I-Q Signal Generation Techniques for Communication IC Testing and ATE Systems

M. Murakami, H. Kobayashi, S. N. B. Mohyar
O. Kobayashi, T. Miki, J. Kojima

Gunma University
Universiti Malaysia Perlis
D-Clue Tech, formerly STARC
Research Objective

- To develop usage of complex multi-band signals for LSI testing applications
- To develop digital centric design of complex multi-band signal generator
  - Multi-bit ΔΣ DA modulator
  - Linearity enhancement algorithms
Outline

• Background to This Research
• Complex Multi-Band Signals
• Complex Multi-BP \( \Delta \Sigma \) DA Modulators
• DWA Algorithm
• Self-Calibration
• Combination of DWA and Self-Calibration
• Conclusions
Outline

- Background to This Research
- Complex Multi-Band Signals
- Complex Multi-BP $\Delta \Sigma$ DA Modulators
- DWA Algorithm
- Self-Calibration
- Combination of DWA and Self-Calibration
- Conclusions
Research Goal

Demand for low cost testing of communication IC

High quality I,Q test signal generation for receiver IC with low cost
Outline

• Background to This Research
• Complex Multi-Band Signals
• Complex Multi-BP ΔΣ DA Modulators
• DWA Algorithm
• Self-Calibration
• Combination of DWA and Self-Calibration
• Conclusions
Complex Signal

2 Real signals $I_{in}$, $Q_{in}$

Complex signal $I_{in} + j Q_{in}$

Complex signal processing is NOT complex.
- Prof. Ken Martin, Toronto Univ.
Complex Signal in Frequency Domain

Complex signal $I_{in} + j Q_{in}$

After Fourier transform $I_{in}(j \omega) + j Q_{in}(j \omega)$

Asymmetric

Complex

Negative freq. Positive freq.
IC Testing with Multi-tone Signal

ADSL ADC Testing

Noise Power Ratio (NPR)

Multi-tone signal

Distortion by DUT

empty
IC Testing
with Complex Multi-tone Signal

Complex Analog Filter Testing

Complex filter gain
IC Testing
with Complex Multi-tone Signal

I-Q ADCs Testing

I-Q ADCs in receiver circuit
IC Testing with Complex Multi-tone Signal

Image Rejection Ratio Testing of Communication ICs

I, Q imbalance

Negative freq. (input)  Positive freq. (output)

Suggested by an ATE vendor
IC Testing with Complex Signal

Clock phase fine adjustment system using complex signal

\[
\sin(2\pi f_0(t - \Delta t)) = \cos(2\pi f_0\Delta t) \sin(2\pi f_0 t) - \sin(2\pi f_0\Delta t) \cos(2\pi f_0 t) \\
= G_c \sin(2\pi f_0 t) + G_s \cos(2\pi f_0 t)
\]

Suggested by an ATE vendor
IC Testing with Complex Signal

High frequency signal generation

\[ Y = \cos \omega_{\text{in}}t \cdot \cos \omega_{\text{c}}t - \sin \omega_{\text{in}}t \cdot \sin \omega_{\text{c}}t \]
\[ = \cos(\omega_{\text{in}} + \omega_{\text{c}})t. \]
Outline

• Background to This Research
• Complex Multi-Band Signals
• Complex Multi-BP ΔΣ DA Modulators
• DWA Algorithm
• Self-Calibration
• Combination of DWA and Self-Calibration
• Conclusions
I,Q Signal Generation

① Analog centric

![Diagram](image1)

② Digital centric (1)

![Diagram](image2)

③ Digital centric (2)

![Diagram](image3)

Proposed
① Analog Centric

Large Nyquist-rate DACs
and
Steep analog filters
Delta Sigma DA Converter
Real vs Complex

② 2 Real-BP ΔΣ DACs

③ 1 Complex-BP ΔΣ DAC

Wider signal band, High SNR
Complex Delta Sigma is Superior

15 dB better SNDR for complex BP ΔΣ modulator

High quality I, Q signals
I,Q Signal Generation

DSP + ΔΣ DAC + Complex

II

Low cost, high quality signal!

Digital rich!
Principle of Complex BP Noise Shape

\[ I_{out} + jQ_{out} = \frac{H(z)}{1 + H(z)}(I_{in} + jQ_{in}) \]

\[ + \frac{1}{1 + H(z)}(E_I + jE_Q) \]

Quantization noises

\[ H(z) \]
Principle of Complex BP Noise Shape

Signal Transfer Function = 1

\[ I_{out} + jQ_{out} = \frac{H(z)}{1 + H(z)} (I_{in} + jQ_{in}) \]

\[ + \frac{1}{1 + H(z)} (E_I + jE_Q) \]

Noise Transfer Function = 0
Principle of Complex BP Noise Shape

\[ I_{out} + jQ_{out} = \frac{1}{(I_{in} + jQ_{in})} + 0(\frac{E_I + jE_Q}{}) \]

Signal Transfer Function = 1

Noise Transfer Function = 0
2nd-order Complex Multi-BP ΔΣ DAC

![Diagram of 2nd-order Complex Multi-BP ΔΣ DAC](image)

- **Digital Input**
  - $I_{in}$
  - $Q_{in}$

- **H(z)**

- **DAC**
  - $E_I$
  - $E_Q$
  - $I_{out}$
  - $Q_{out}$

**Output spectrum**

- Single-band: $N = 1$
- Multi-band: $N = 4$

$$\frac{\omega_{in}}{\omega_s}$$
$N^{th}$-order Complex Resonator

$H(z)$

Output spectrum

$N = 1$ Single-band

$N = 4$ Multi-band
Outline

• Background to This Research
• Complex Multi-Band Signals
• Complex Multi-BP ΔΣ DA Modulators
• DWA Algorithm

DWA: Data Weighted Averaging

One of Dynamic Element Matching (DEM) algorithms
Multi-bit DA Modulator

Multi-bit DA modulator (2~3bit)

Quantization noise reduction

Linearity degradation

Analog filter

Quantization noise
Multi-bit DAC

Normal unary DAC

\[ e_i : \text{current source mismatch} \]
Multi-bit DAC

Accumulate mismatch of particular cell

Normal unary DAC

$e_i$: current source mismatch
Multi-bit DAC + DWA

Memorize next cell selection start point

DWA*DAC

*Data Weighted Averaging | Select the element with DSP algorithm
Effect of DWA

Steep notch at DC
Equivalent Circuit of Complex DWA

Complex resonator

\[ I_{\text{in}} \]

\[ Q_{\text{in}} \]

\[ Z^{-N} \]

\[ Z^{-N} \]

\[ \delta Q \]

\[ \delta I, \delta Q \text{ affected by only complex notch} \]

DAC input can be \( \infty \)

Can’t be realized directly
Equivalent Circuit Implementation

- Attach pointers
- Exchange upper-path and lower-path every N clock

Complex DWA is realized.
Complex Multi-Bandpass DWA Algorithm

\( N = 4 \) (four zero points)

### DAC\(_1\) (LP operation)

<table>
<thead>
<tr>
<th>( I_{in} )</th>
<th>( Q_{in} )</th>
<th>( I_0 )</th>
<th>( I_1 )</th>
<th>( I_2 )</th>
<th>( I_3 )</th>
<th>( I_4 )</th>
<th>( I_5 )</th>
<th>( I_6 )</th>
<th>( I_7 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### DAC\(_2\) (HP operation)

<table>
<thead>
<tr>
<th>( I_{in} )</th>
<th>( Q_{in} )</th>
<th>( I_0 )</th>
<th>( I_1 )</th>
<th>( I_2 )</th>
<th>( I_3 )</th>
<th>( I_4 )</th>
<th>( I_5 )</th>
<th>( I_6 )</th>
<th>( I_7 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

34/50
Simulation Result

~Ideal Linear DAC~
Simulation Result ~Actual Nonlinear DAC~

- **Digital input**
- **Complex Bandpass ΔΣ Modulator**
- **DAC**
- **Complex Bandpass Filter**
- **Analog output**

Notches filled with noise
Simulation Result
~ Actual Nonlinear DAC + DWA ~
Outline

• Background to This Research
• Complex Multi-Band Signals
• Complex Multi-BP ΔΣ DA Modulators
• DWA Algorithm
• Self-Calibration
• Combination of DWA and Self-Calibration
• Conclusions
# Look Up Table

## Example

<table>
<thead>
<tr>
<th>Cat Age</th>
<th>Human Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>27</td>
</tr>
<tr>
<td><strong>3</strong></td>
<td><strong>33</strong></td>
</tr>
<tr>
<td>4</td>
<td>39</td>
</tr>
<tr>
<td>5</td>
<td>45</td>
</tr>
<tr>
<td>6</td>
<td>50</td>
</tr>
<tr>
<td>7</td>
<td>55</td>
</tr>
<tr>
<td>8</td>
<td>60</td>
</tr>
</tbody>
</table>

- **Memory**
  - **address**: 3
  - **data**: 33

---

39/50
DAC Nonlinearity Measurement

Results are stored in LUTs

2nd Complex Multi-BP ΔΣ DA Modu. + Non-Linear DAC

![Diagram showing the DAC nonlinearity measurement process](image)

\[ \Delta \Sigma \text{ ADC inside SoC} \]

LUT

<table>
<thead>
<tr>
<th>Address</th>
<th>I</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>2.03</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>4.05</td>
</tr>
</tbody>
</table>

Noise by Non-Linearity
ΔΣ DAC with Self-Calibration of DAC1, DAC2

CLK(1)

LUT

<table>
<thead>
<tr>
<th>Address</th>
<th>I</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1</td>
<td>1.05</td>
<td>0.97</td>
</tr>
<tr>
<td>2</td>
<td>2.03</td>
<td>2.04</td>
</tr>
<tr>
<td>3</td>
<td>2.99</td>
<td>3.01</td>
</tr>
<tr>
<td>4</td>
<td>4.02</td>
<td>4.05</td>
</tr>
</tbody>
</table>
ΔΣ DAC with Self-Calibration of DAC1, DAC2

CLK(2)

LUT

<table>
<thead>
<tr>
<th>Address</th>
<th>I</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1</td>
<td>1.05</td>
<td>0.97</td>
</tr>
<tr>
<td>2</td>
<td>2.03</td>
<td>2.04</td>
</tr>
<tr>
<td>5</td>
<td>4.97</td>
<td>5.03</td>
</tr>
</tbody>
</table>
Simulation Results

Simulation Conditions

1. w/o DWA
2. w/ DWA
3. Self-calibration

\[ \delta = 1.0\% \]
\[ \delta = 0.9\% \]
\[ \delta = 0.7\% \]

\[ \delta = 0.5\% \]
\[ \delta = 0.3\% \]
\[ \delta = 0.1\% \]
When DAC nonlinearity is large, self-calibration (③) is more effective than DWA (②).
Pros and Cons of Self-Calibration

<table>
<thead>
<tr>
<th>Pros</th>
<th>DWA</th>
<th>Self-Calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAC Nonlinearity Noise Shaping</td>
<td>Specific Bands</td>
<td>All Bands</td>
</tr>
</tbody>
</table>

- Better SNDR than DWA is obtained.

Cons

- DAC nonlinearity measurement with delta-sigma ADC is required.
Outline

• Background to This Research
• Complex Multi-Band Signals
• Complex Multi-BP ΔΣ DA Modulators
• DWA Algorithm
• Self-Calibration
• Combination of DWA and Self-Calibration
• Conclusions
Combination of DWA and Self-Calibration

LP case
Combination of DWA and Self-Calibration

For large variation, combination of DWA and self-calibration is the best.
Outline

• Background to This Research
• Complex Multi-Band Signals
• Complex Multi-BP ΔΣ DA Modulators
• DWA Algorithm
• Self-Calibration
• Combination of DWA and Self-Calibration
• Conclusions
Conclusion

• I-Q signal generation with digital centric
• Complex multi-BP ΔΣ DAC
• Multi-bit DAC
  ○ Relaxes analog filter requirements
  x Degrades system linearity
  → DWA algorithm
  → Self-calibration algorithm
  → Their combination

Low cost, high quality I-Q signal generation.
Back Up
## Type of DWA

<table>
<thead>
<tr>
<th></th>
<th>Conventional 1 (Real MBP DWA)</th>
<th>Conventional 2 (Complex SBP DWA)</th>
<th>Proposed (Complex MBP DWA)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Before DAC</strong></td>
<td></td>
<td>fs/4</td>
<td></td>
</tr>
<tr>
<td>(BP-noise shape)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>After</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-Linear DAC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>with DWA</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>after Non-Linear DAC</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**DWA II DSP algorithm**

```
Digital

Complex Bandpass ΔΣ Modulator

...1010

Digital input

...0101

1

DAC

Complex Bandpass Filter

2 3

Analog

Analog output
```
Simulation Result
~ Actual Nonlinear DAC + DWA ~

N (number of notches)

SNDR [dB]

N increases ➔ SNDR decreases
Simulation Conditions: DAC unit cell variation Standard deviation 1.0%

Current Amount of Each Unit Cell

DAC1 Total Current: 7.98
DAC2 Total Current: 7.96
DWA = ΔΣ

Non-Linearity

Integration

Differentiation

δ affected by only Differentiation

Can’t be realized directly

Input

DAC

Output

Input

DAC

Output

Equivalent circuit for implementation

Memorize next cell selection start point