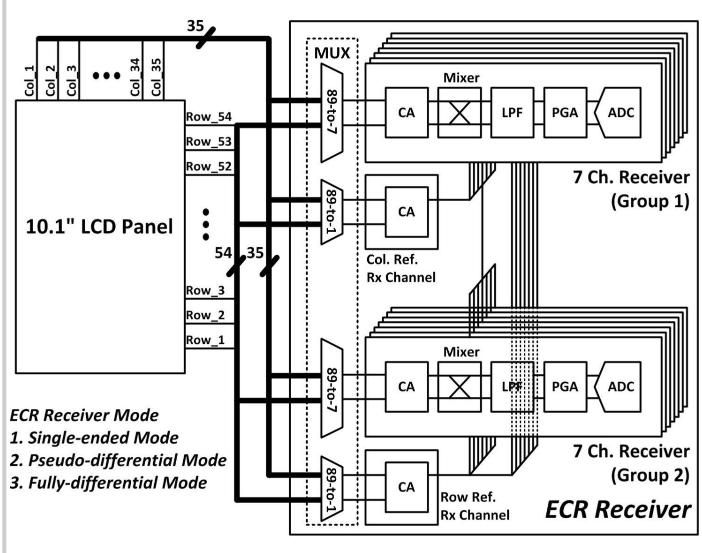

Figure 10.4.2: Block diagram of the stylus pen AFE.

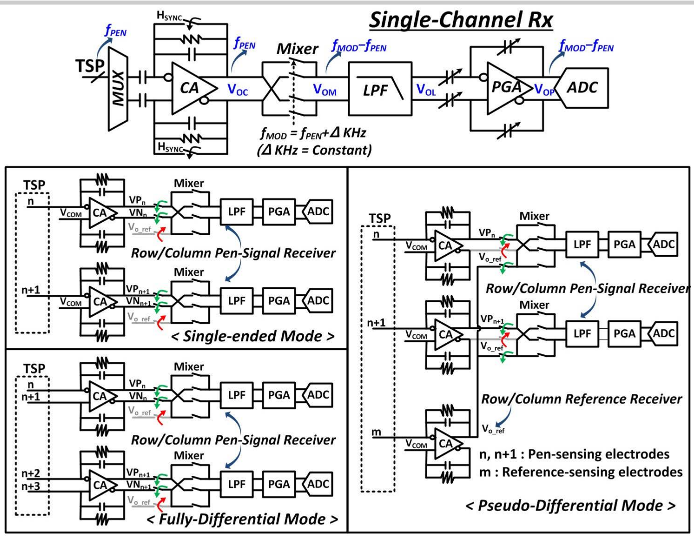

Figure 10.4.3: Block diagram of single-channel RX and configuration of AFE for three sensing modes.

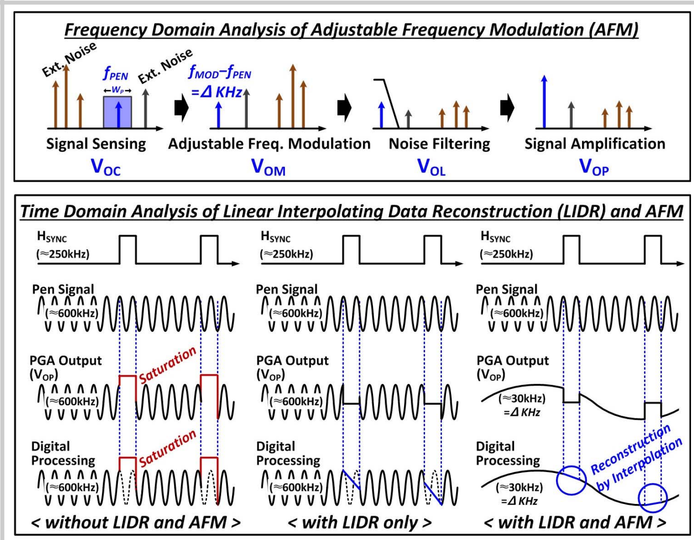

Figure 10.4.4: Frequency-domain and time-domain analysis of proposed AFM and LIDR.

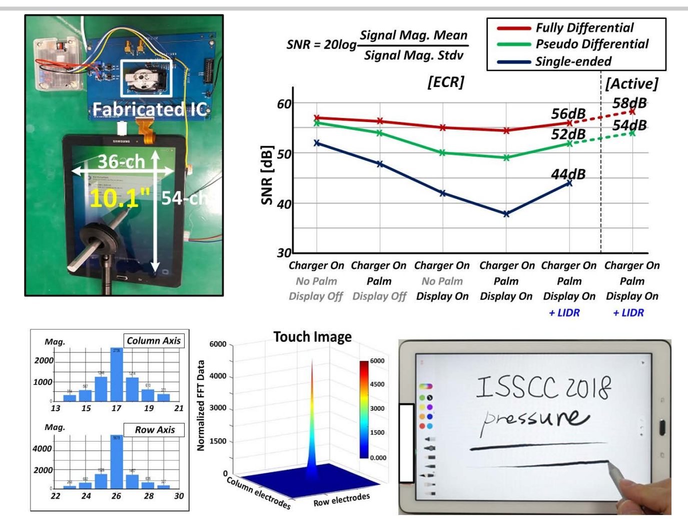

Figure 10.4.5: Measurement setup for experimental verification and measured results, and demonstration of the proposed AFE with a commercial 10-inch tablet.

List		[3] ISSCC2015	[4] ISSCC2015	[5] ISSCC2017	This work
TSP Size		10.1 inch	13 inch	65 inch	10.1 inch
# of Channels		48 x 32	57 x 35	104 x 64	54 x 35
Scan rate		120 Hz	240 Hz	3906 Hz	133 Hz
SNR	Display / Charger	OFF / -	ON / -	ON / -	ON / ON
	Passive	49.0 dB (Φ=1mm)	38.0 dB (Φ=1mm)	41.0 dB (Φ=1mm)	**56.0 dB** (Φ=1mm)
	Active	-	41.0 dB (Φ=0.5mm)	50.1 dB (Φ=1mm)	**58.0 dB** (Φ=1mm)
Pressure		Yes (6 bit)	Yes (N/A)	Yes (6 bit)	**Yes (10 bit)**
Process		180 nm BCD	85 nm CMOS	130 nm CMOS	100 nm CMOS
Chip area		14.7 mm^2	12.5 mm^2	42.3 mm^2	39.2 mm^2
Power (@ touch)		30.0 mW	62.0 mW	96.3 mW	24.0 mW

Figure 10.4.6: Performance summary and comparison.

10

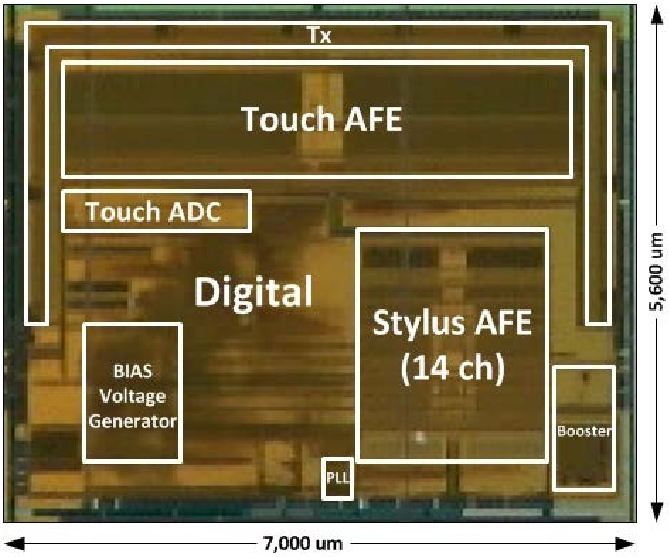

Figure 10.4.7: The micrograph of the proposed IC.