An Impedance Measurement SoC with Highly Digital Magnitude and Phase-to-Digital Converter

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2021 IEEE International Symposium on Circuits and Systems
May 22-28, 2021 Virtual & Hybrid Conference
Electrochemical Impedance Spectroscopy (EIS)

- EIS is an electrochemical techniques:
  - Measure the impedance of a system in dependence of the AC potentials frequency

- EIS is the response of an electrochemical system to an applied potential
  - The frequency dependence can reveal underlying chemical processes
  - Exploits variations that arise during bio-recognition events (R & C)

- EIS is formed by injecting a small sinusoidal stimulus voltage (current)
  - Adjustable frequency (several mHz to several kHz)
  - Measuring the output current (or voltage)
  - Amplitude and/or phase difference are related to the bio-recognition events

EIS Applications

- Biosensors have substantial potential for wearable applications:
  - Portability
  - Speed
  - High specificity
  - Low cost
  - Low power requirements

- Applications
  - Point-of-care (PoC) diagnostics
  - In-vitro molecular analysis
  - Cancer research
  - Water quality monitoring
  - Food processing.
  - Analysis of biofluids, such as saliva, sweat, tears, and interstitial fluid

Conventional EIS

- Frequency Response Analysis (FRA)
  - 😊 Measure real and imaginary parts of the complex impedance
  - 😊 Most of the unwanted noise can be removed via intensive analog filtering
  - ☹ Requires lock in amplifiers
  - ☹ Synchronization errors create phase offsets

Proposed EIS System

- This proposed EIS system composes:
  a. Sine Wave Synthesizer (SWS)
  b. Magnitude Detection Module (MDM)
  c. Phase Detection Module (PDM)

- The magnitude & phase of the impedance of the sample are measured:
  - Spectrum of input frequencies ranging from 579 µHz to 48.9 kHz

Sine Wave Synthesizer (SWS)

- SWS on-chip that comprises three components:
  1. Voltage-controlled square wave generator
  2. Clock divider
  3. Tunable low-pass filter (LPF).

Voltage-Controlled Square-Wave Generator

- EN is a control signal to allow larger capacitors
  - Connecting $C_{11}$ with $C_{12}$, and $C_{21}$ with $C_{22}$ when set to high.
  - The frequency of the square wave determines the switching frequency of this SC-LPF.
Proposed SC-LPF

- Fifth-order Chebyshev type-I filter $\rightarrow$ significant attenuation at higher frequencies
- Differential amplifier (DA) $\rightarrow$ two-stage opamp (gain, & bandwidth) of (35 dB & 12.5MHz)

\[
\text{LPF Transfer Functions Examples}
\]

Output sine wave: 10Hz (LOW Frequency)

\[
H(s) = \frac{1.581 \times 10^8}{s^5 + 93.63 s^4 + 1.169 e4 s^3 + 5.881 e5 s^2 + 2.659 e7 s + 4.743 e8}
\]

Output sine wave: 100Hz (MEDIUM Frequency)

\[
H(s) = \frac{1.581 \times 10^{13}}{s^5 + 936.3 s^4 + 1.169 e6 s^3 + 5.881 e8 s^2 + 2.659 e11 s + 4.743 e13}
\]

Output sine wave: 10kHz (HIGH Frequency)

\[
H(s) = \frac{1.581 \times 10^{23}}{s^5 + 9.363 e04 s^4 + 1.169 e10 s^3 + 5.881 e14 s^2 + 2.659 e19 s + 4.743 e23}
\]
Magnitude Detection Module (MDM)

- MDM is composed of:
  - A charging capacitor $C_m \rightarrow$ charged from the current source $I_{CH}$
  - Digital control unit $\rightarrow$ correct switching
  - Comparator & a 10-bit counter $\rightarrow$ digital output
Phase Detection Module (PDM)

- Measure the phase difference between the Input signal $V_{\text{REF}}$ and the response signal $V_{\text{IN}}$

**PHASE DETECTION BLOCK**

\[ y = 5.67781 \times 0.50608 \]

\[ R^2 = 0.99999 \]
Measurement Results

- The EIS measurement SoC was implemented using the TSMC 0.18 μm

- An active area of 0.35 mm²

- The proposed system consumes:
  - 175 μW for the sine generation
  - 93 μW for the MDM
  - 117 μW for the PDM

- This reduces the power consumption by:
  - 38% and 31%, for MDM and PDM [4].

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Measurement Results (SWS)

- SWS output spectra measured by the network/spectrum analyzer, PicoScope 5444D at various input frequencies.
- Frequencies of 100 Hz and 10 kHz, respectively, with THD of <0.2%.
- THD is computed by including five harmonic terms.

**100 Hz**
- SFDR = 57.9 dB
- FFT points = 1024

**10 kHz**
- SFDR = 62.5 dB
- FFT points = 4096
Nyquist plot for TNF-α detection at different concentrations

- Finding tumor necrosis factor α (TNF-α) at different concentrations:
  (266 pg/mL to 666 ng/mL)
- Using a sine wave of frequency 1-10 kHz.
- There is a rise in polarization resistance with growing steps
- Starting from:
  • Bare gold
  • Gold-coated with CMA
  • Anti-TNF-α antibody to cytokines
- Growing cytokine concentrations
  • (13 ng/mL and 666 ng/mL)

Comparison with the state-of-the-art work

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<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Technology (µm)</td>
<td>0.13</td>
<td>0.35</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>Supply (V)</td>
<td>0.9</td>
<td>3.3</td>
<td>1.8</td>
<td>1.8</td>
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<tr>
<td>Power (µW)</td>
<td>0.386</td>
<td>0.32</td>
<td>0.197</td>
<td>0.38</td>
</tr>
<tr>
<td>SWS $f_{\text{sin}}$</td>
<td>3.9-7.1 kHz</td>
<td>0.1m-100kHz</td>
<td>5k-1MHz</td>
<td>0.579m-48.9kHz</td>
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<tr>
<td>Magnitude Error</td>
<td>-</td>
<td>0.28%</td>
<td>-</td>
<td>0.19%</td>
</tr>
<tr>
<td>Phase Error</td>
<td>-</td>
<td>0.12%</td>
<td>0.04%</td>
<td>0.08%</td>
</tr>
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</table>

Conclusion

- A highly digital EIS SoC utilizing:
  - 10-bit impedance magnitude-and-phase-to-digital converters
  - Integrates a wide-range filter-based programmable SWS
  - The proposed EIS system was fabricated using a 180nm process
  - An area of only 0.35 mm$^2$

- The SWS produces output frequency in the range of 579 µHz–48.9 kHz
  - THD of 0.152% at 100 Hz and 0.116% at 10 kHz

- The proposed system consumes 175 µW for the sine generation, 93 µW, and 117 µW for the MDM and PDM, respectively.