Study of Complex Multi-Bandpass Δ Σ Modulator for I-Q Signal Generation

M. Murakami, S. Mohyar, H. Kobayashi

T. Matsuura, O. Kobayashi, M. Tsuji, S. Umeda, R. Shiota,   N. Dobashi,
M. Watanabe,   I. Shimizu, K. Niitsu, N. Takai, T. J. Yamaguchi

Gunma University , Japan   STARC   Nagoya University

OUTLINE

▶ Research Background

▶ Complex Multi-BP ΔΣ DA Modulator

▶ DWA Algorithm
  – Conventional Method
  – Proposed Method

▶ Conclusion

OUTLINE

▶ **Research Background**

▶ Complex Multi-BP ΔΣ DA Modulator

▶ DWA Algorithm
  – Conventional Method
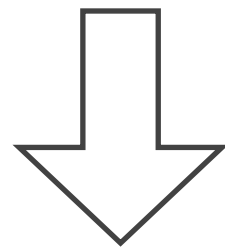 – Proposed Method

▶ Conclusion

Necessity of I,Q signal

RF analog front-end of Receiver IC

$\cos(\omega_{LO}t)$

RF

In-phase

mixer

$-\sin(\omega_{LO}t)$

Quadrature-phase

ADC

DSP
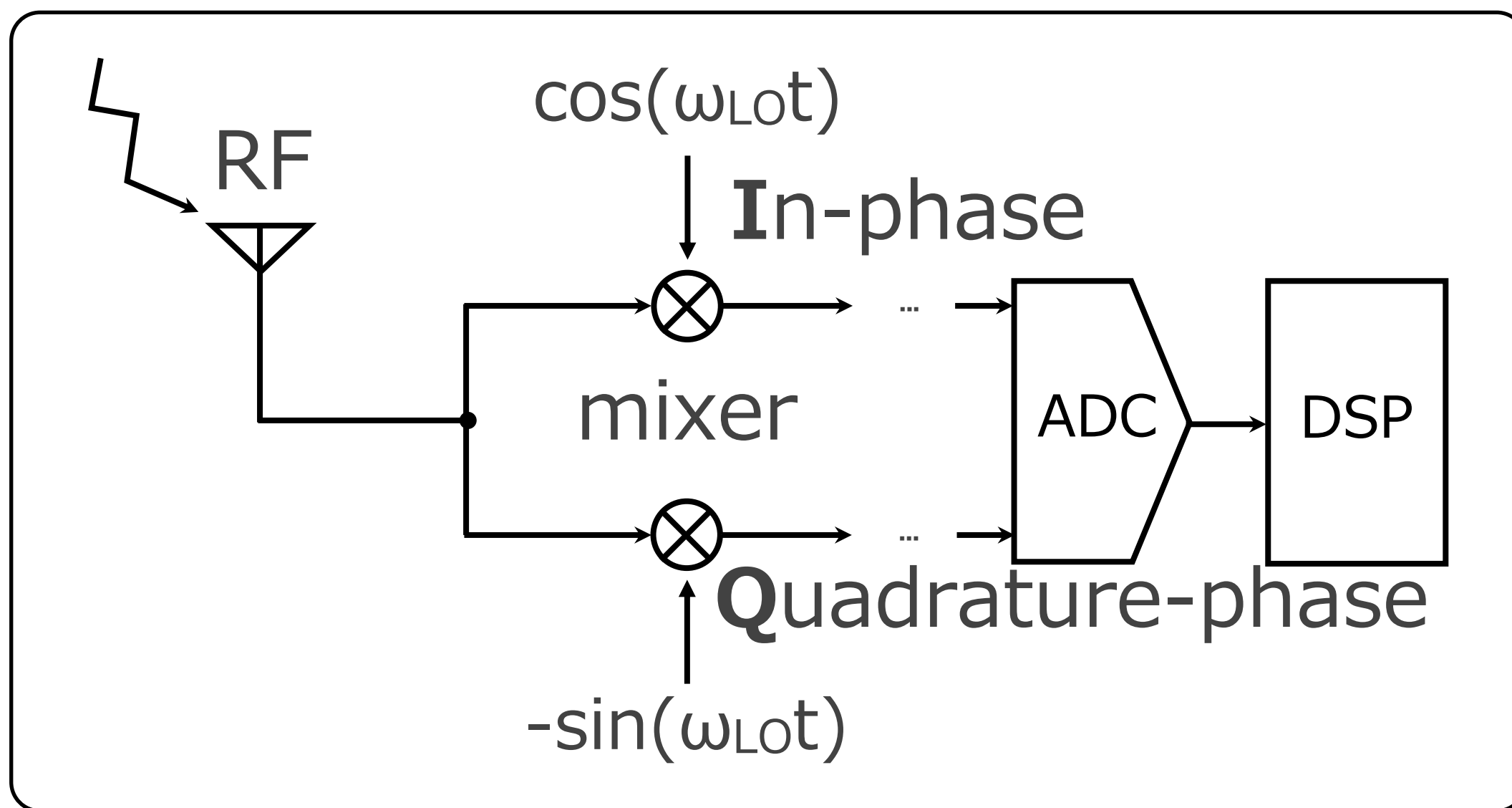
Need testing!

Research Goal

Demand for low cost testing
of communication IC

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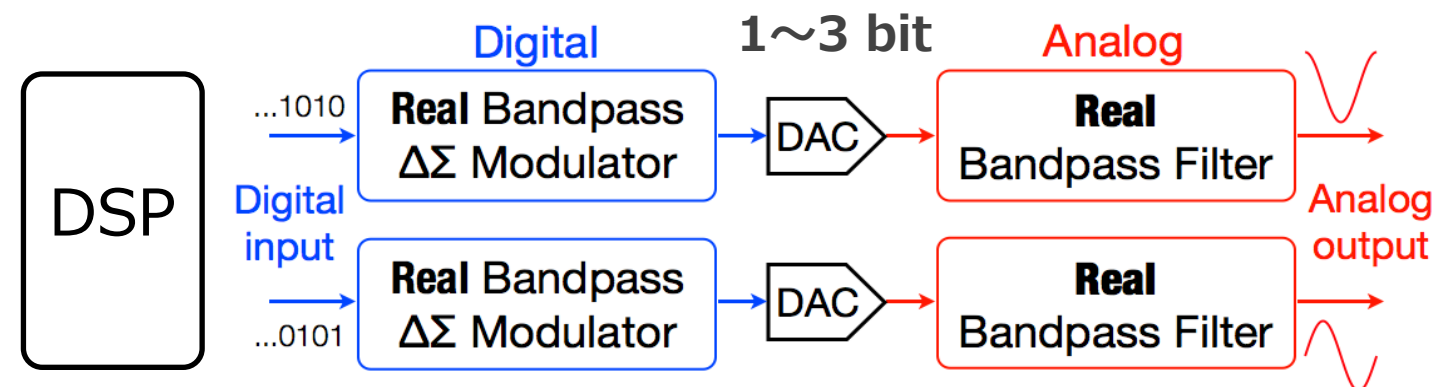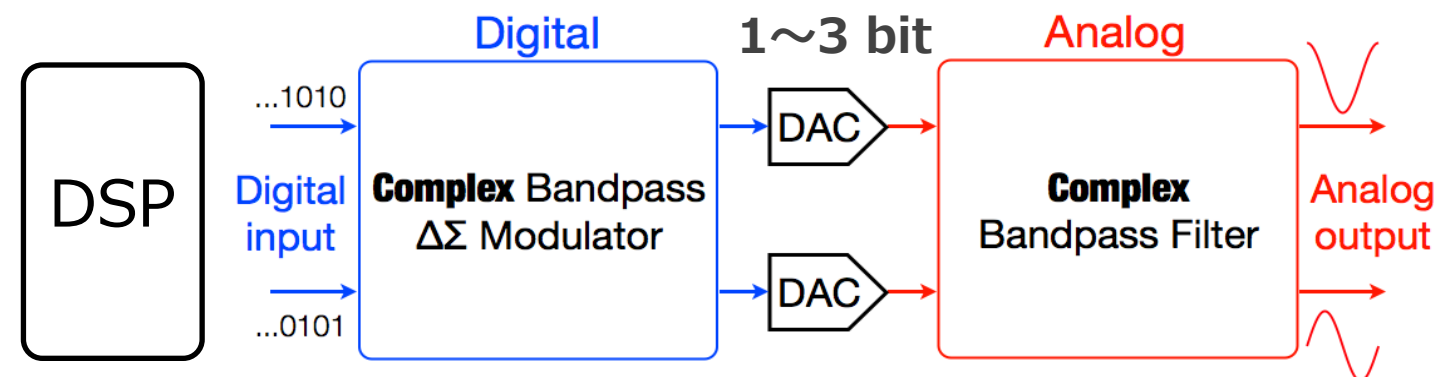with

Low cost ¥

I,Q signal generation

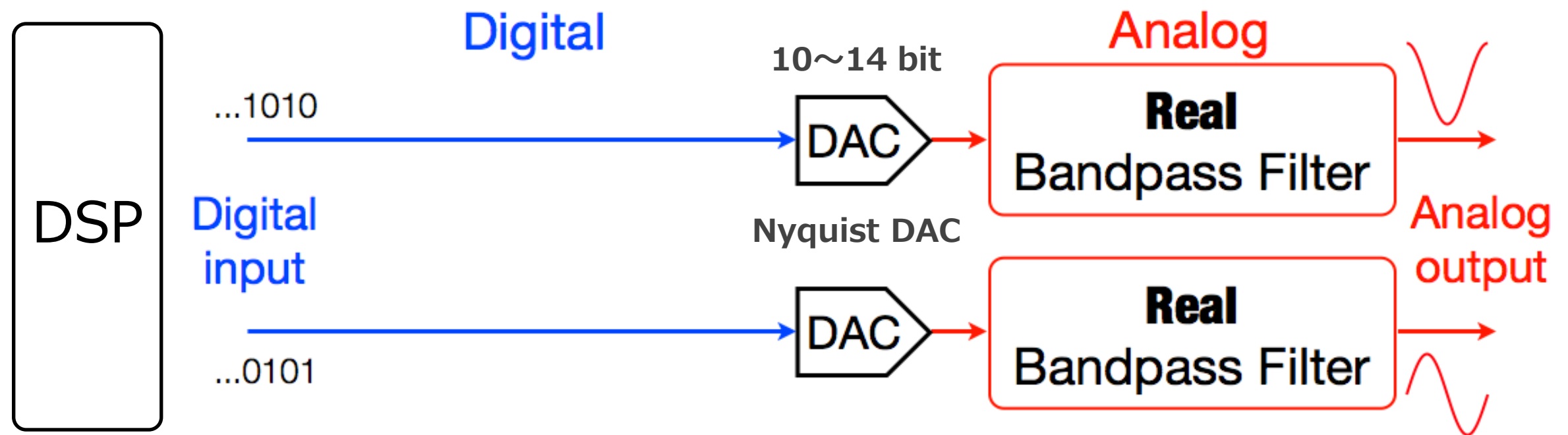## ① Analog centric
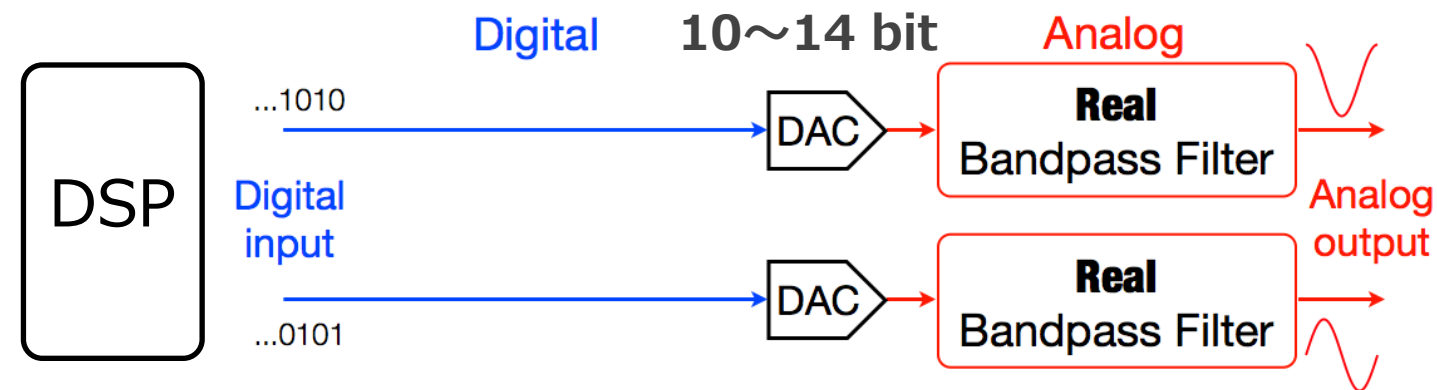
② Digital centric（1）

③ Digital centric（2）
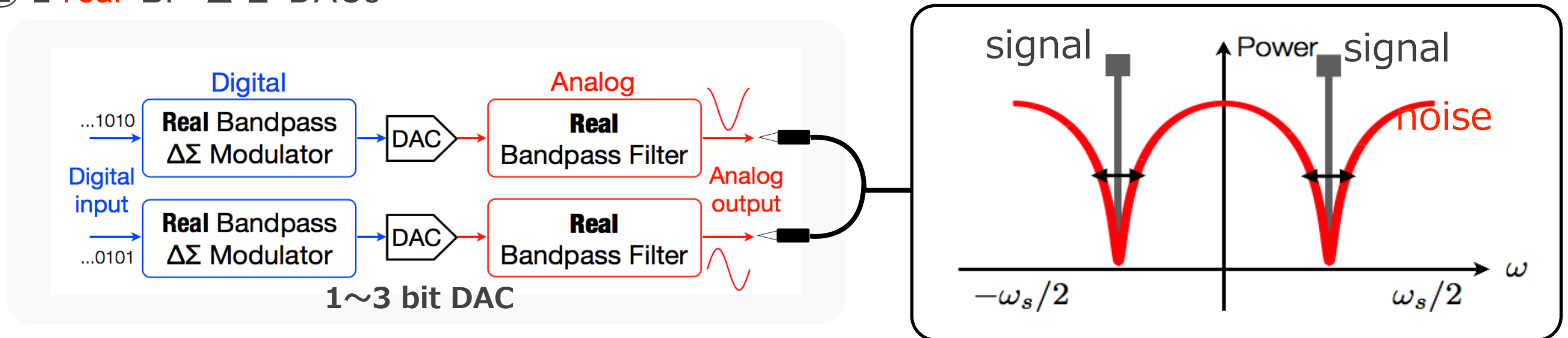
① Analog centric

Large Nyquist-rate DACs

and
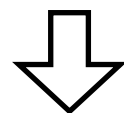
Steep analog filters

Delta Sigma DA Converter

Digital centric

② 2 real−BP Δ Σ DACs

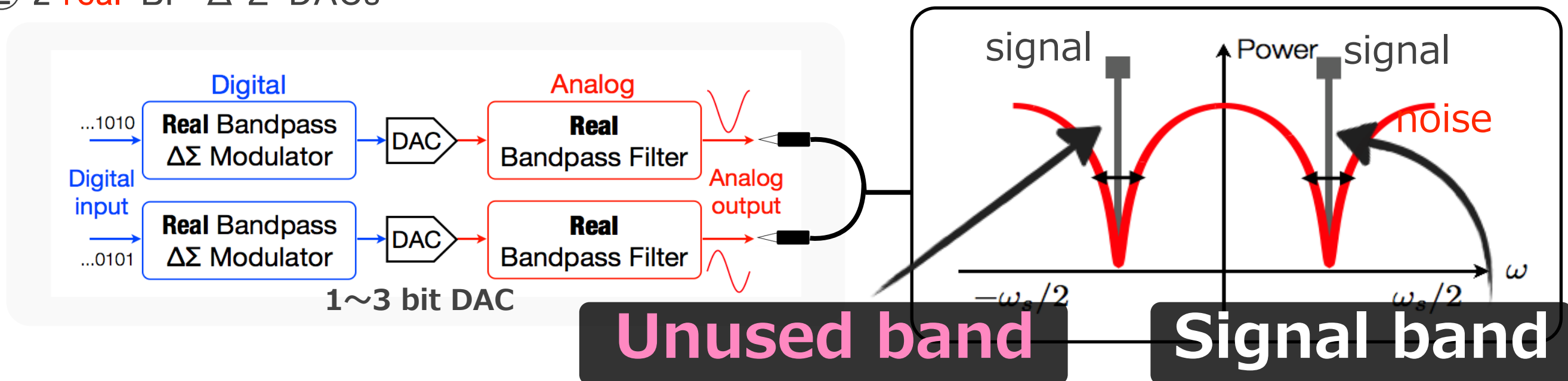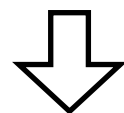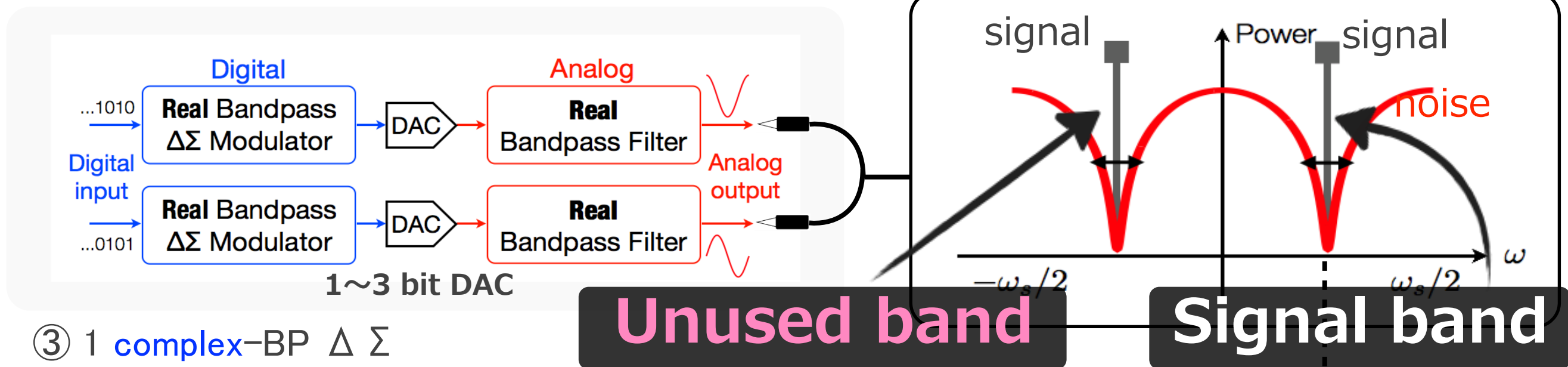## **Delta Sigma**

- Digital modulator
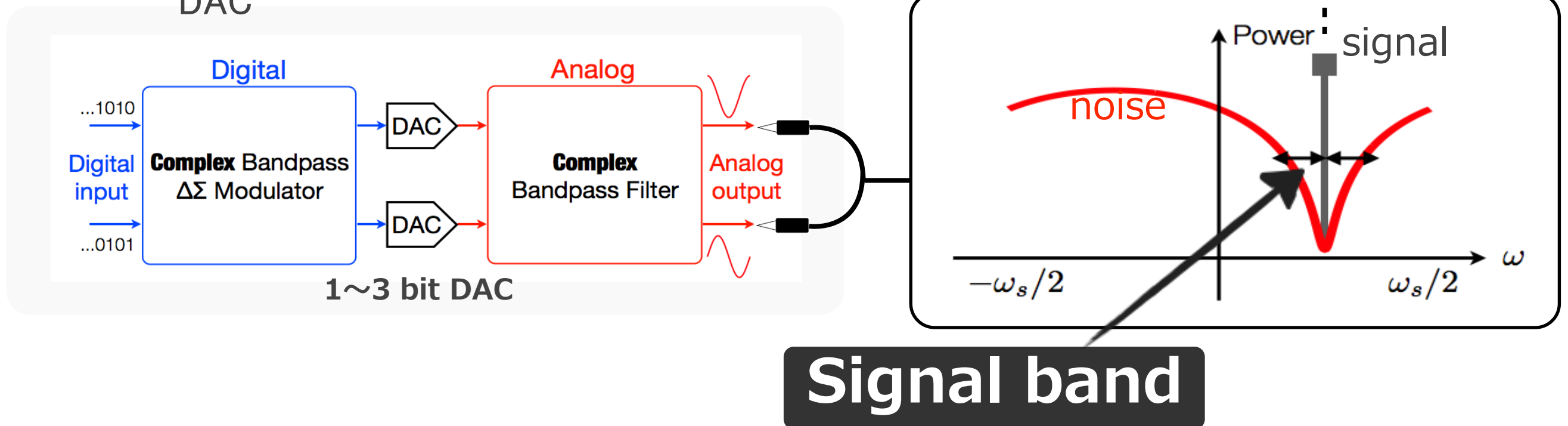- 1~3 bit DAC
- Oversampling

⇩

Relaxes analog filters

Delta Sigma DA Converter

Digital centric

② 2 real−BP Δ Σ DACs

Unused band **Signal band**

Delta Sigma

- Digital modulator
- 1~3 bit DAC
- Oversampling

⇓

Relaxes analog filters

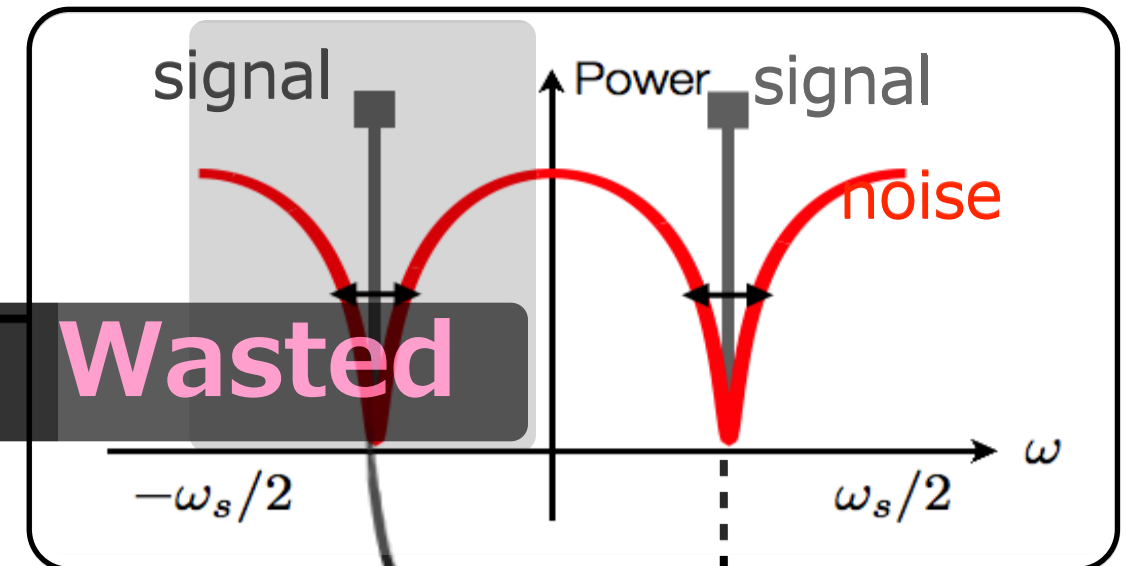# Delta Sigma DA Converter

Real vs Complex

② 2 real–BP Δ Σ DACs

③ 1 complex–BP Δ Σ DAC

Unused band **Signal band**

Signal band

Complex Delta Sigma is Superior

Real vs Complex

② 2 real–BP Δ Σ DACs
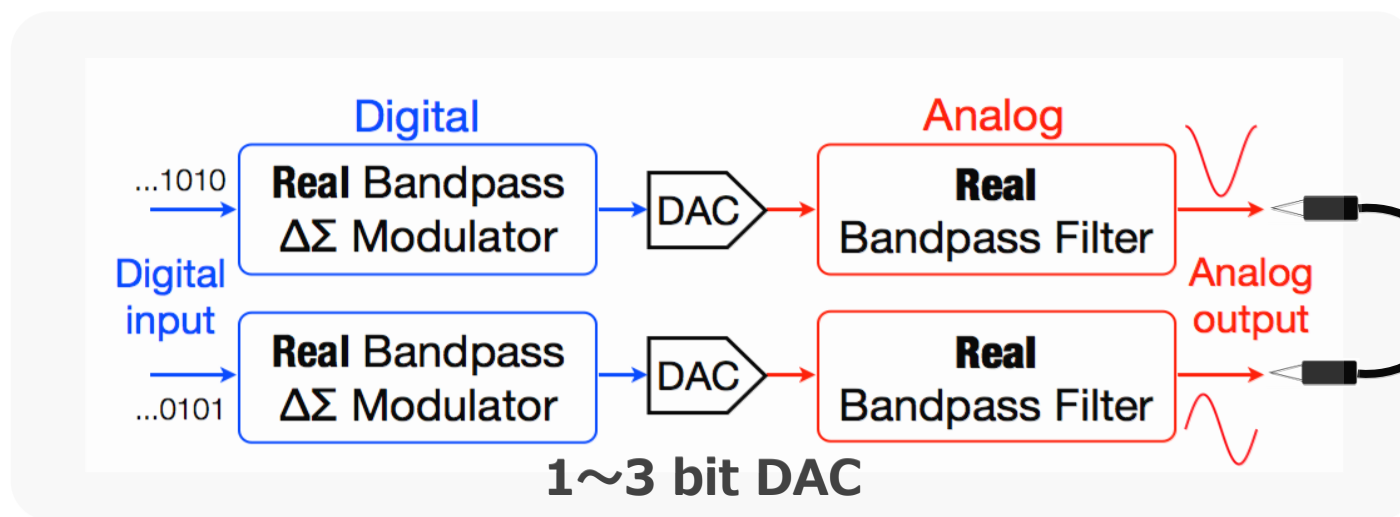
③ 1 complex–BP Δ Σ DAC
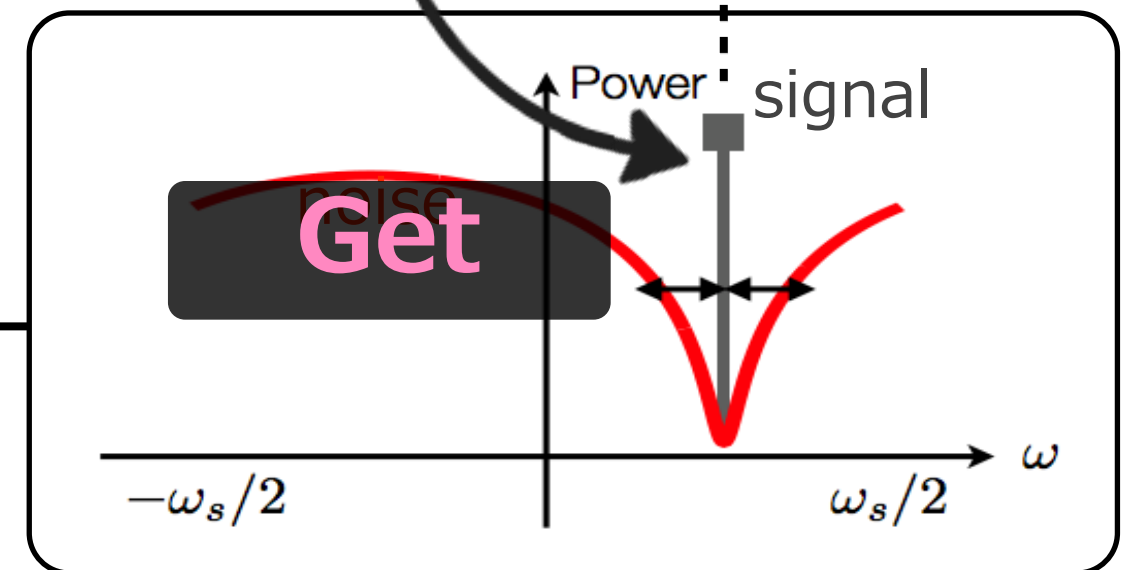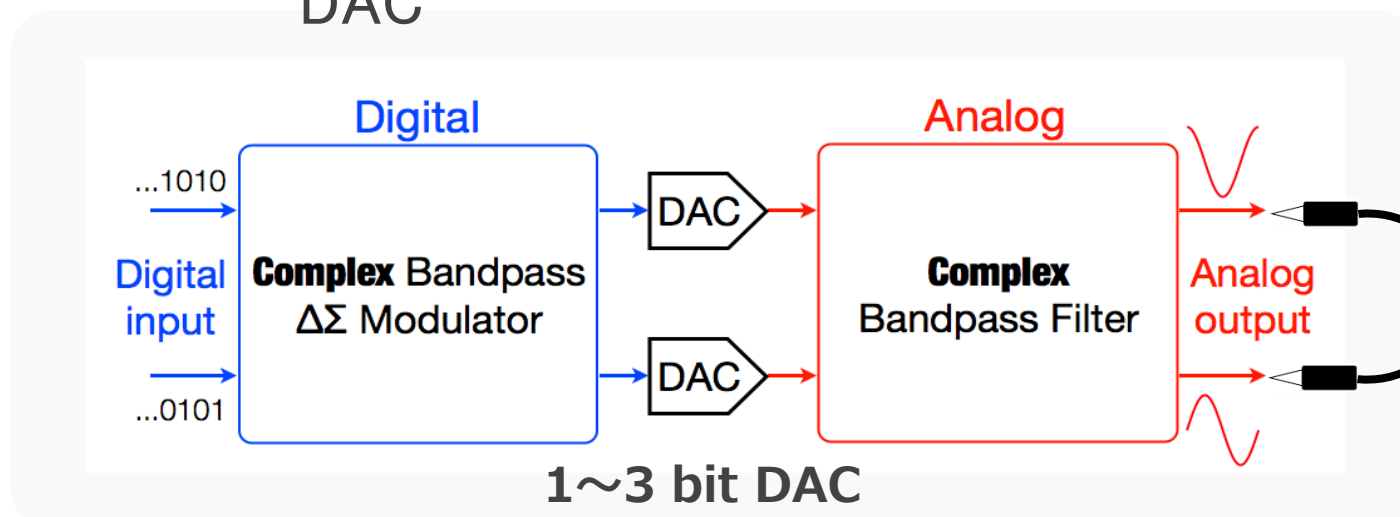
Wide band, High SNR

Complex Delta Sigma is Superior

SNDR | Signal to **N**oise and **D**istortion **R**atio
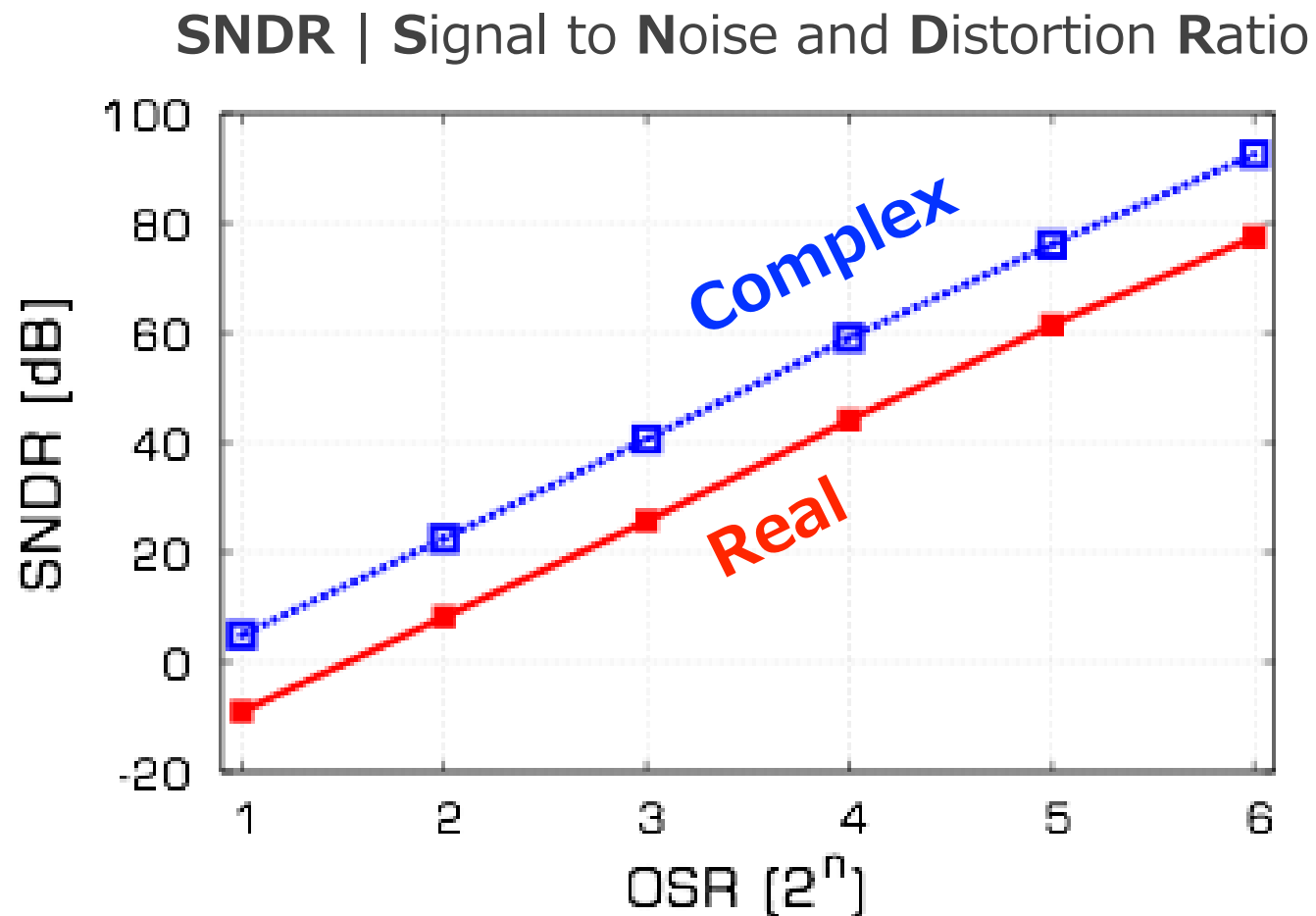
Complex

Real

20dB better SNDR
for complex BP ΔΣ modulator

Real

signal   Power signal

noise

$-\omega_s/2$ $\omega_s/2$ ω

Complex

Power signal

noise

$-\omega_s/2$ $\omega_s/2$ ω
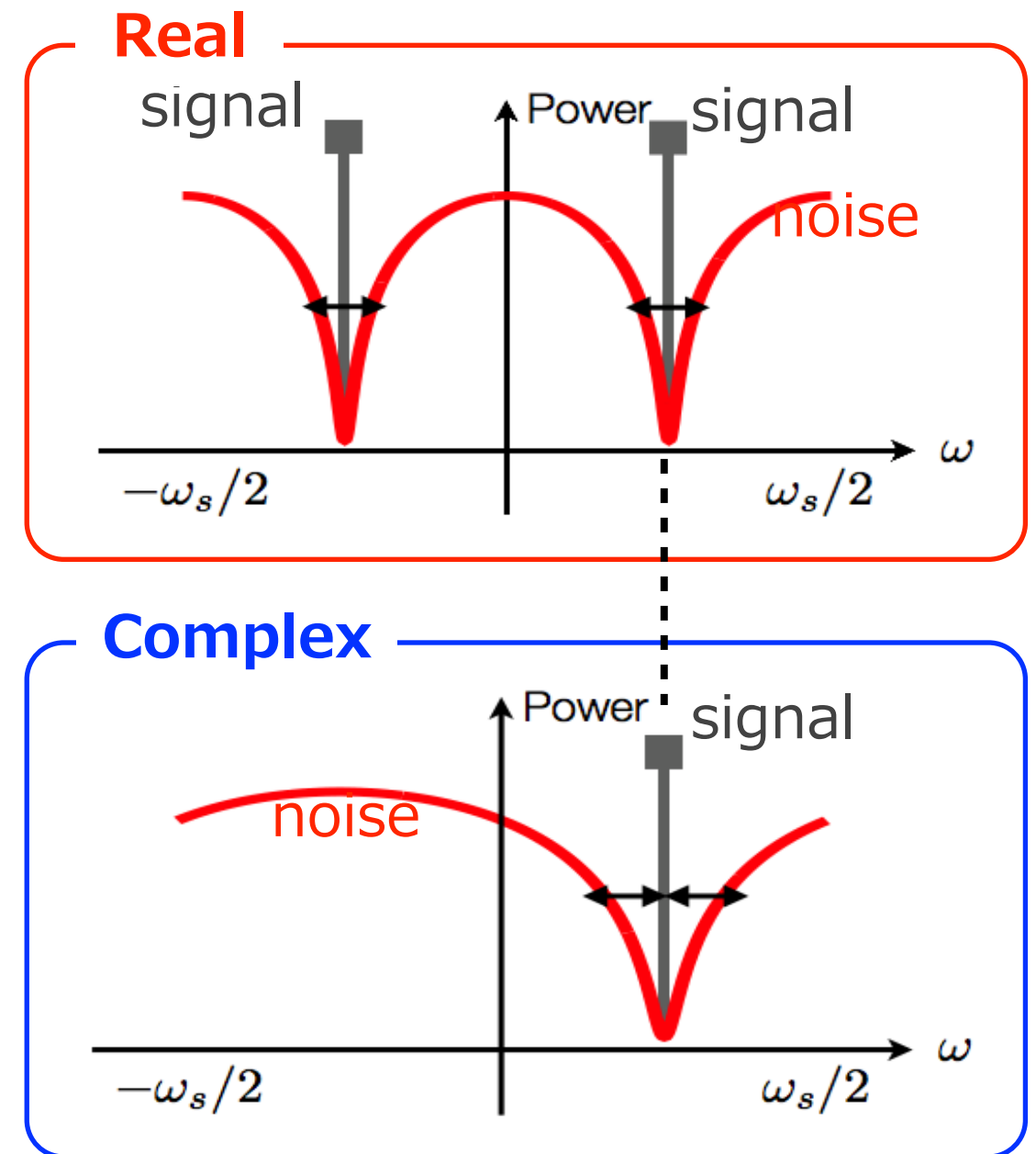
High quality I,Q signals

Complex signal

Real signal $\qquad$ I_{in} , Q_{in}

$\Downarrow$
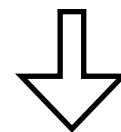
Complex signal $\qquad$ $I_{in} + jQ_{in}$ $\qquad$ $j = \sqrt{-1}$

Complex signal processing is NOT complex. (K.Martin)

I,Q signal generation
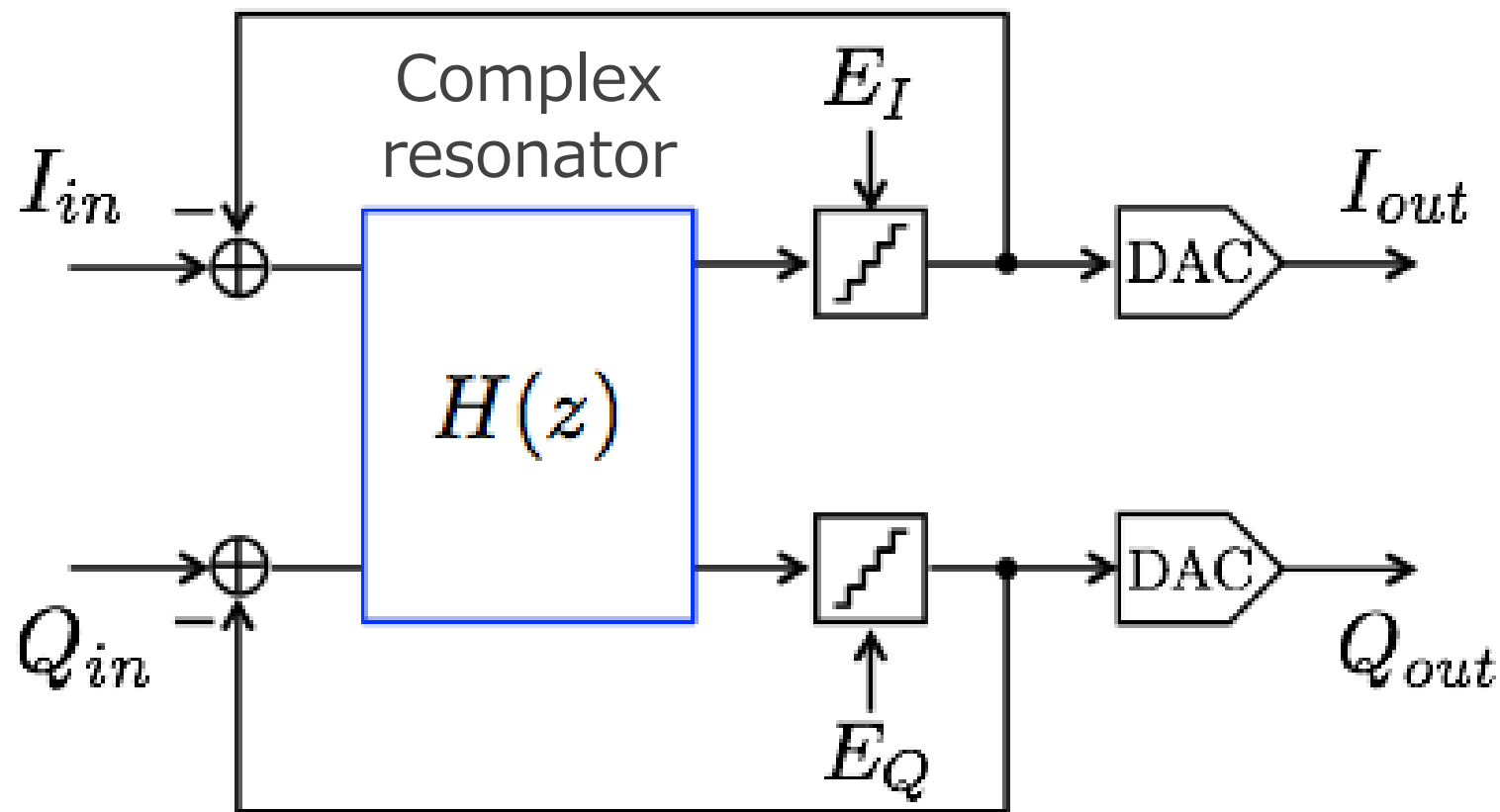
DSP, DAC

+

ΔΣ

+

Complex
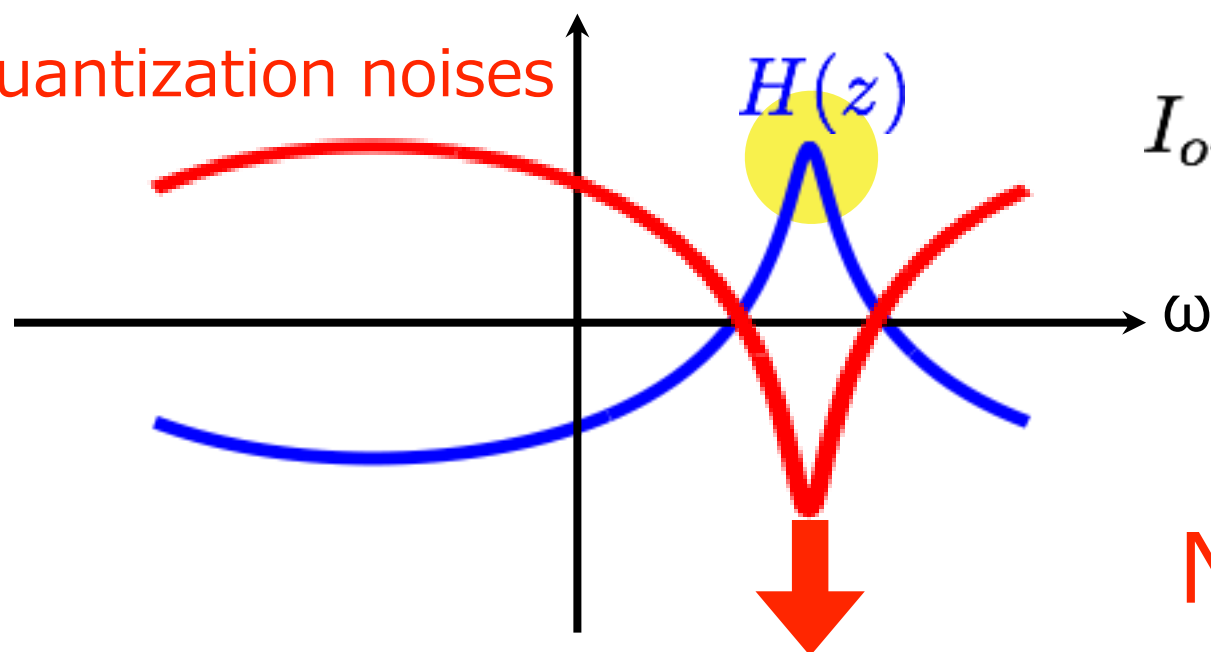
=

Low cost, high quality signal !

Digital rich !

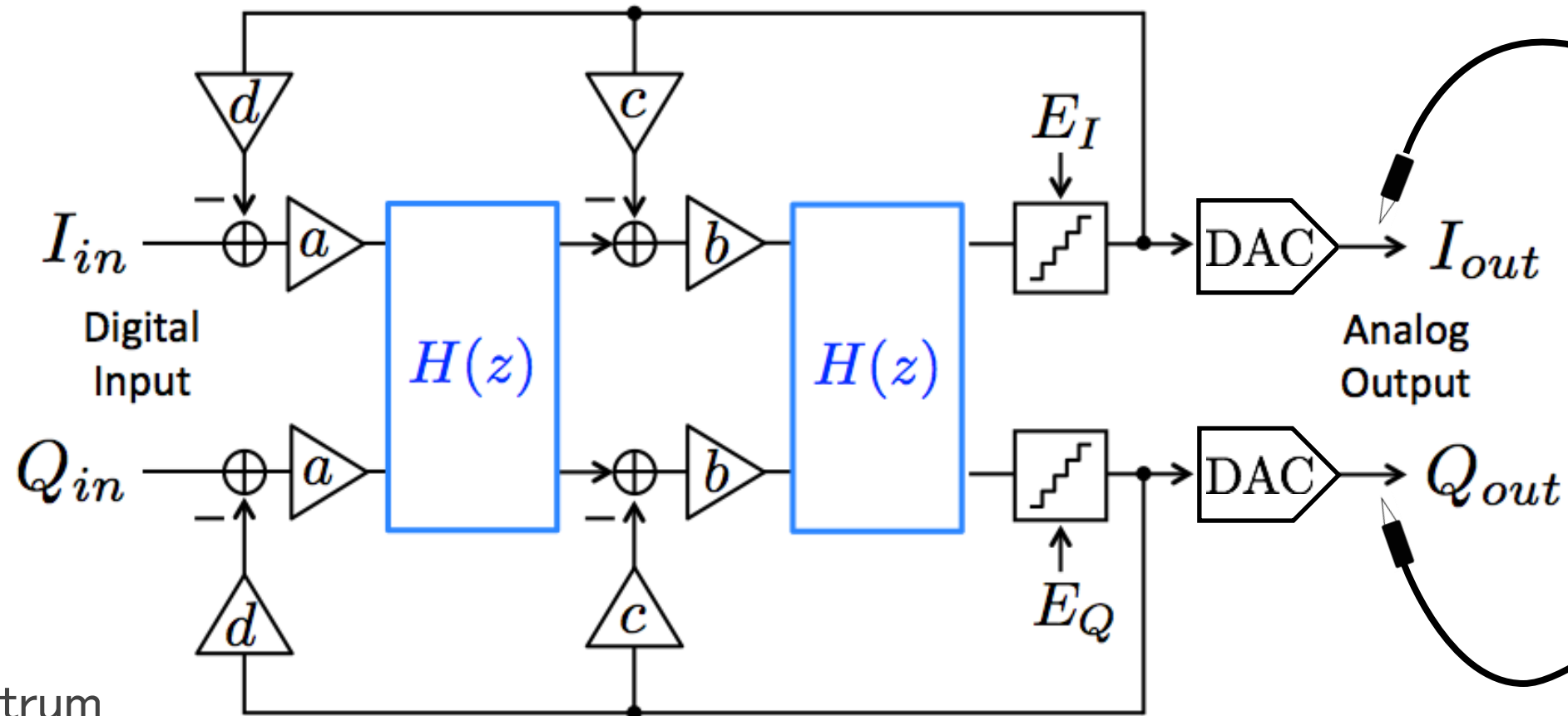# OUTLINE

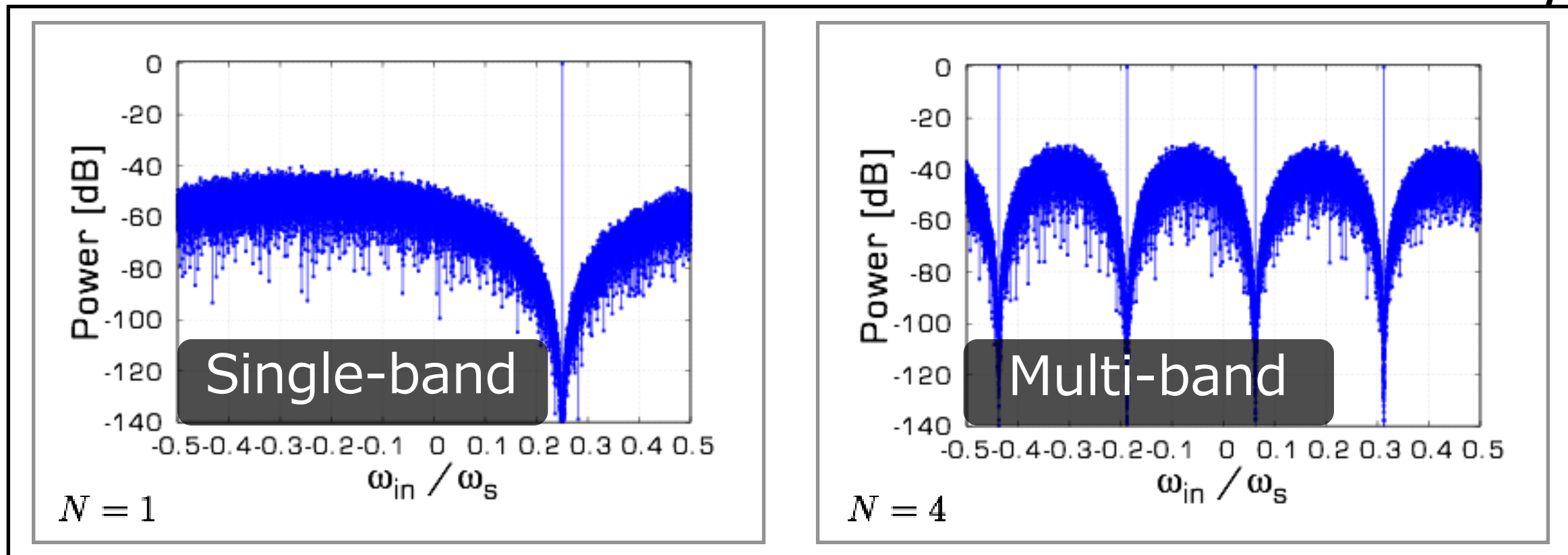# Principle of complex BP noise shape

Signal Transfer Function = 1

$$I_{out} + jQ_{out} = \boxed{1}(I_{in} + jQ_{in})$$

$$+ \boxed{0}(E_I + jE_Q)$$

Noise Transfer Function = 0

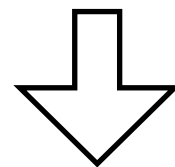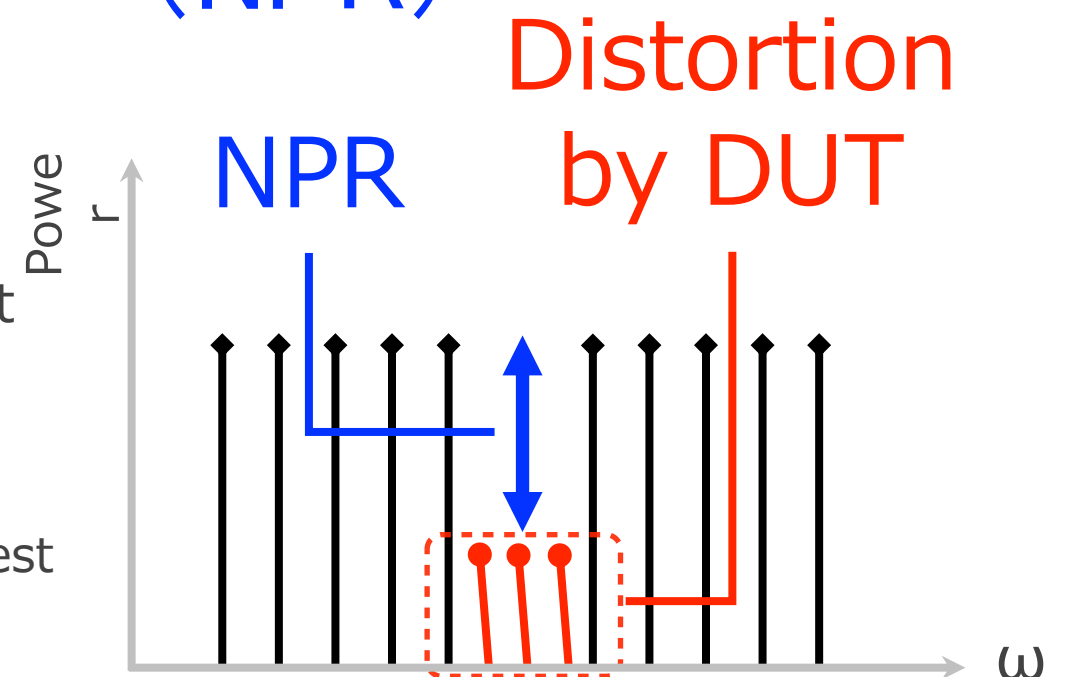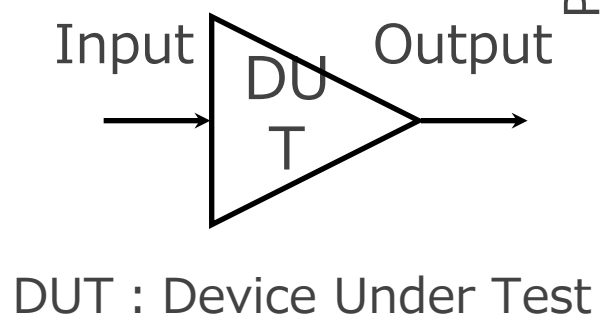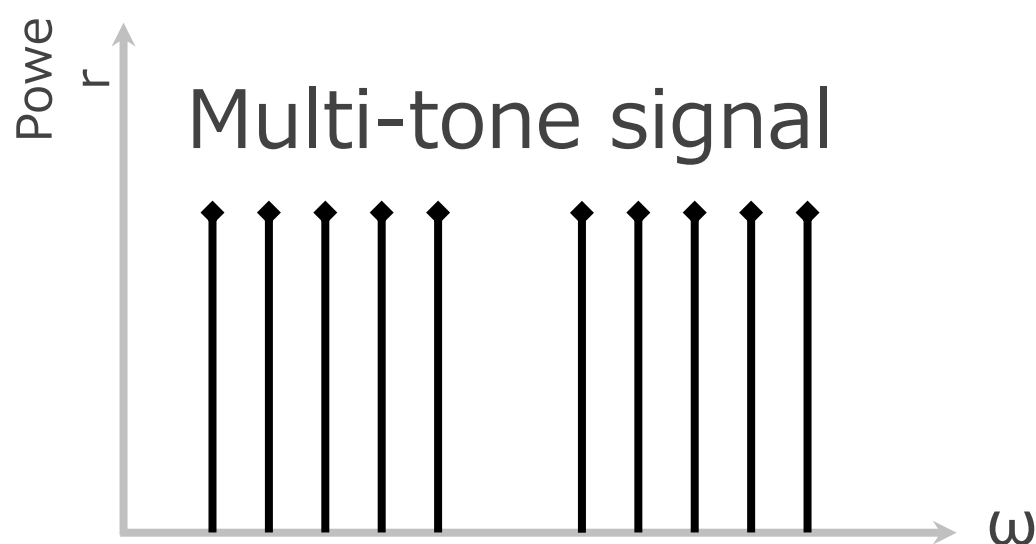# 2nd–order complex multi–BP Δ Σ DAC
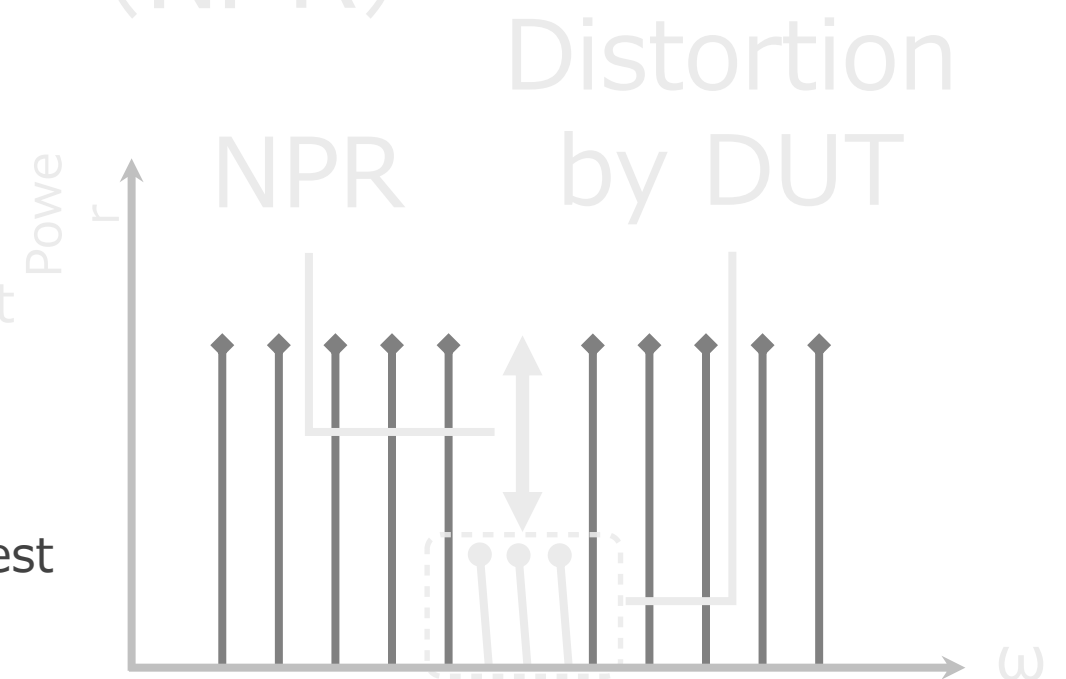

Output spectrum

Necessity of multi-tone signal

Linearity testing

of

✓ Mixer
✓ Up/Down converter
✓ Radio communication system ,
etc.

⬇

Noise **P**ower **R**atio （NPR）

Power

Multi-tone signal

Input ▷ DU T Output ▷

DUT : Device Under Test

Power

NPR   Distortion by DUT

ω

ω

Necessity of multi-tone signal

Linearity testing

of

✓ Mixer
✓ Up/Down Converter
✓ Radio communication system
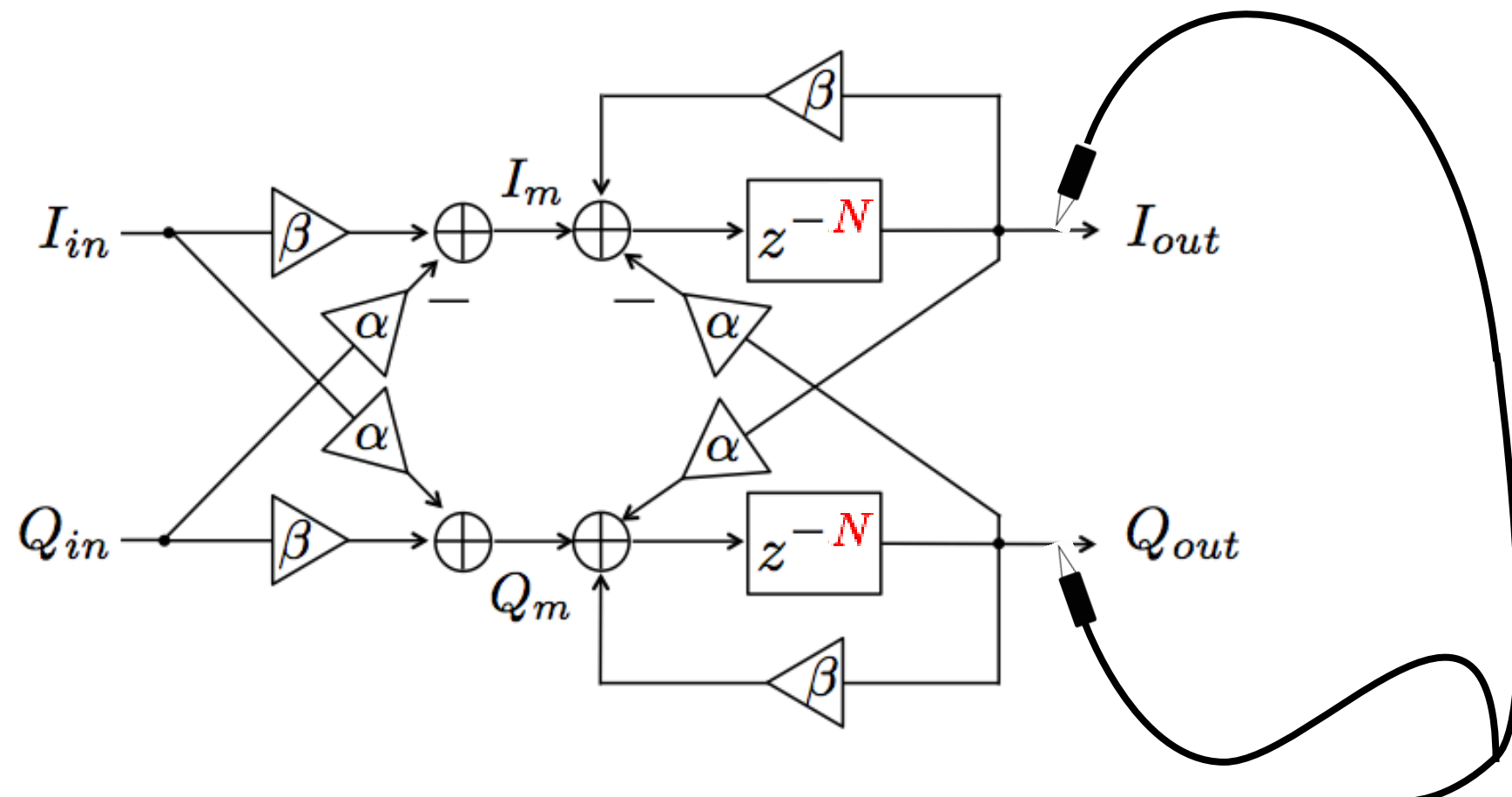etc…

⬇

Noise **P**ower **R**atio (NPR)

Distortion
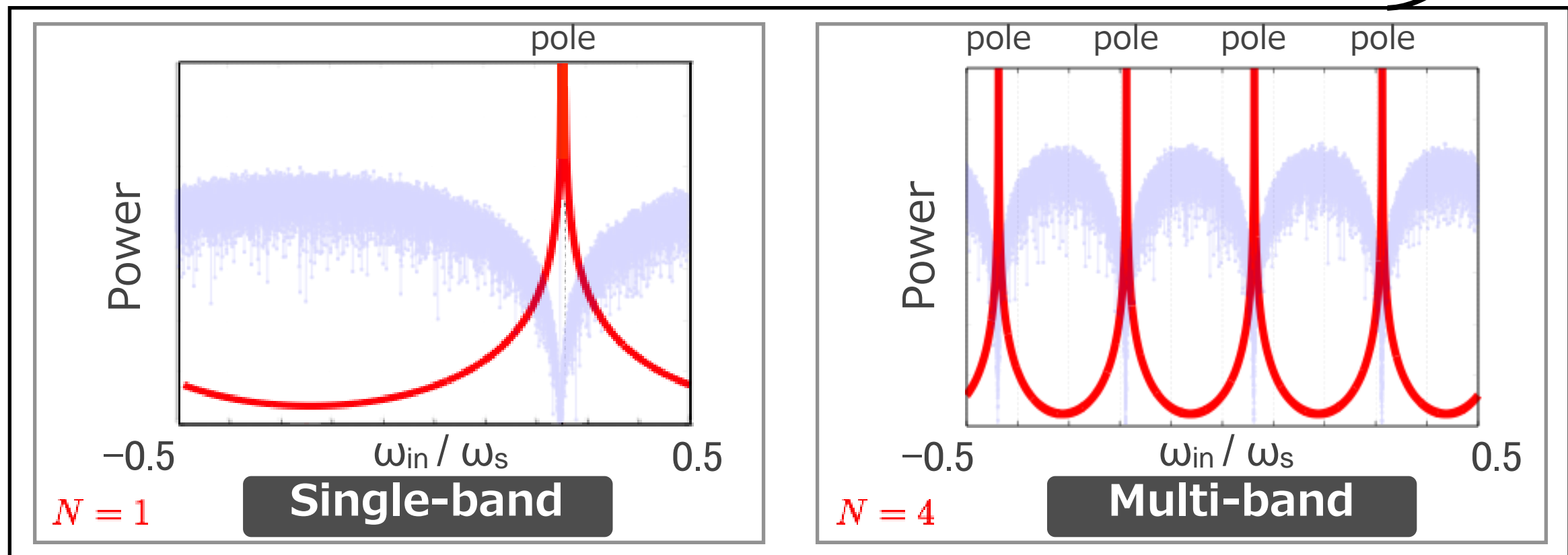NPR   by DUT

Need!

Multi-tone signal

Input   DUT   Output

DUT : Device Under Test
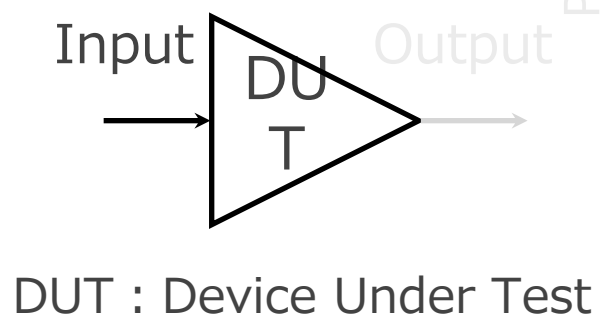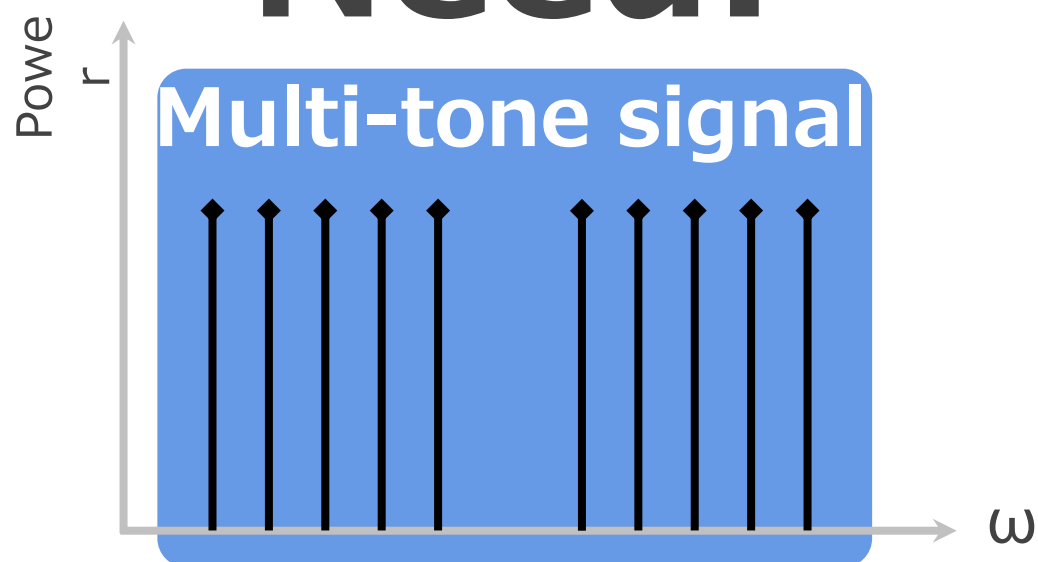
Complex Resonator

Output spectrum
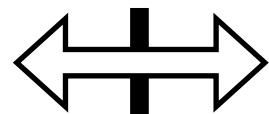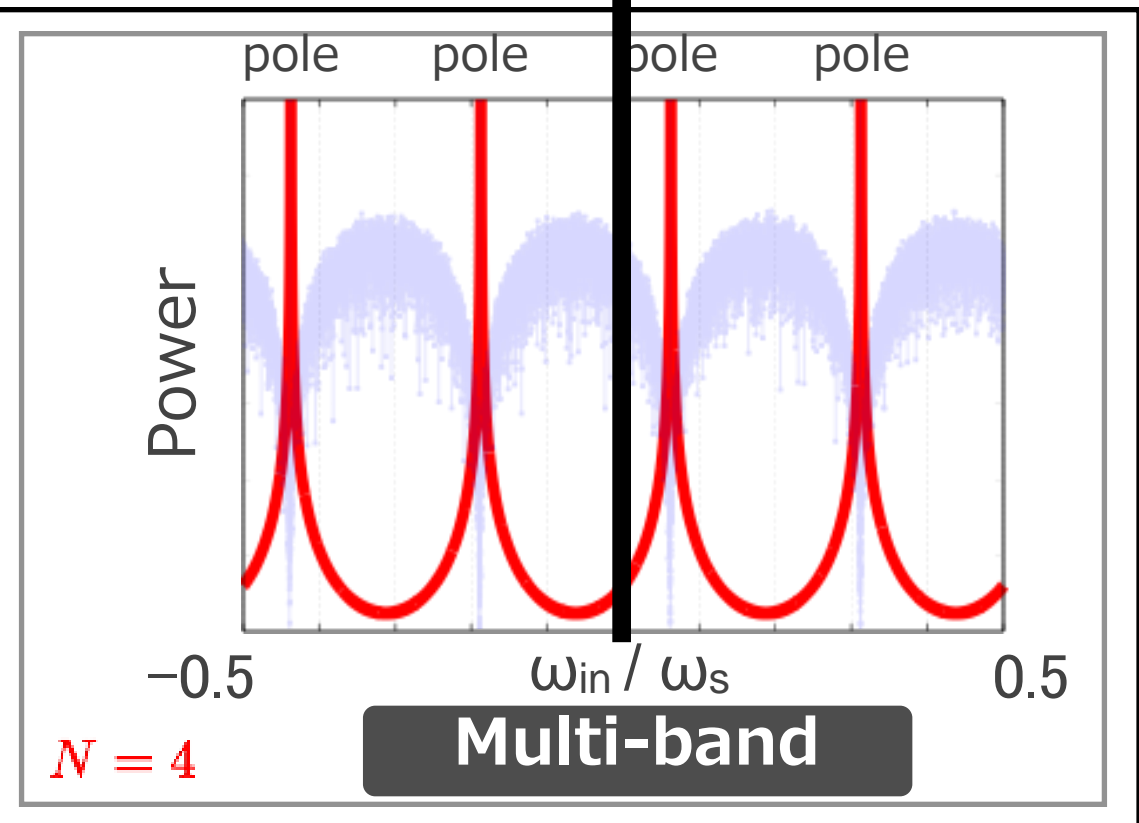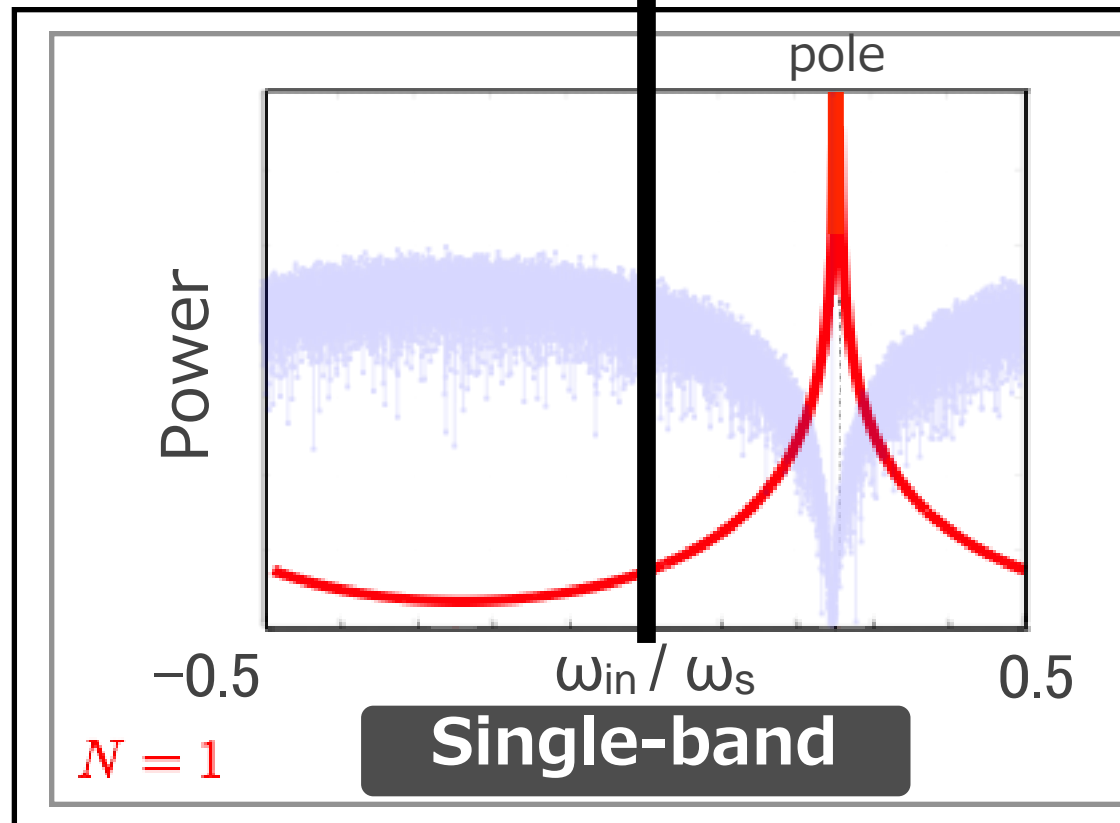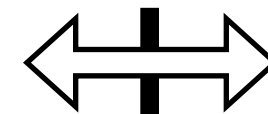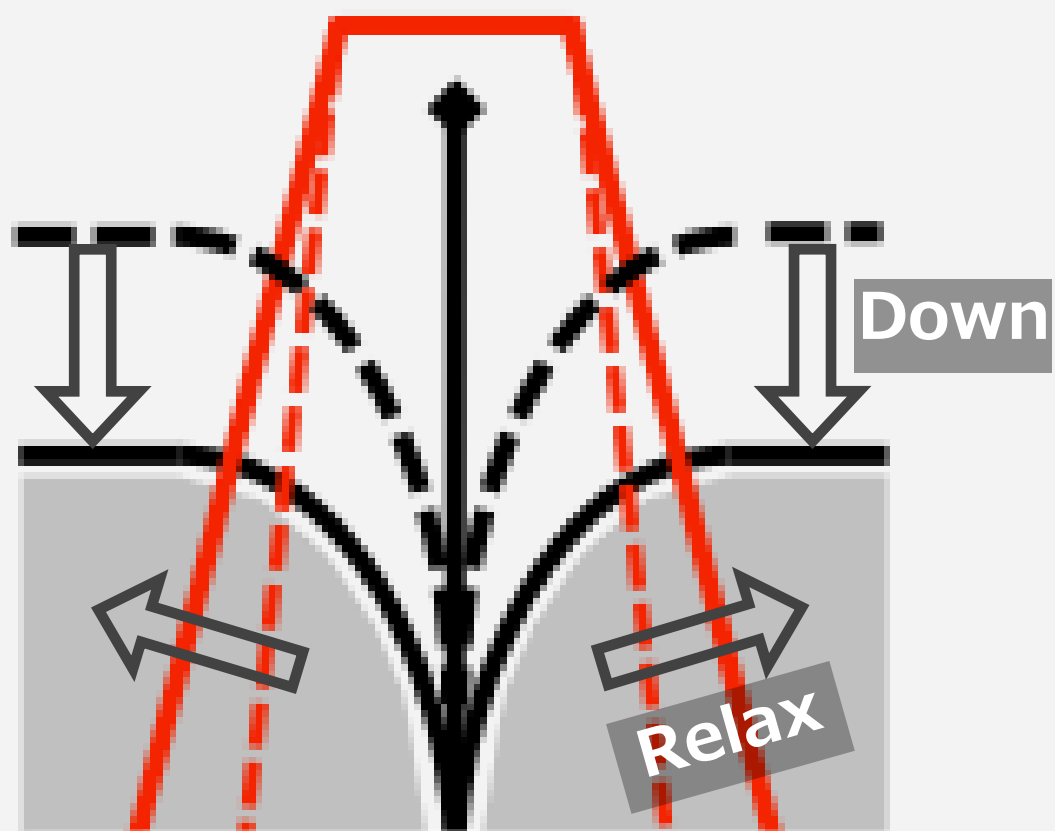

$N = 1$ **Single-band**

$N = 4$ **Multi-band**

Complex Resonator

OUTLINE

▶ Research Background

▶ Complex Multi-BP ΔΣ DA Modulator

▶ DWA Algorithm
  ▬ Conventional Method
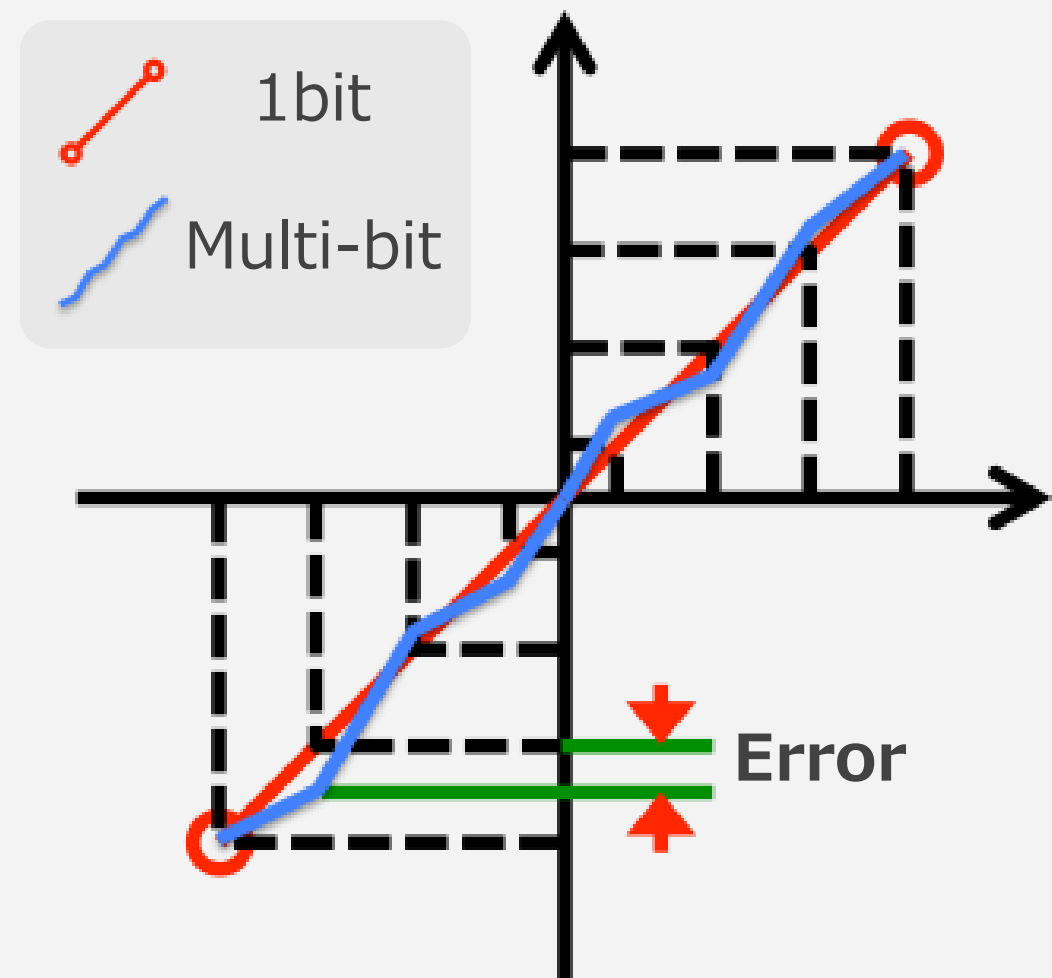 ▬ Proposed Method

▶ Conclusion

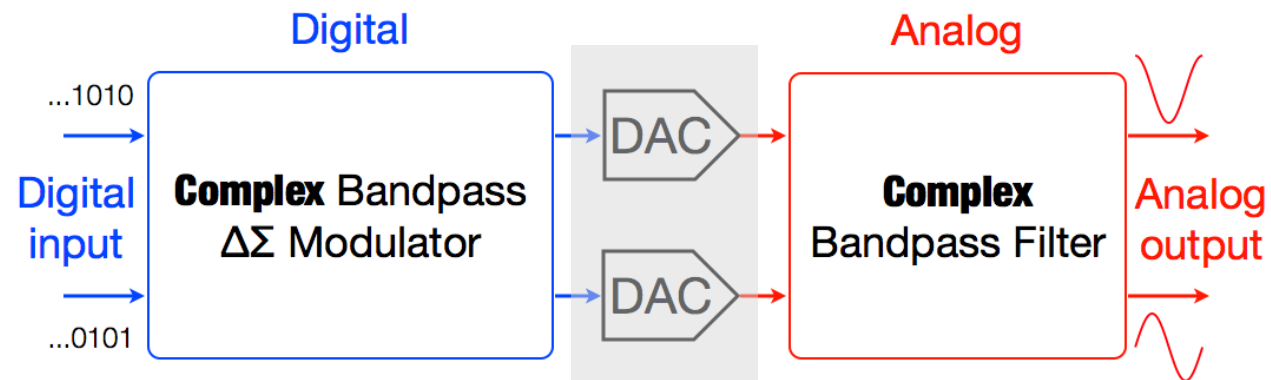# Multi-bit DA modulator

Multi-bit DA modulator（2~3bit）
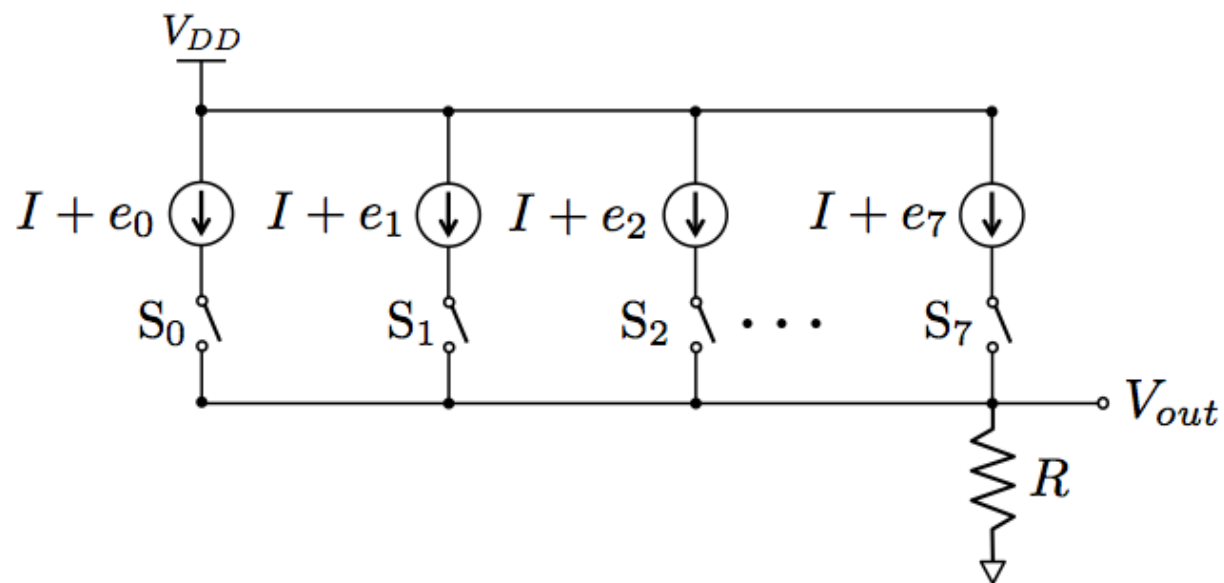
Quantization noise reduction

Linearity degradation

Multi-bit DAC

Digital

...1010

Digital input

...0101

Complex Bandpass ΔΣ Modulator

DAC

DAC

Analog

Complex Bandpass Filter

Analog output

Normal unary DAC

e_i : current source mismatch
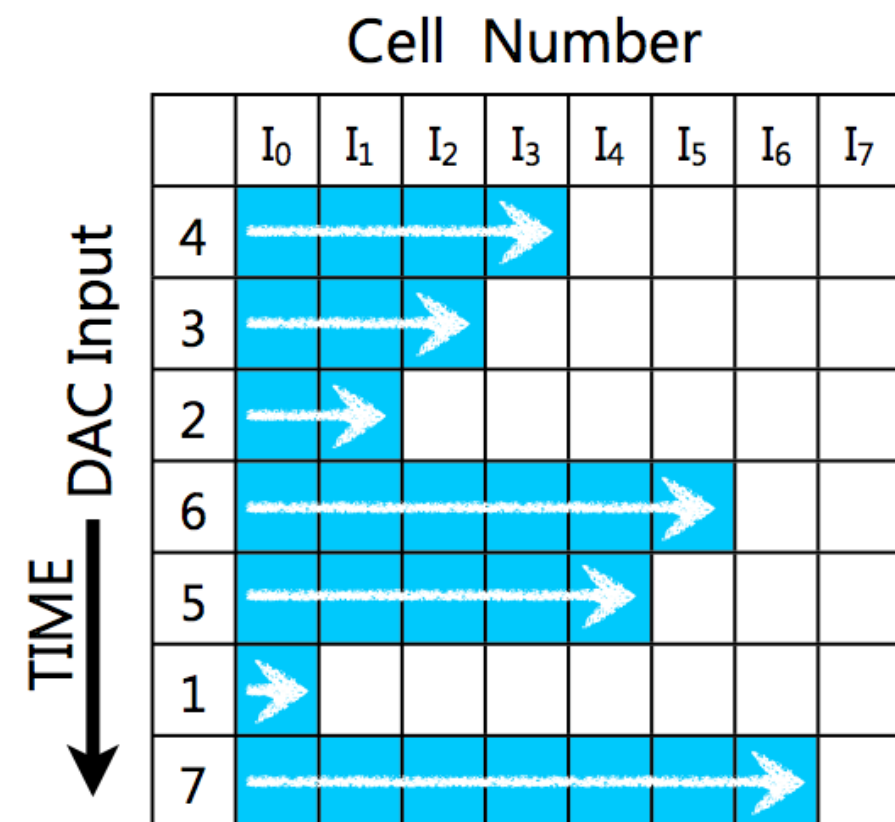
Multi-bit DAC

Accumulate mismatch of particular cell

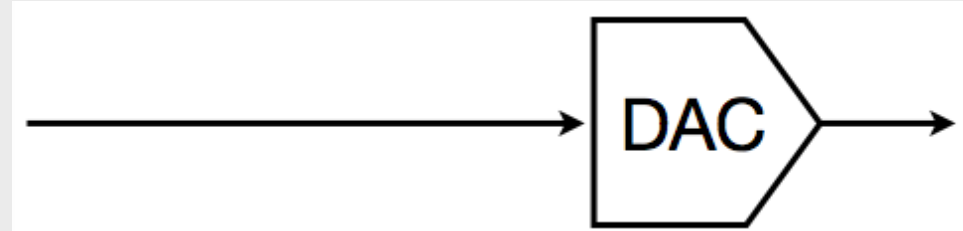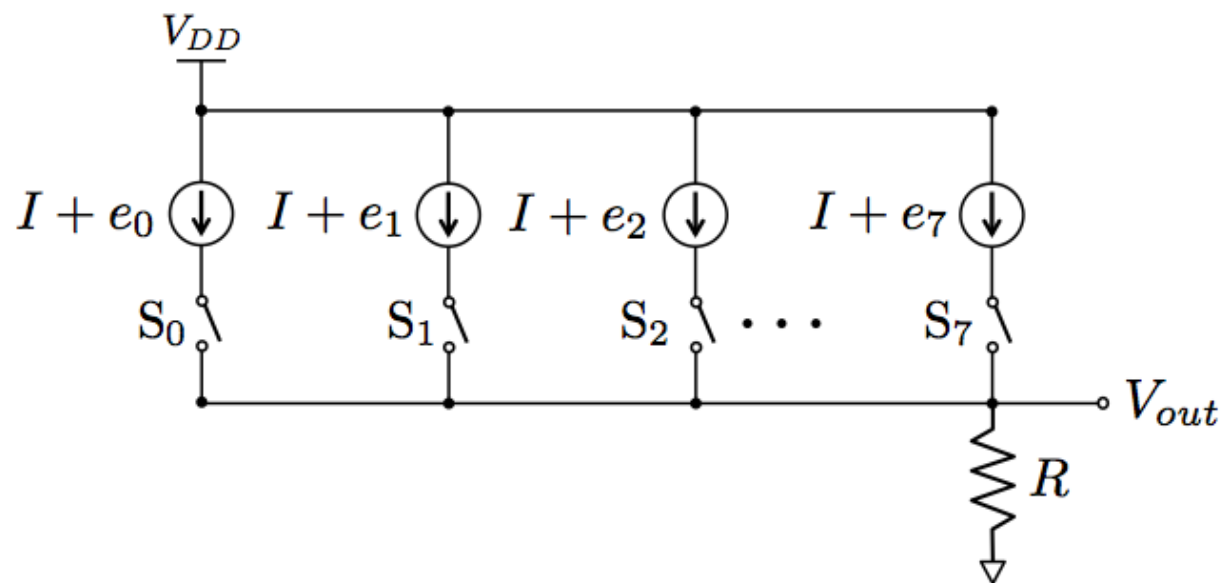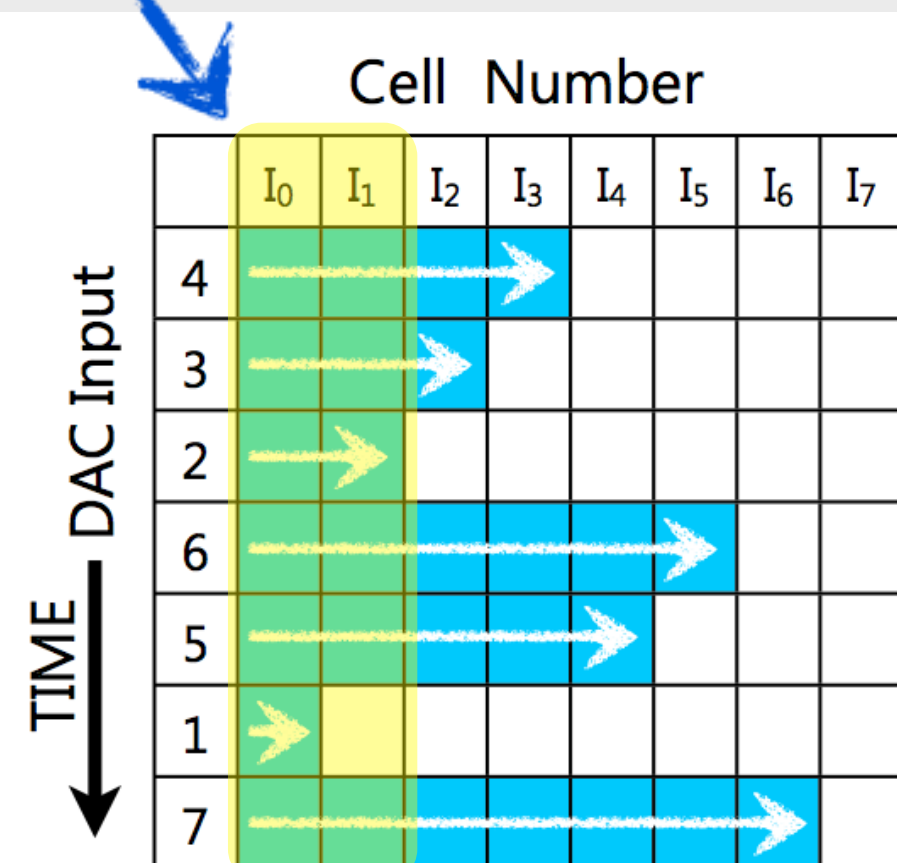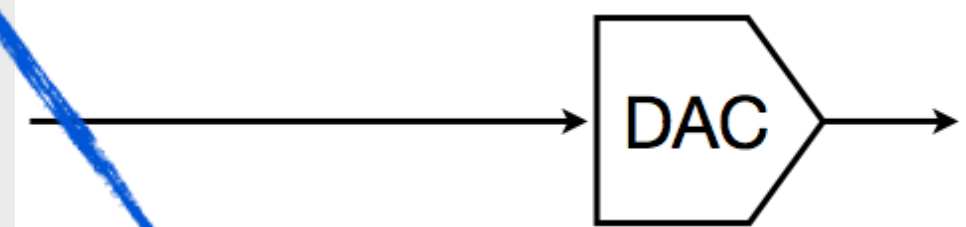**Normal** unary DAC

e_i : current source mismatch
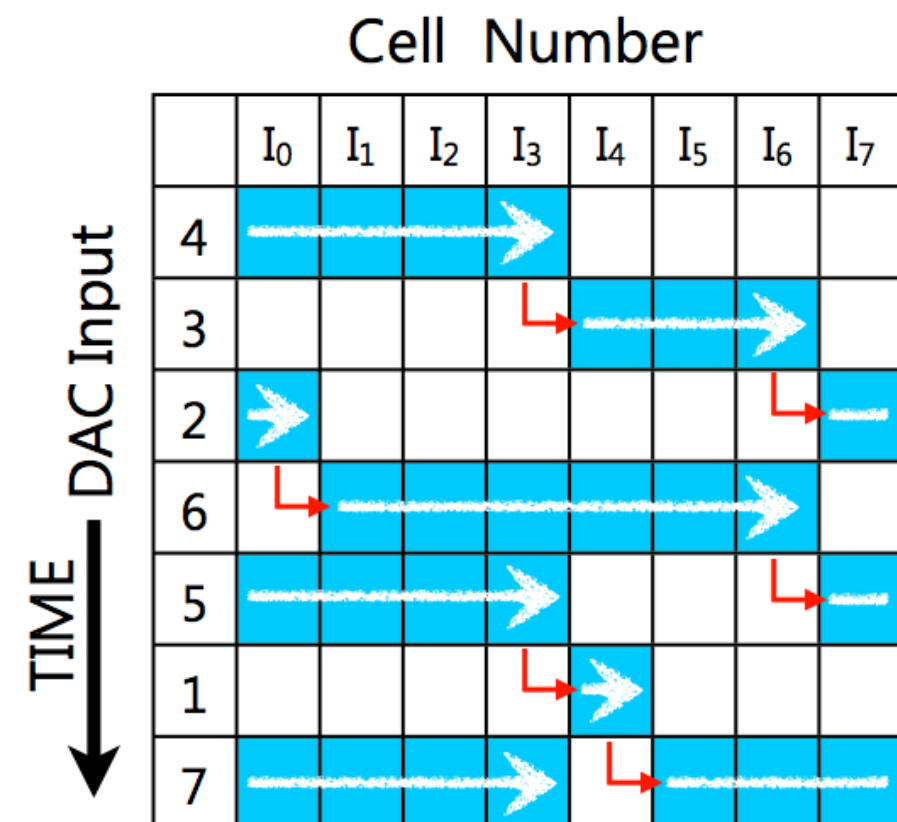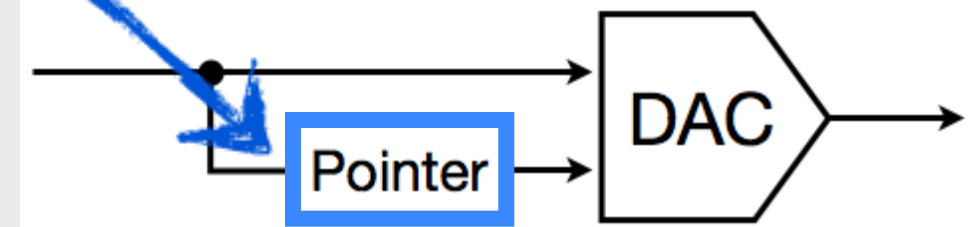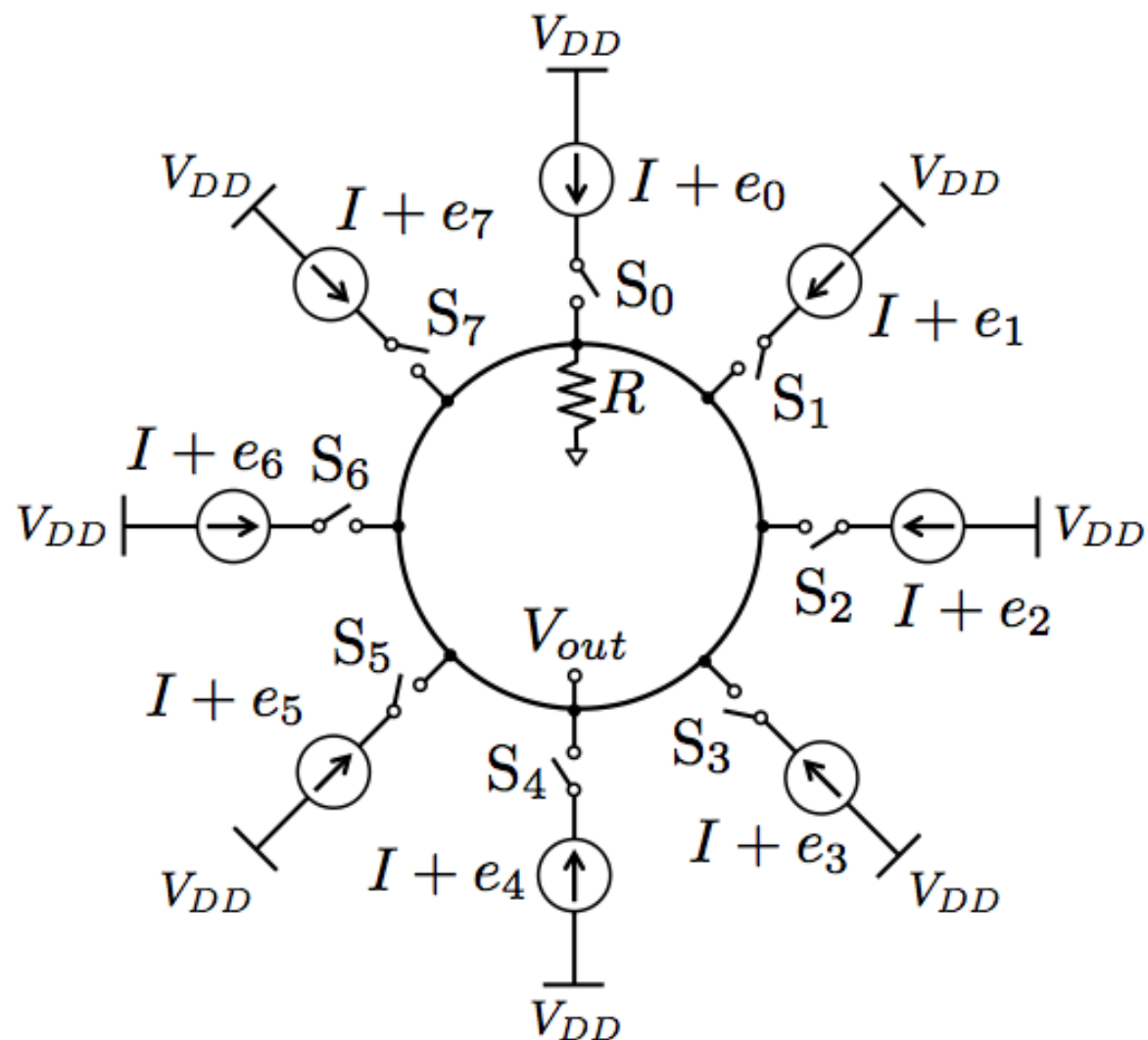

Cell Number

DAC Input

TIME

Multi-bit DAC + DWA

Memorize next cell selection start point

DWA* DAC   ***D**ata **W**eighted **A**veraging *Select the element with DSP algorithm
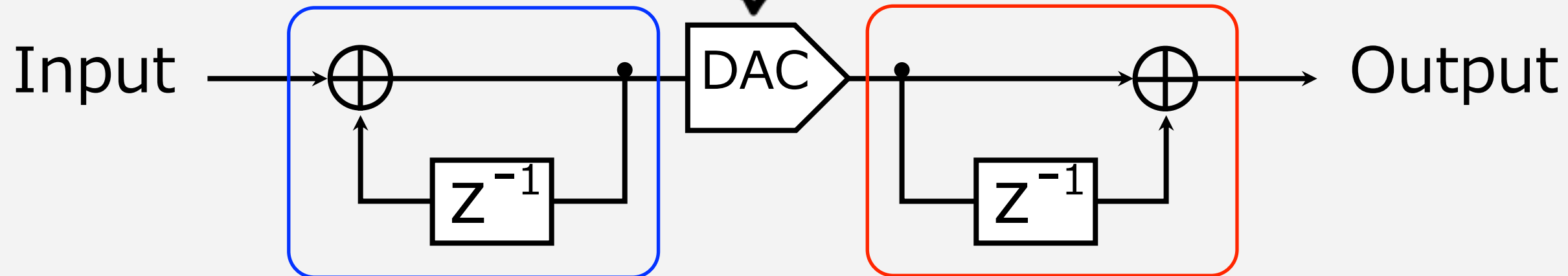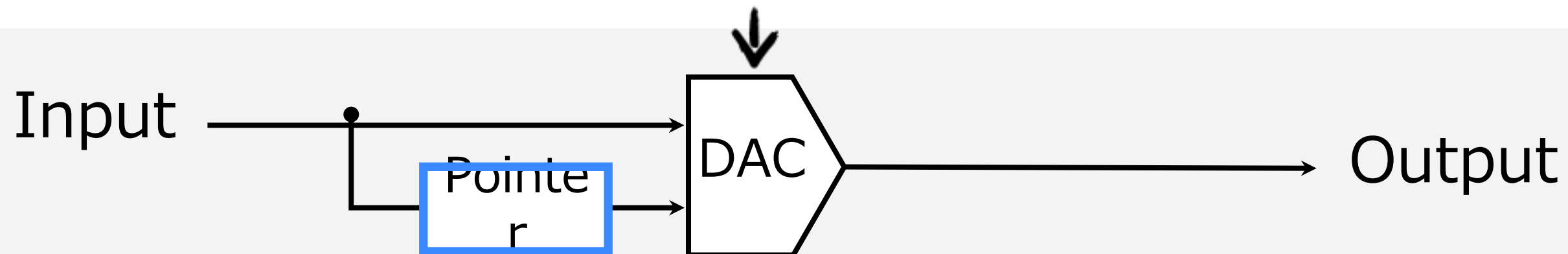
DWA = Δ Σ

Non-Linearity

δ

Integration

Differentiation

Input ⊕ DAC ⊕ Output

Z^{-1}

Z^{-1}

δaffected by only Differentiation

Can't be realized directly

δ

Input DAC Output

Pointer

Equivalent circuit for implementation

Memorize next cell selection start point
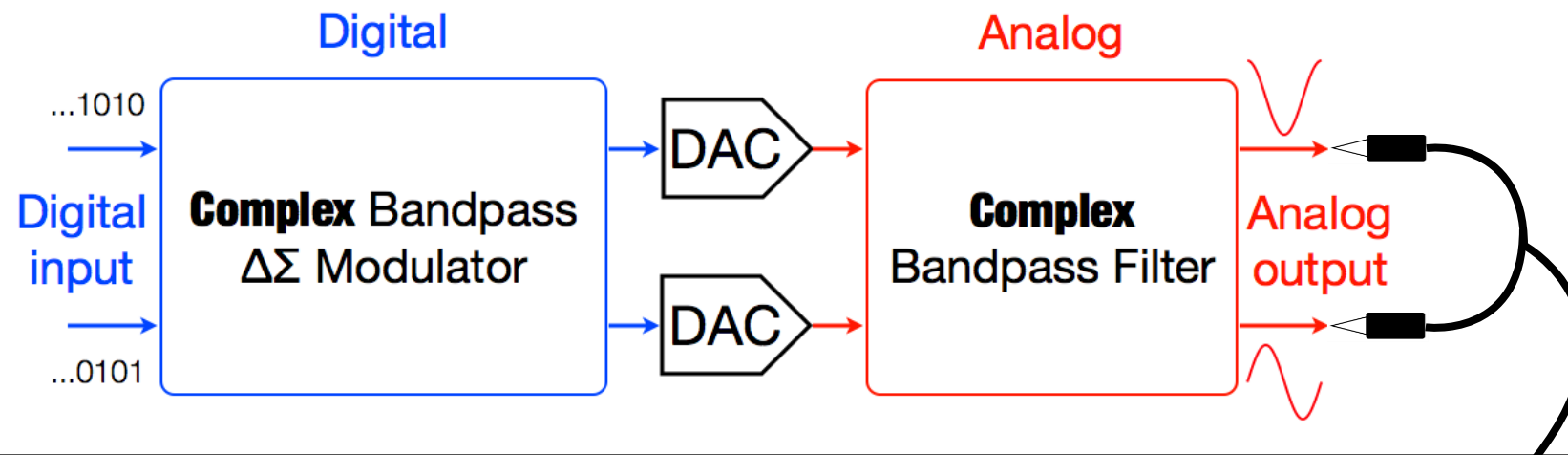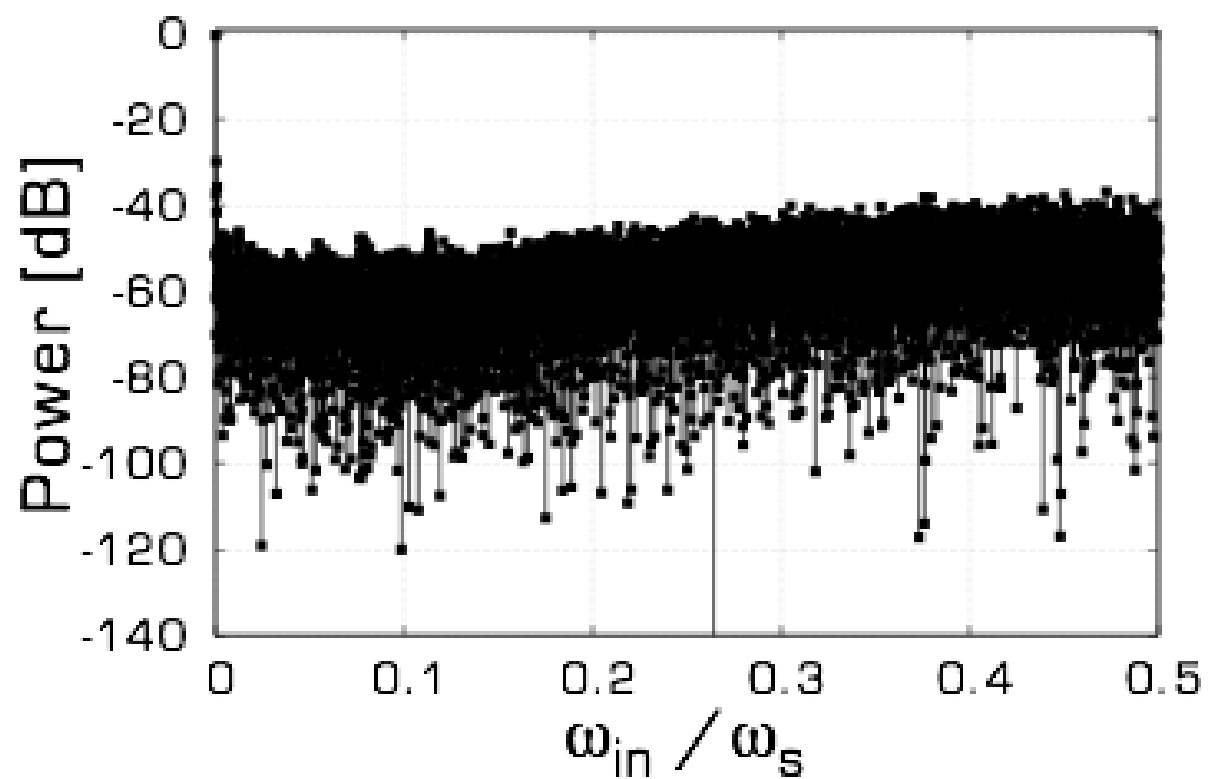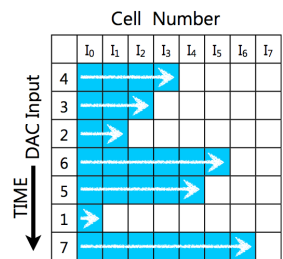
Effect of DWA
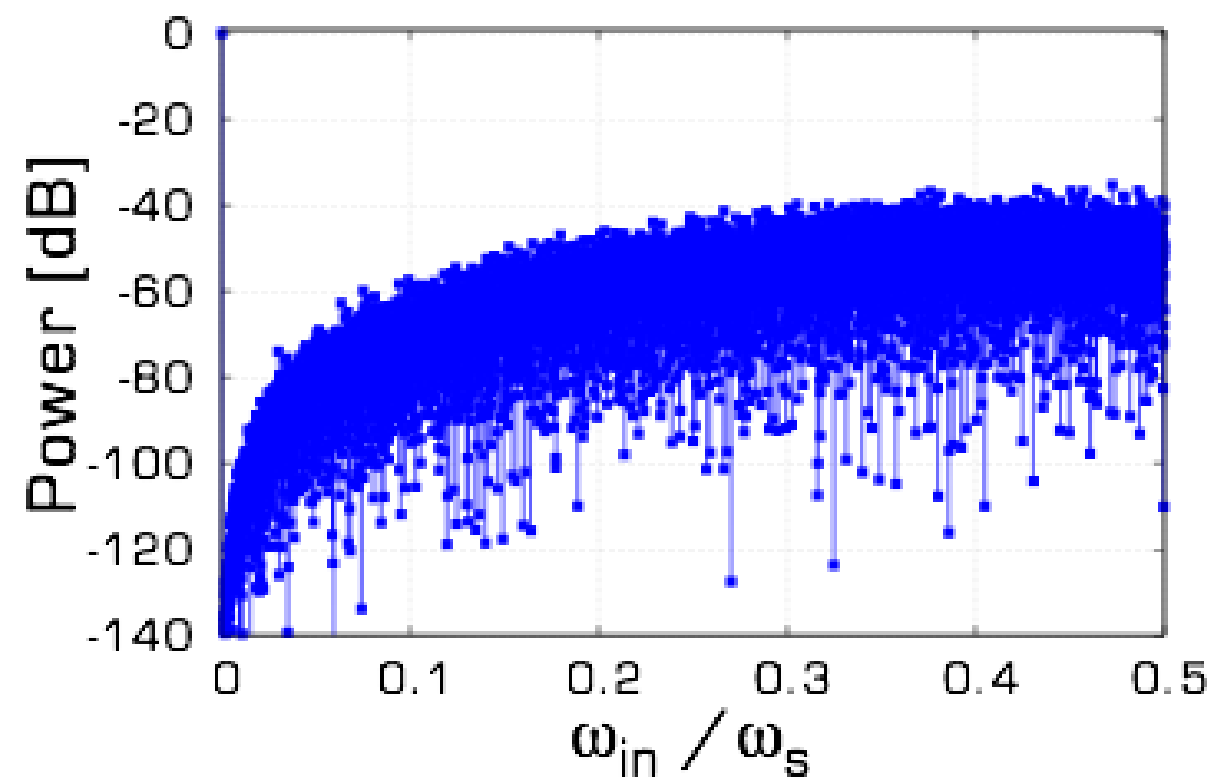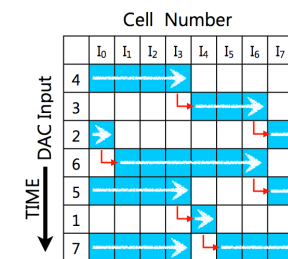
Signal band

zero point
at DC

Asymmetry
with respect to ω=0.
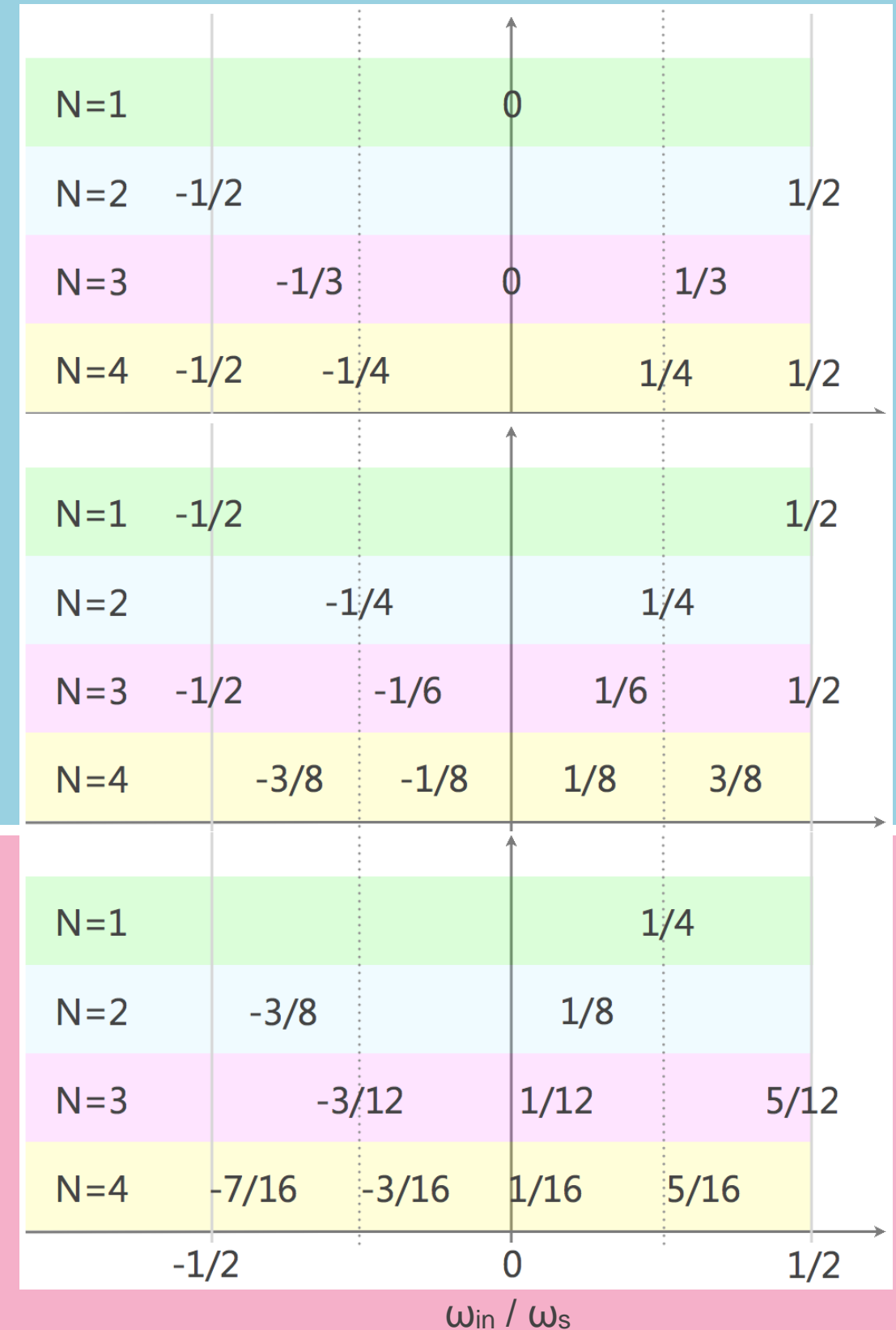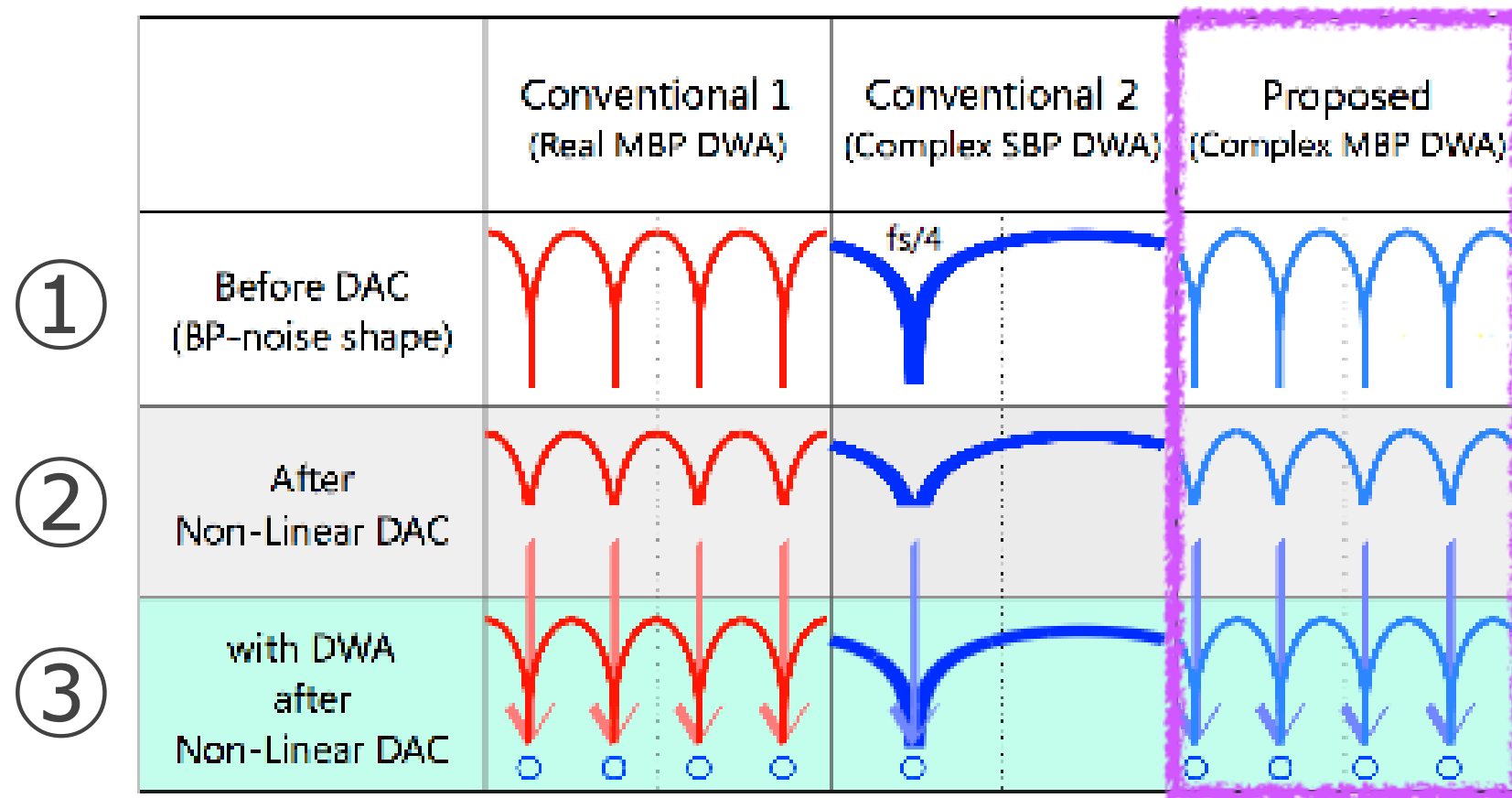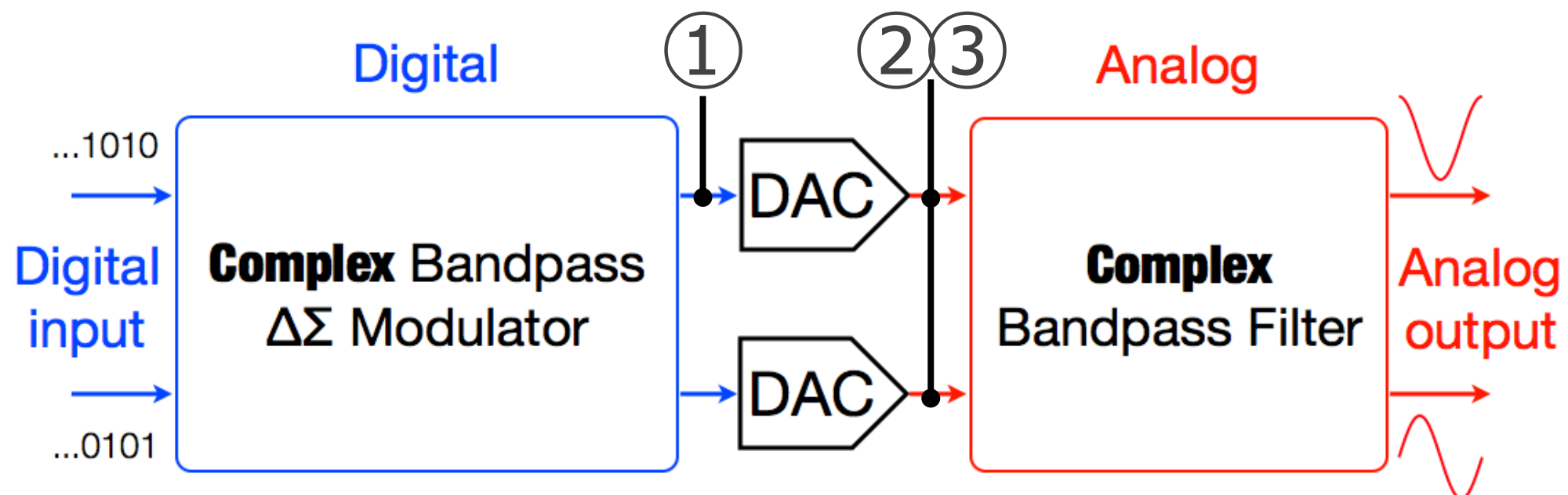
	REAL				
N=1			0		
N=2	-1/2				1/2
N=3		-1/3	0	1/3	
LowPass N=4	-1/2	-1/4		1/4	1/2

N=1	-1/2			1/2
N=2		-1/4	1/4	
N=3	-1/2	-1/6	1/6	1/2
High Pass N=4	-3/8	-1/8	1/8	3/8

	COMPLEX			
N=1			1/4	
N=2	-3/8		1/8	
N=3	-3/12	1/12		5/12
N=4	-7/16	-3/16	1/16	5/16

-1/2   0   1/2

ω_{in} / ω_s

Type of DWA

	Conventional 1 (Real MBP DWA)	Conventional 2 (Complex SBP DWA)	Proposed (Complex MBP DWA)
① Before DAC (BP-noise shape)		fs/4	
② After Non-Linear DAC			
③ with DWA after Non-Linear DAC			

DWA
ǁ
DSP algorithm

Digital

① ② ③ Analog

...1010

Digital input

Complex Bandpass ΔΣ Modulator

DAC

DAC

Complex Bandpass Filter

Analog output

...0101

OUTLINE

Equivalent circuit of Complex DWA
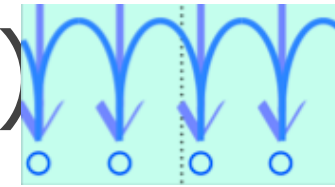
Equivalent circuit implementation
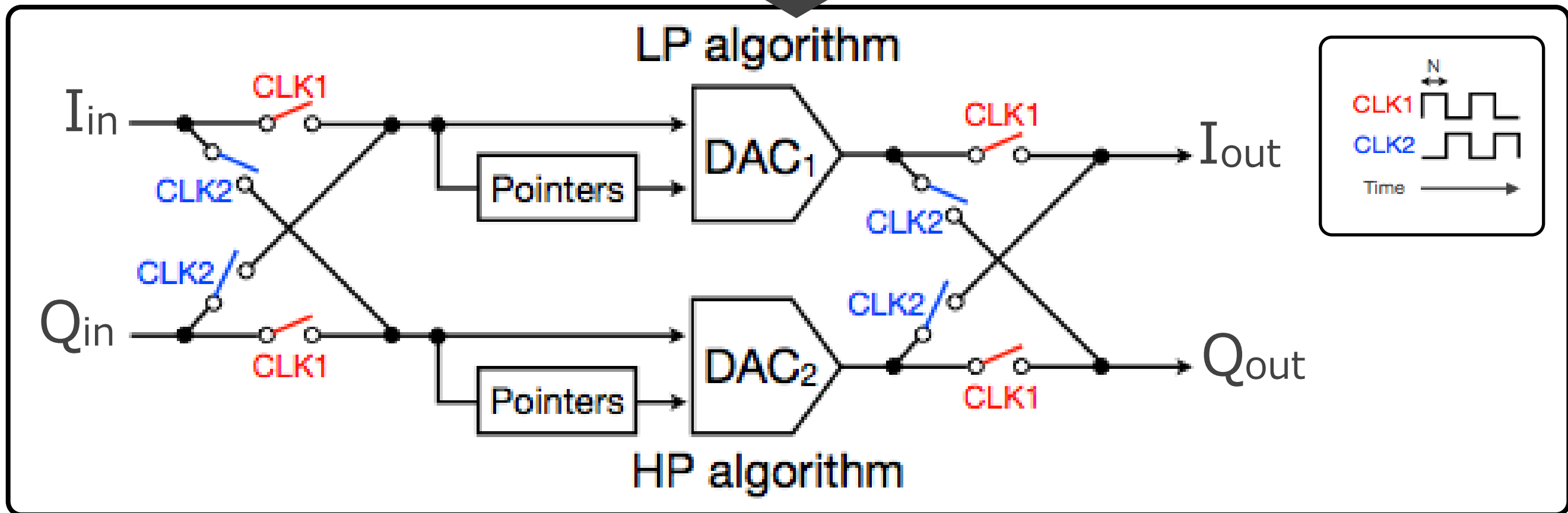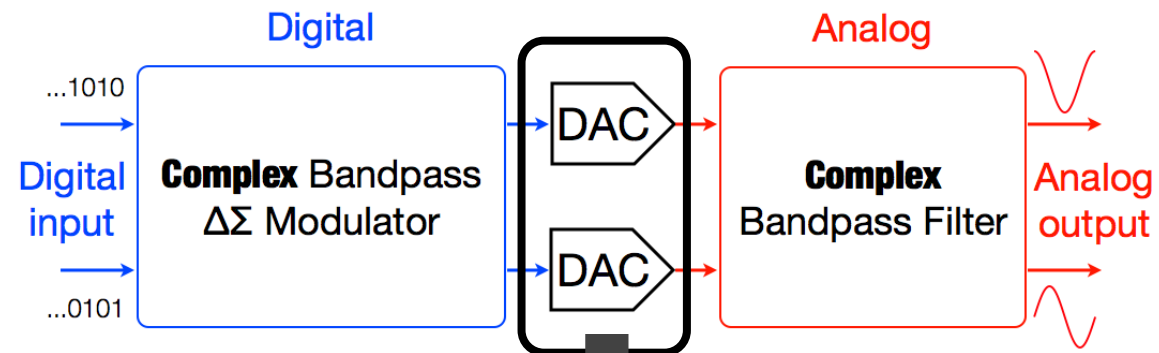
✦ Attach pointers

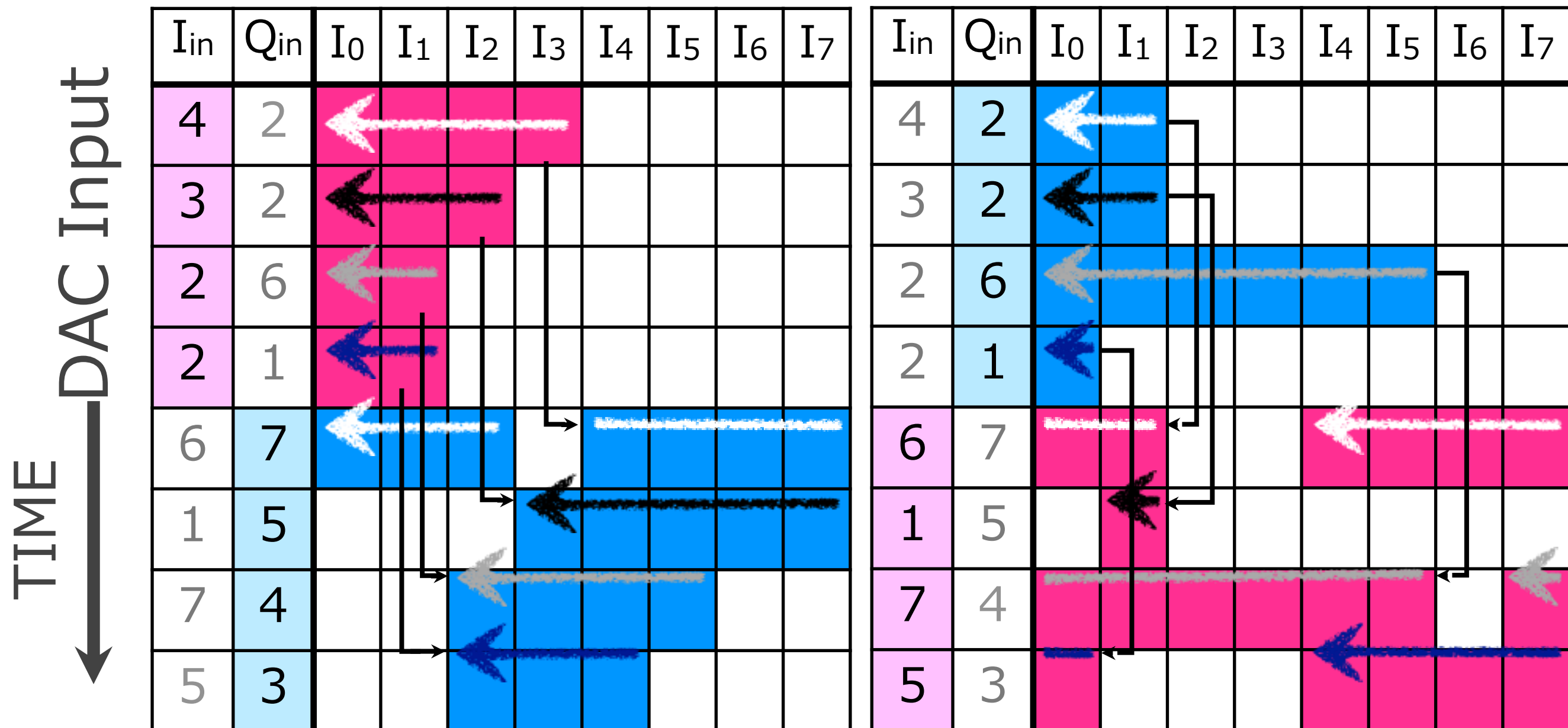✦ Exchange upper-path and lower-path every N clock

➡ Complex DWA is realized.

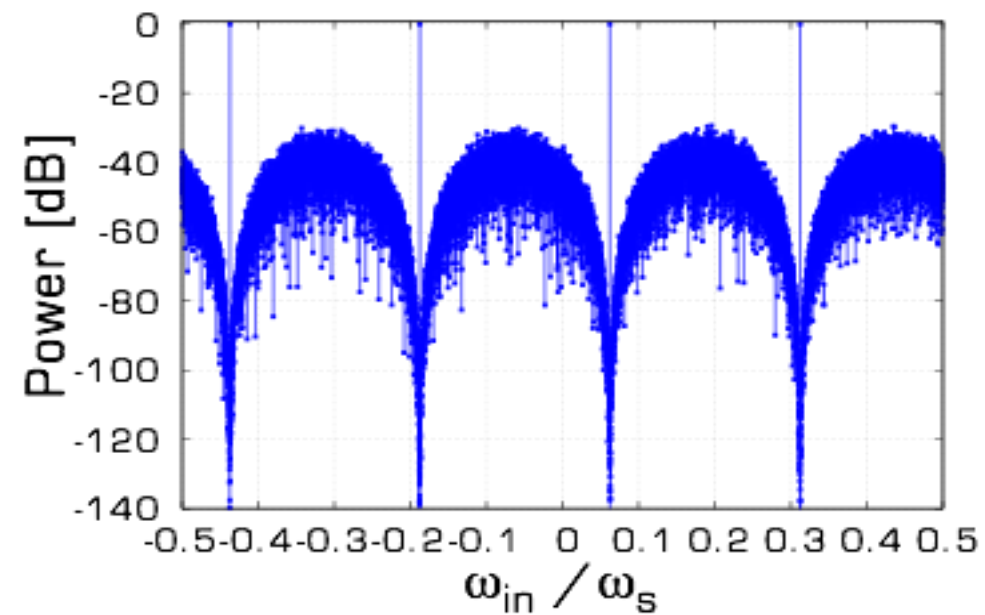# Complex Multi-Bandpass DWA algorithm

N = 4 （four zero points）
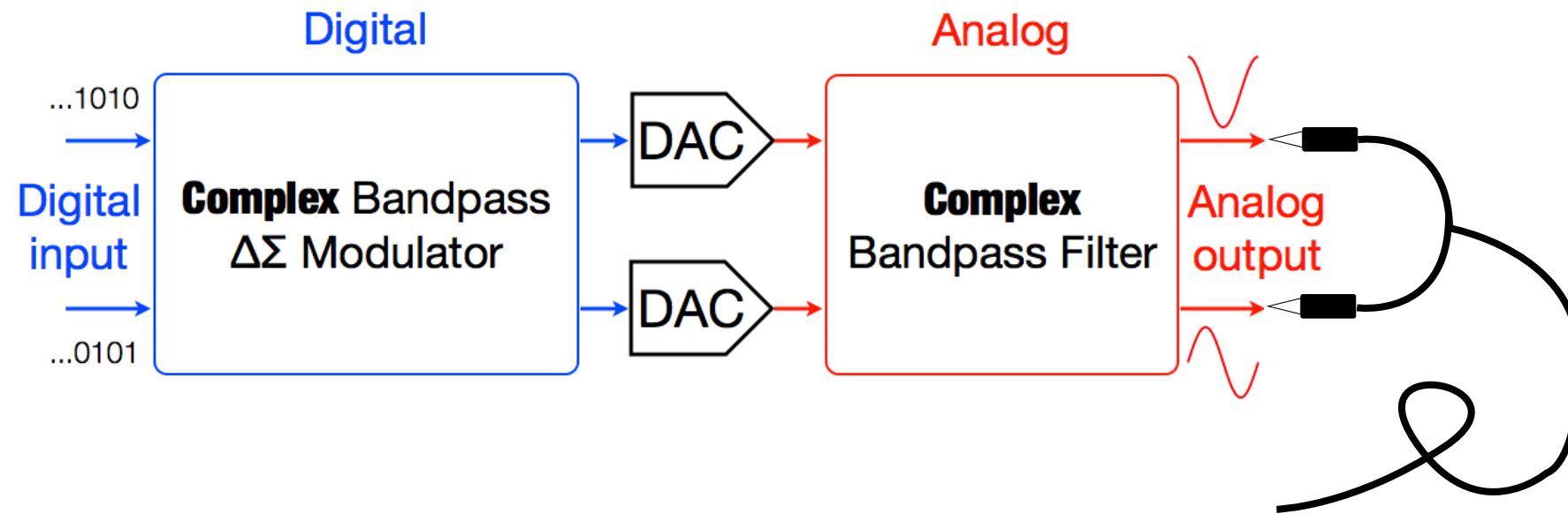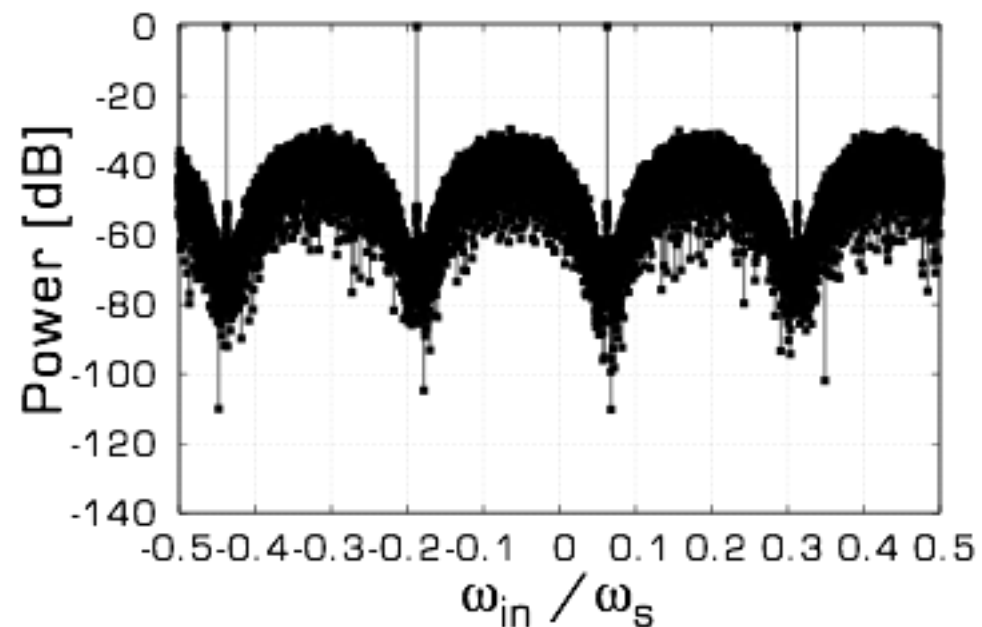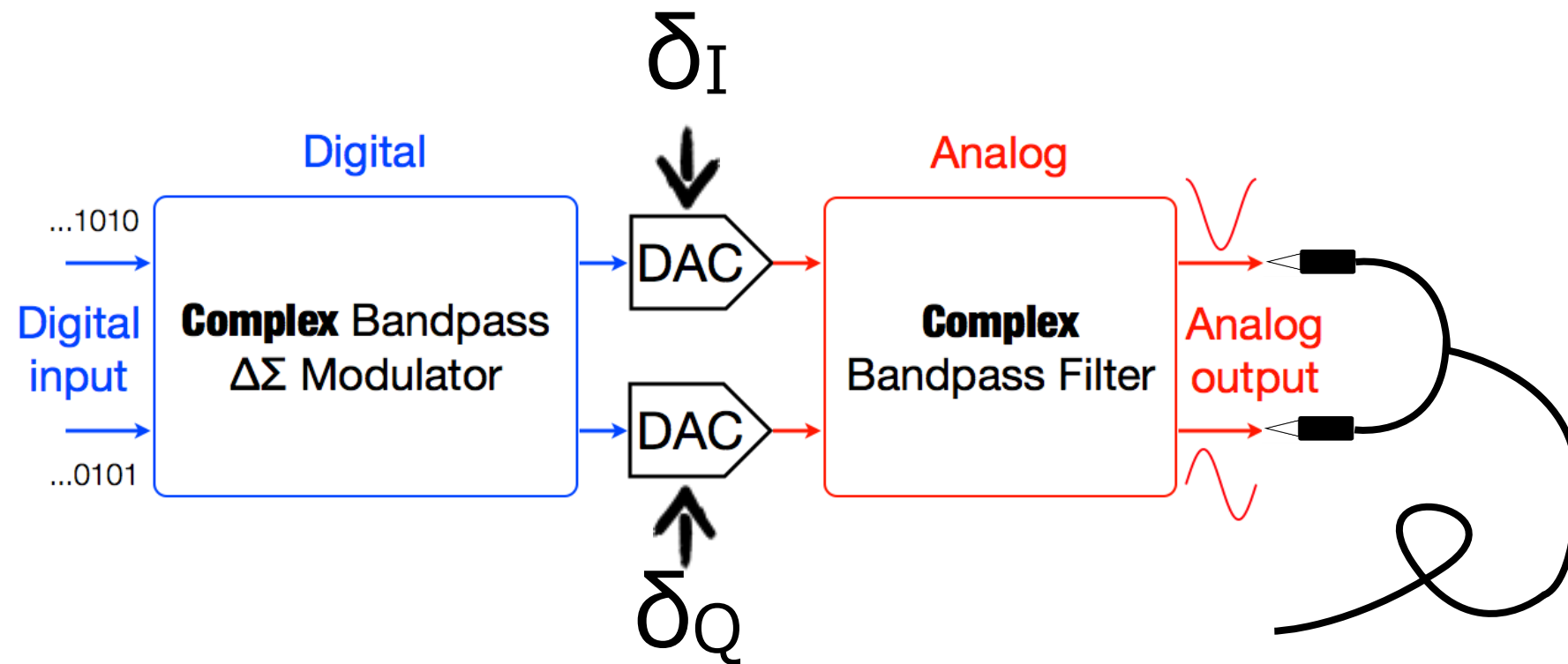

DAC$_1$ （**LP** operation）   DAC$_2$ （**HP** operation）

Simulation result ~Ideal Linear DAC~

Simulation result ~Actual Non-Linear DAC~

δ_I

Digital

...1010

Digital input

...0101

Complex Bandpass $\Delta\Sigma$ Modulator

DAC

DAC
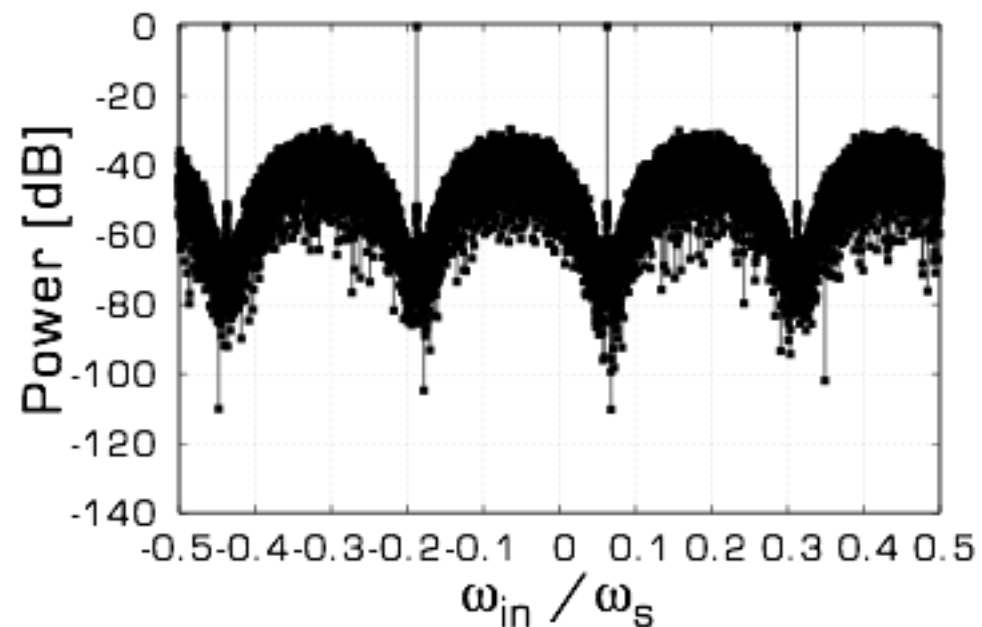
δ_Q

Analog

Complex Bandpass Filter

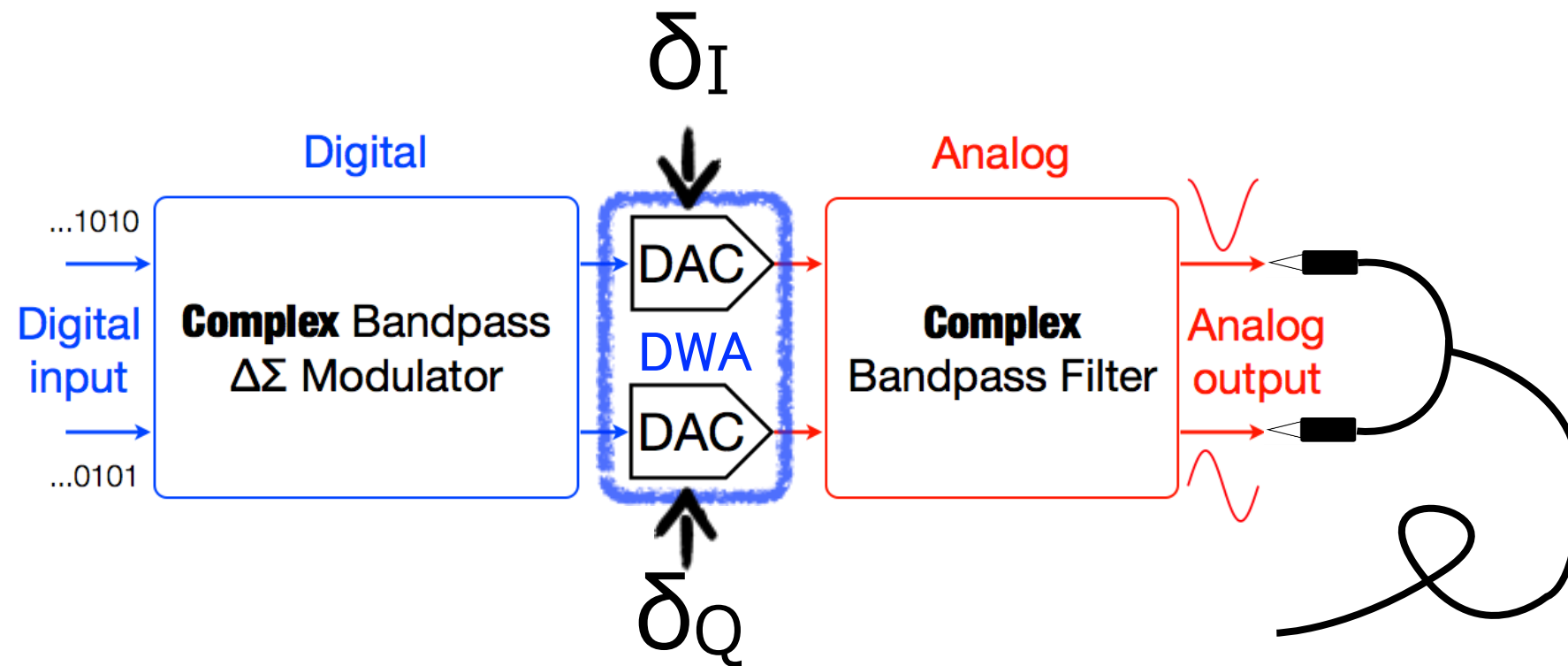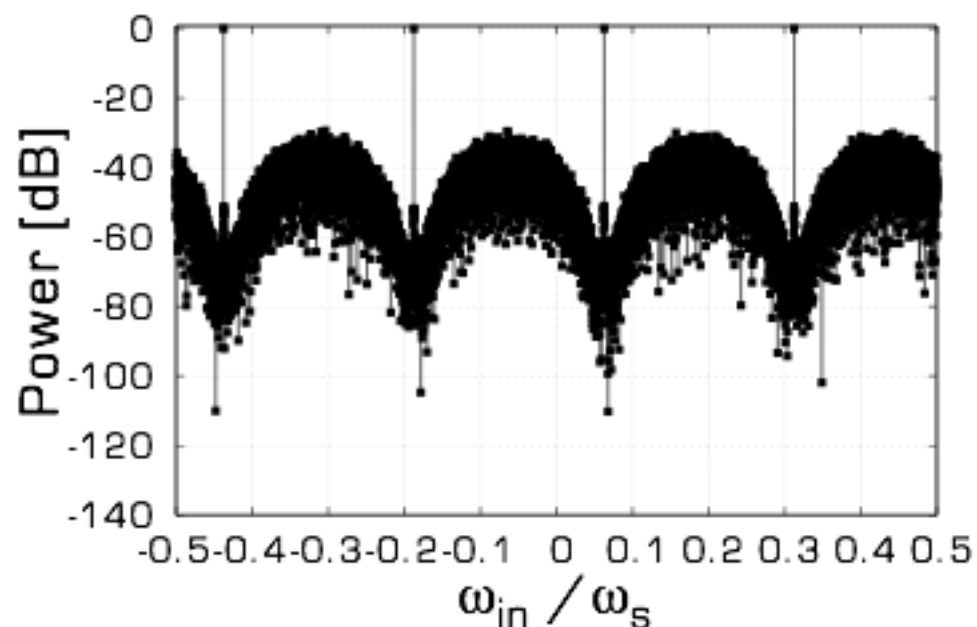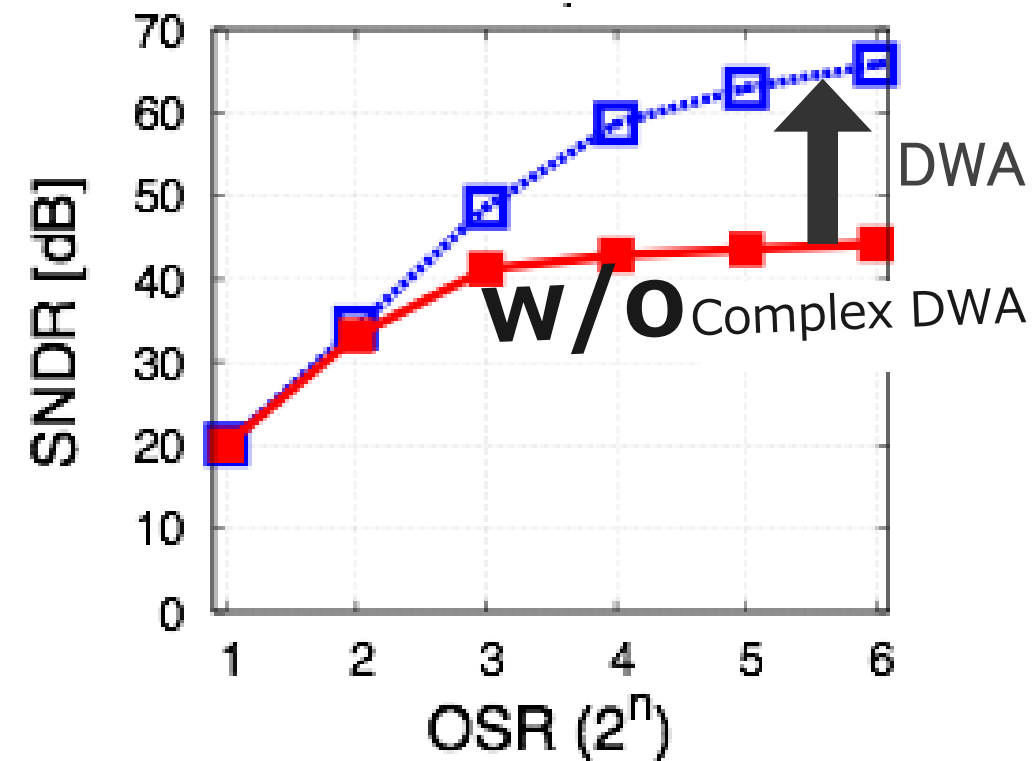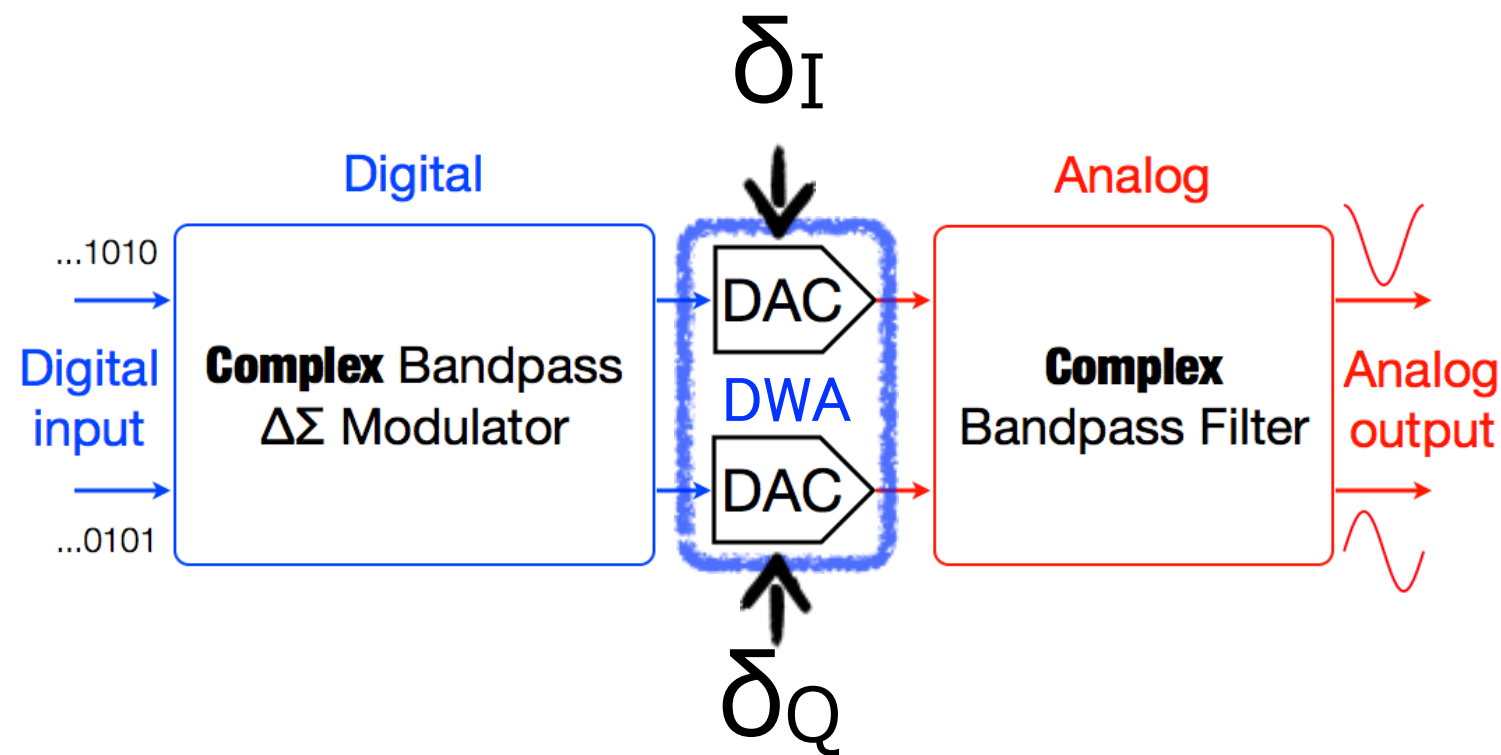Analog output

Notches filled with noise

Simulation result ~Actual Non-Linear DAC + DWA~

Notches filled with noise
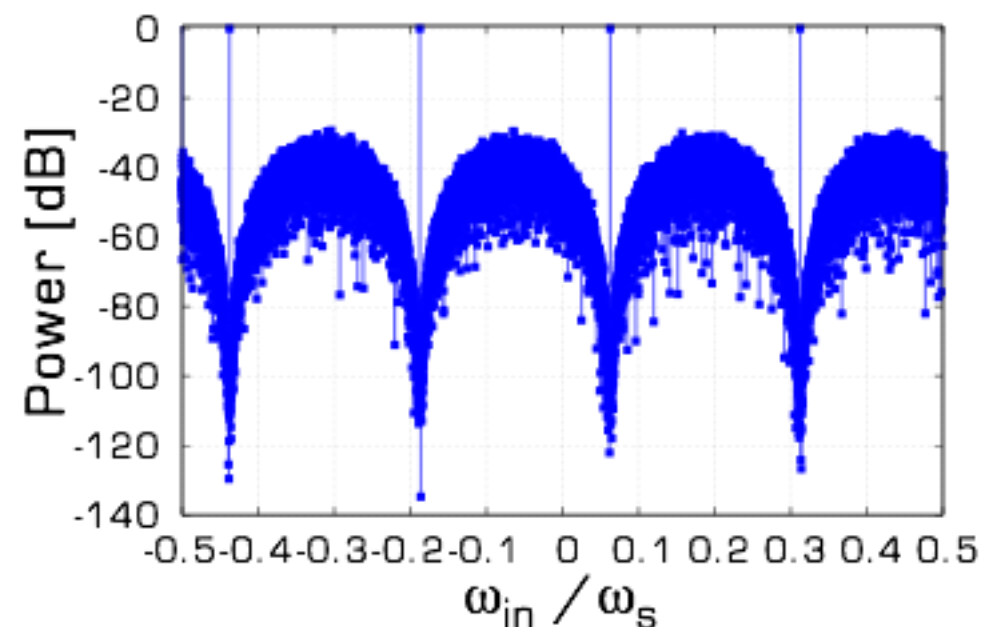
Simulation result ˜Actual Non-Linear DAC ＋ DWA˜

Notches filled with noise ➡ Steep Notches

OUTLINE

▸ Research Background

▸ Complex Multi-BP ΔΣ DA Modulator

▸ DWA Algorithm
  ▬ Conventional Method
  ▬ Proposed Method

▸ **Conclusion**

Conclusion

▸ I,Q signal generation with digital centric for testing communication IC.

▸ Complex multi-BP ΔΣ DAC

▸ Multi-bit DAC

　　◎ Relaxes the analog filter requirements

　✕ Degrades system linearity
　　　　　➡ ◎ DWA algorithm

Low cost, high quality I,Q signal generation.