Phase Noise Measurement Techniques Using Delta-Sigma TDC

Yusuke Osawa Daiki Hirabayashi Naohiro Harigai
Haruo Kobayashi Kiichi Niitsu Osamu Kobayashi

群馬大学 GUNMA UNIVERSITY

Gunma University *Nagoya University* *STARC*

Outline

- Research Background & Objective
- Delta-Sigma TDC
- Phase Noise Measurement using ΔΣTDC with Reference Clock
- Phase Noise Measurement using ΔΣTDC without Reference Clock
  - Self-Referenced Clock Technique
- Conclusion

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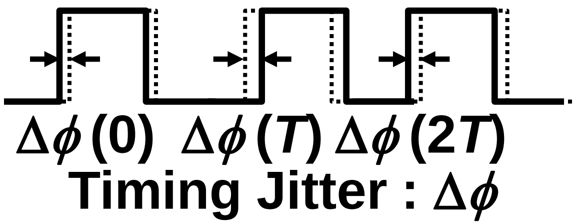
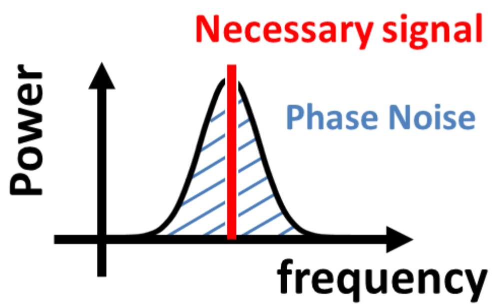
Research Background

Phase noise of clock can cause malfunctions of electronic systems



Oscillator phase noise



Electronic system performance degradation

- RF circuit & system
- ADC

Test & measurement for phase noise, jitter is important

Conventional Method Ⅰ

Conventional Phase Noise Measurement

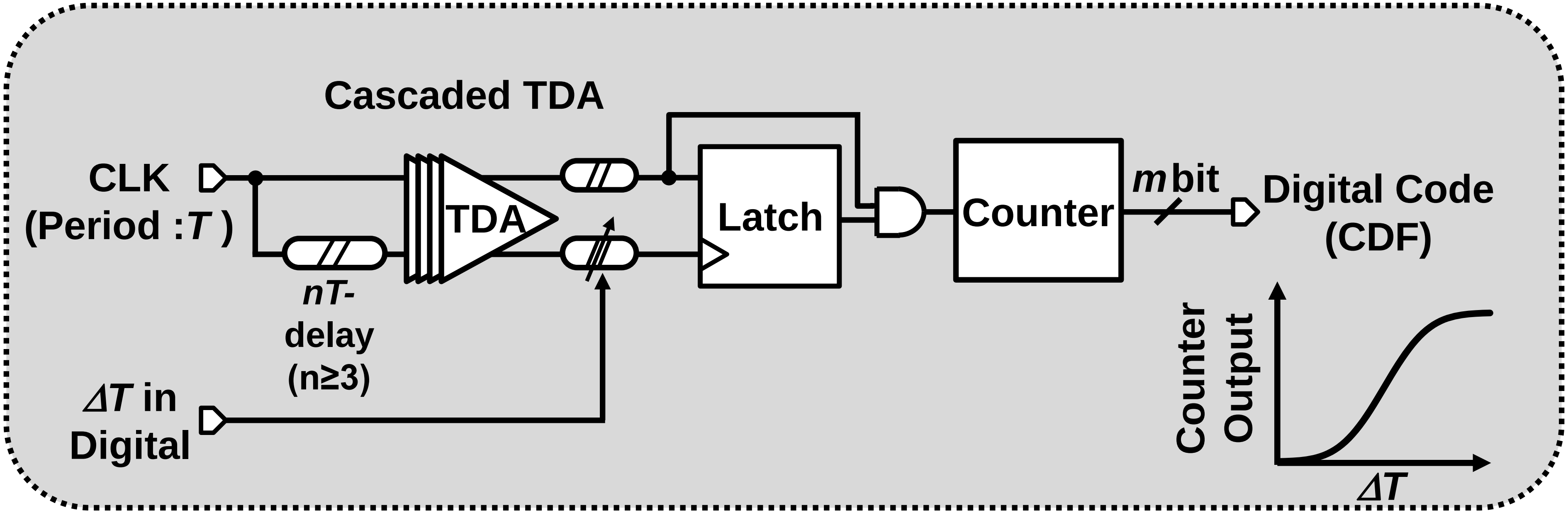
- **Expensive : Spectrum Analyzer**
- **Long testing time： ~10 seconds**

Mass production

Test cost → high

Conventional Method Ⅱ

On-chip Jitter Measurement Circuit



Can NOT measure jitter power spectrum

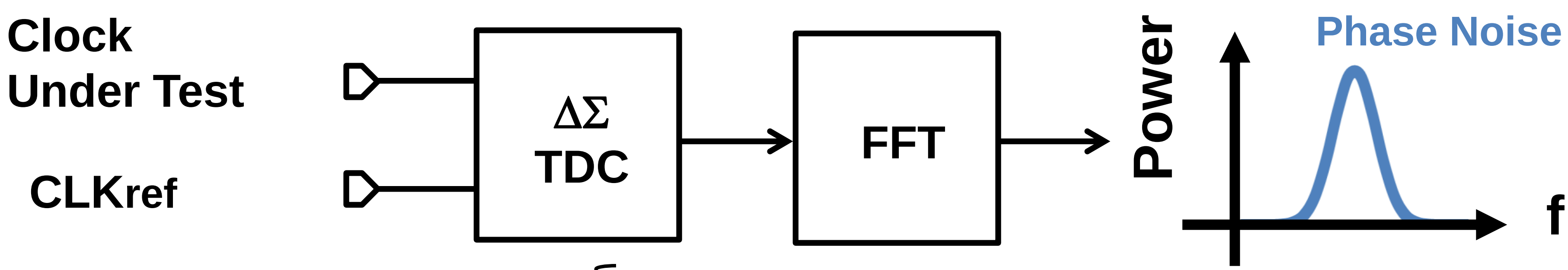
[1] K. Niitsu, et al., "CMOS Circuits to Measure Timing Jitter Using a Self-Referenced Clock and a Cascaded Time Difference Amplifier with Duty-Cycle Compensation," IEEE Journal of Solid-State Circuits, Nov. 2012.

Research Objective

Low cost, high quality phase noise measurement

- **w/o Spectrum Analyzer**

- **w/ BIST or BOST Simple circuit**



※ { **BIST : Built-In Self-Test**
BOST : Built-Out Self-Test }

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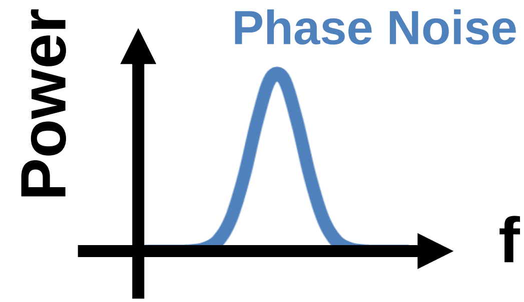
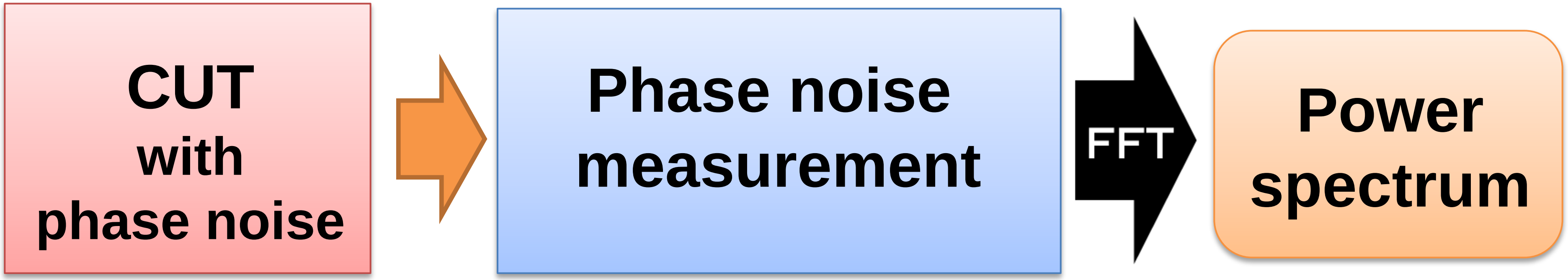
Phase Noise Measurement Flow

Phase noise : Frequency characteristics

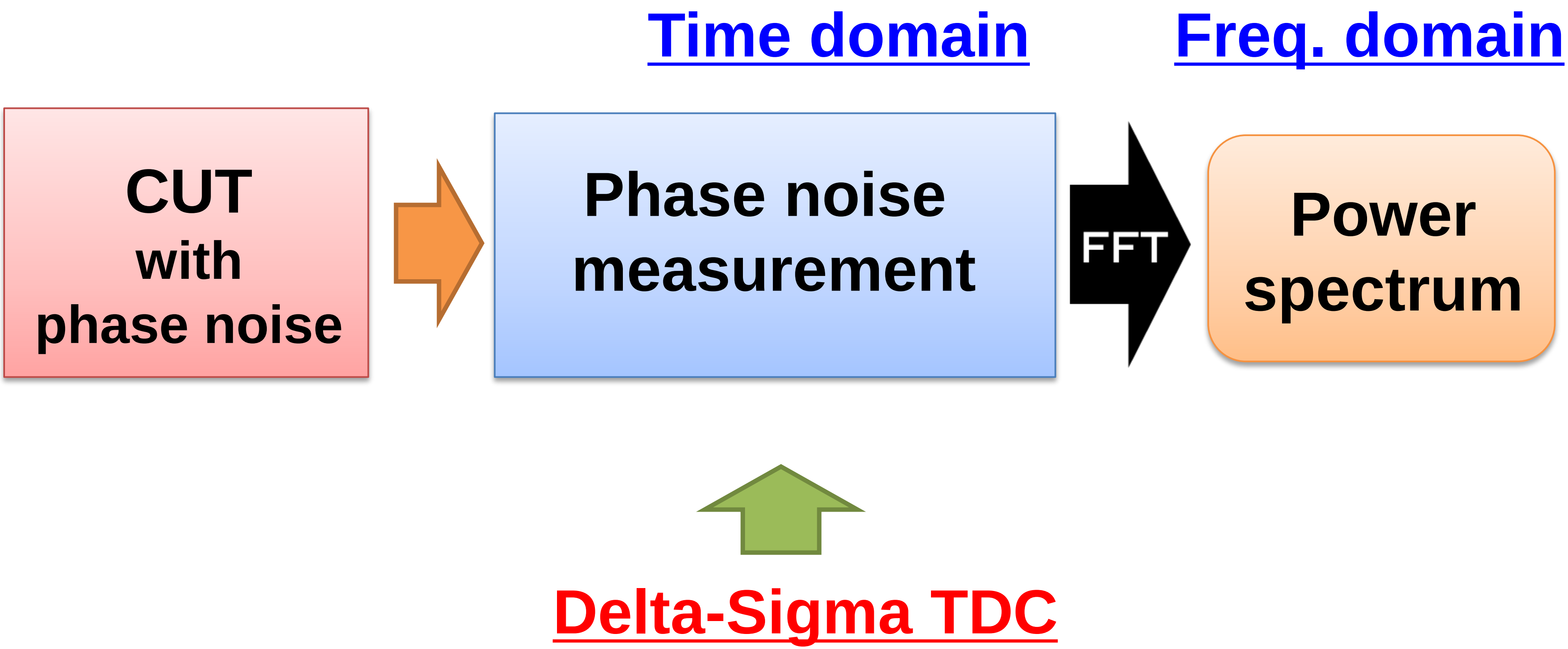


Time domain **Freq. domain**



CUT : Clock Under Test

Proposed Method



TDC : Time-to-Digital Converter

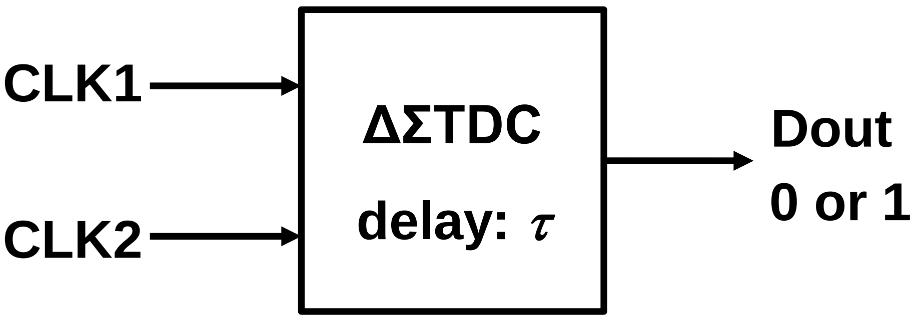
Time resolution improved by longer measurement time

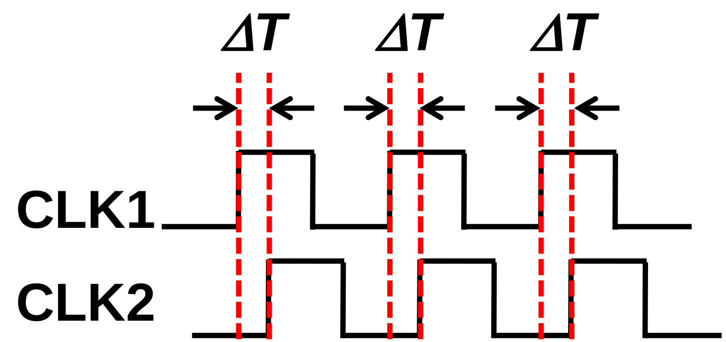
$$T\_resolution \propto \frac{2\tau}{time}$$

Ex: τ = 1ns, N_{DATA} =64K

→ T_resolution = 0.03ps

Principle of ΔΣTDC

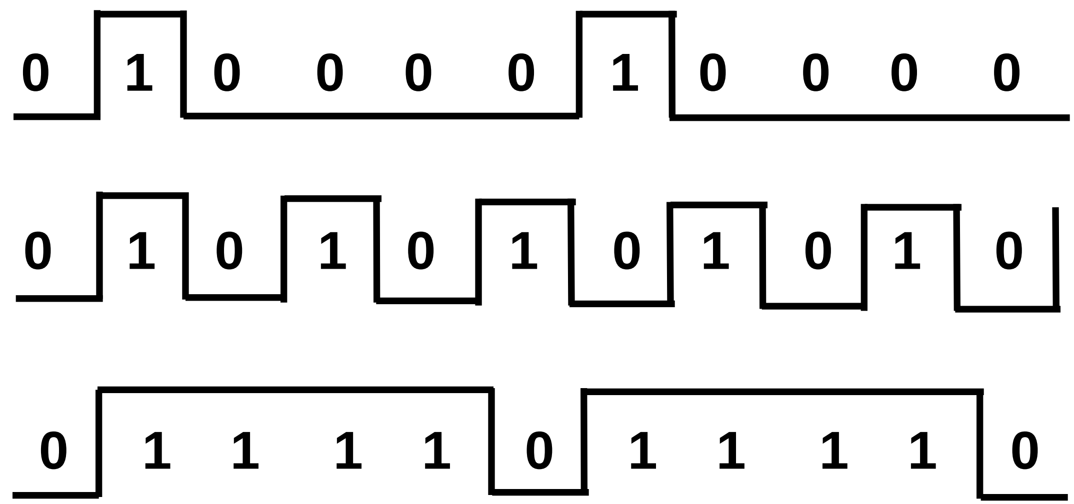




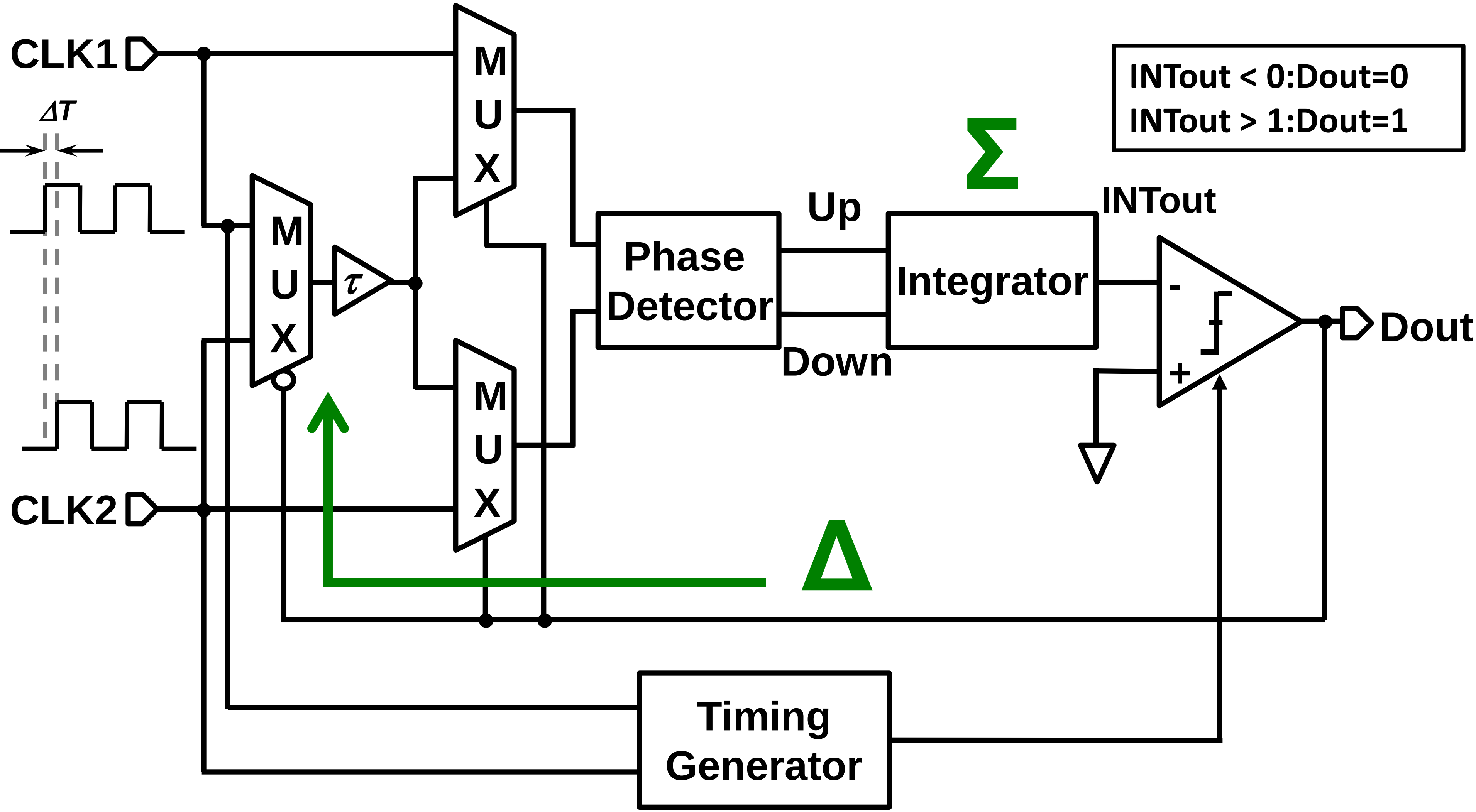
Dout # of 1's is proportional to ΔT

ΔT	# of 1's
short	few
long	many

Dout



ΔΣTDC Configuration



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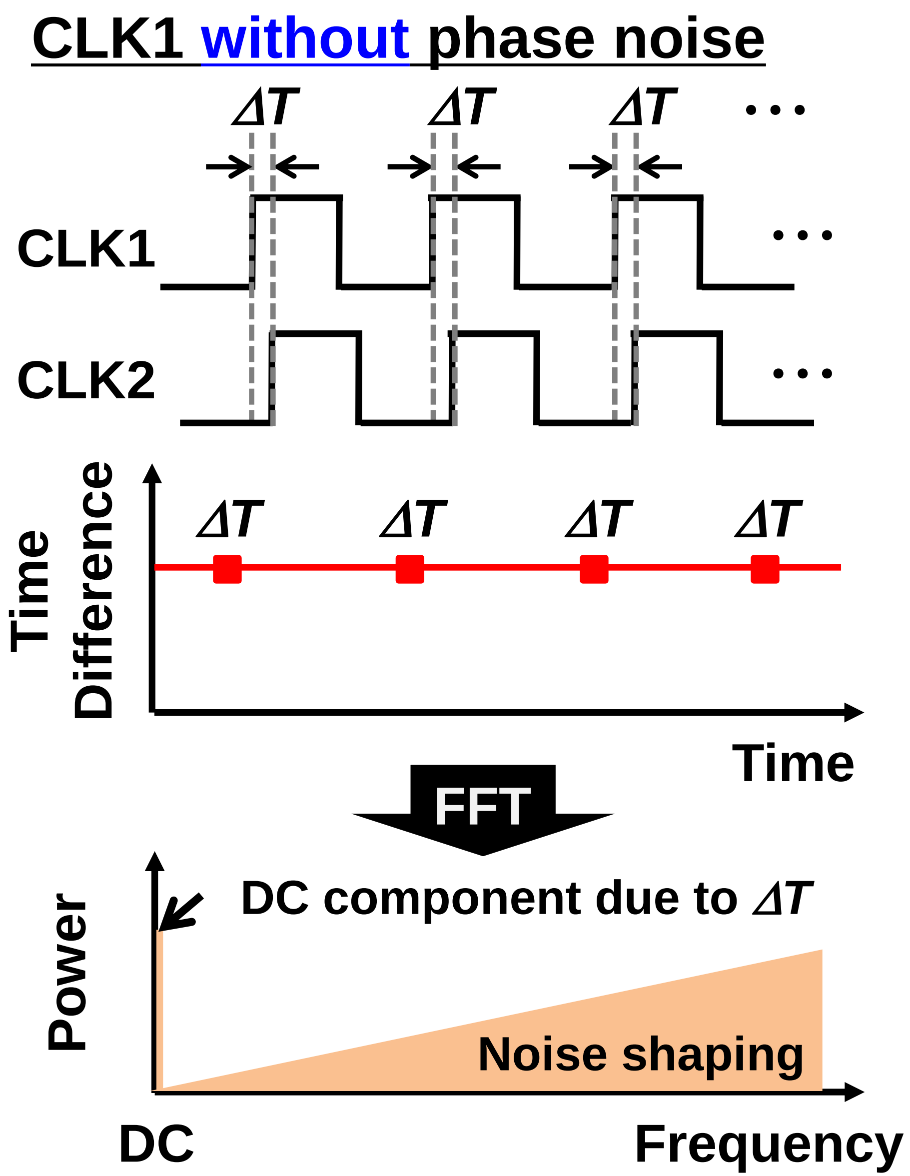
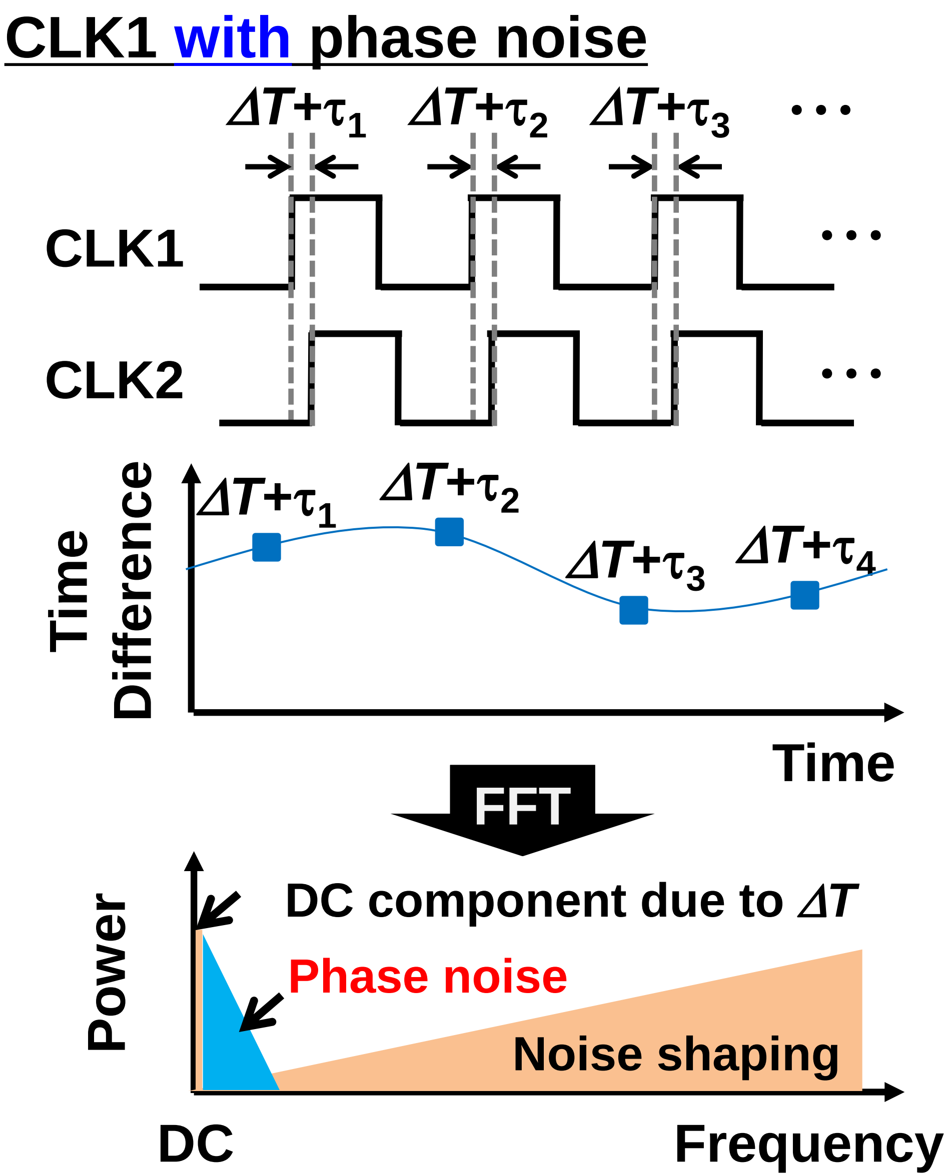
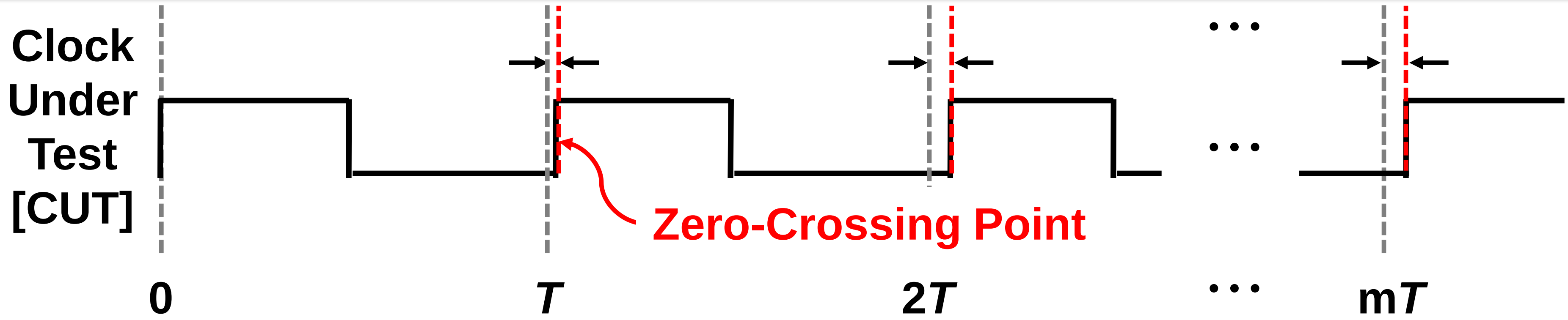
Principle of Phase Noise Measurement





Mathematical Analysis



$$CUT(t) \approx \sin(2\pi f_{in} t + \phi(t))$$

$\tau(m)$: m-th zero-crossing point variation function (noise component)

$$\therefore \phi(mT) = -2\pi f_{in} \tau(m)$$: phase noise (time domain)

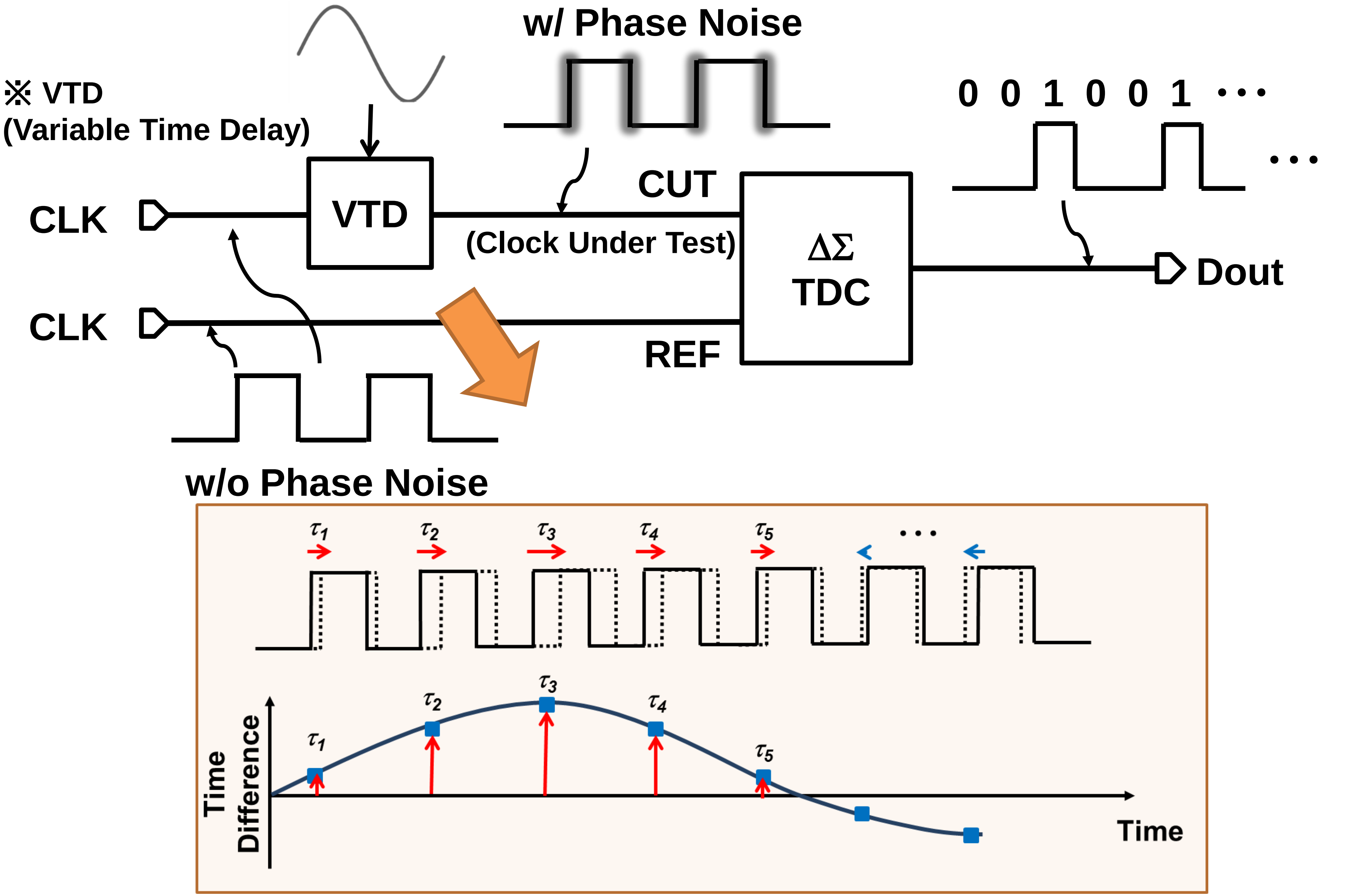
In case of sinusoidal phase fluctuation

$$\tau(m) = T \cdot \alpha_j \cdot \sin(\omega_j mT) \qquad 0 \le \alpha_j \le 1$$

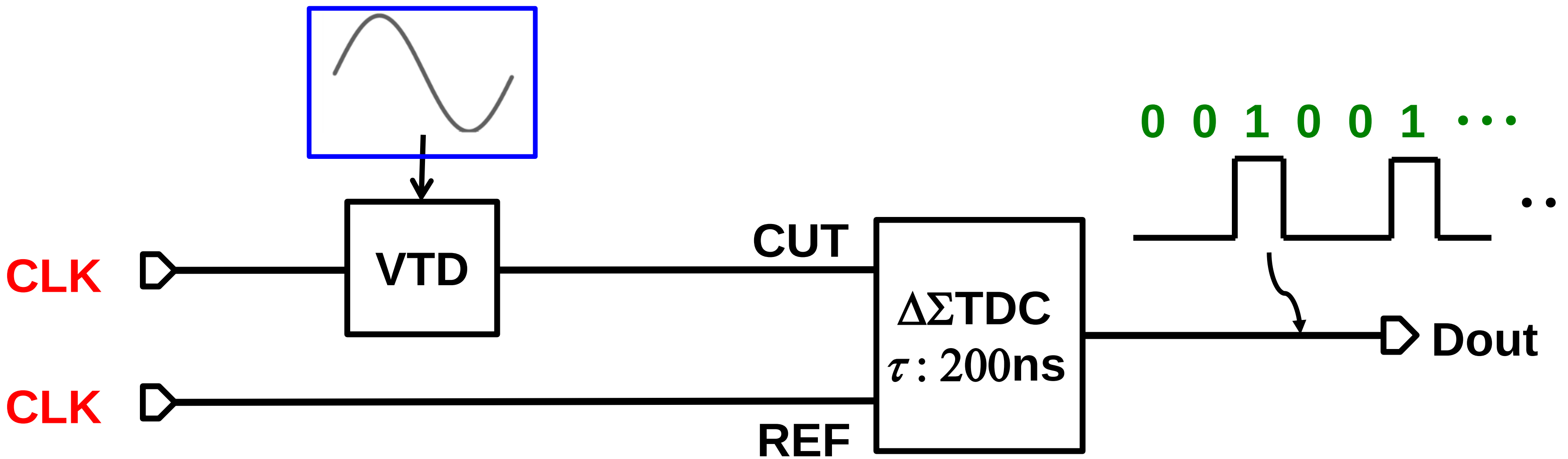
$$\phi(mT) = -2\pi\alpha_1 \cdot \sin(\omega_1 mT)$$: phase noise (time domain)

$$\Phi(\omega_1) = \frac{1}{2}(2\pi\alpha_1)^2$$: phase noise (freq. domain)

MATLAB Simulation



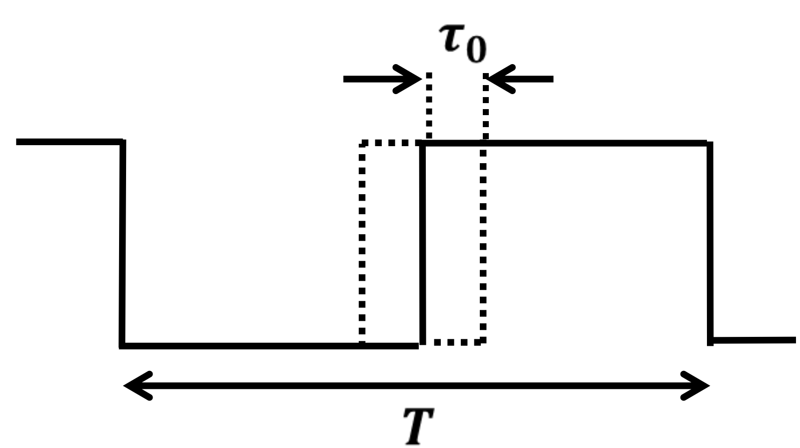
Simulation Conditions



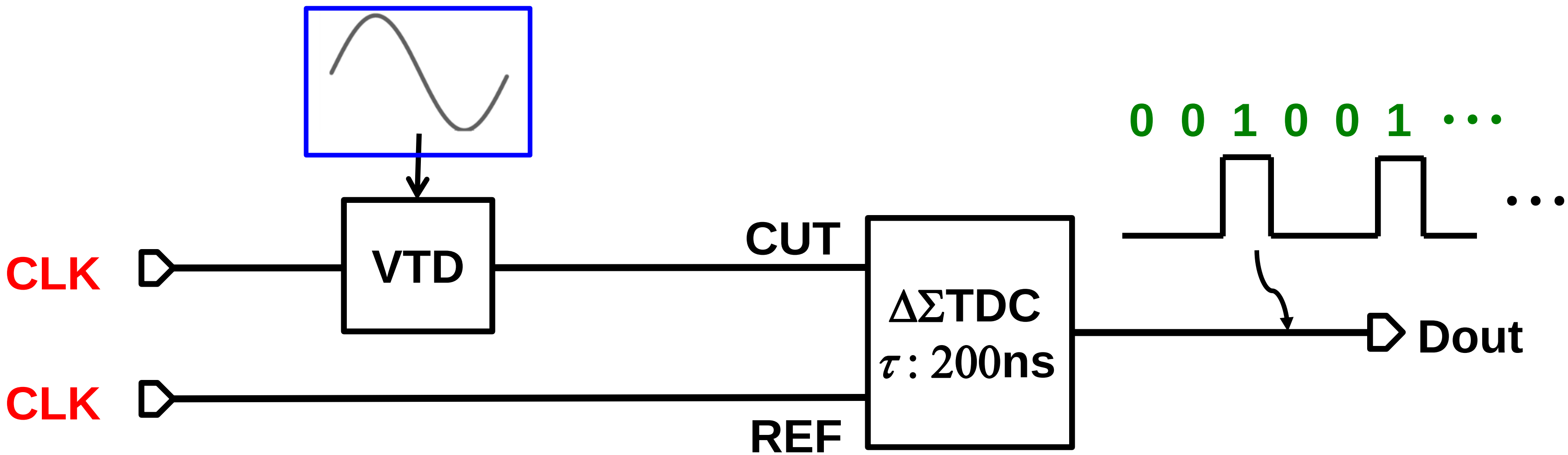
- **CLK:**
  Input freq. = 1 MHz (T = 1 μs)

Phase variation（sinusoidal）

- **Phase noise frequency :**
  f_j ➡ **varied**
- **Jitter variation :**
  $-0.1\mu s \leq \tau_0 \leq 0.1\mu s \; (=\frac{T}{10})$
- **Number of data:**
  4096



Simulation Conditions



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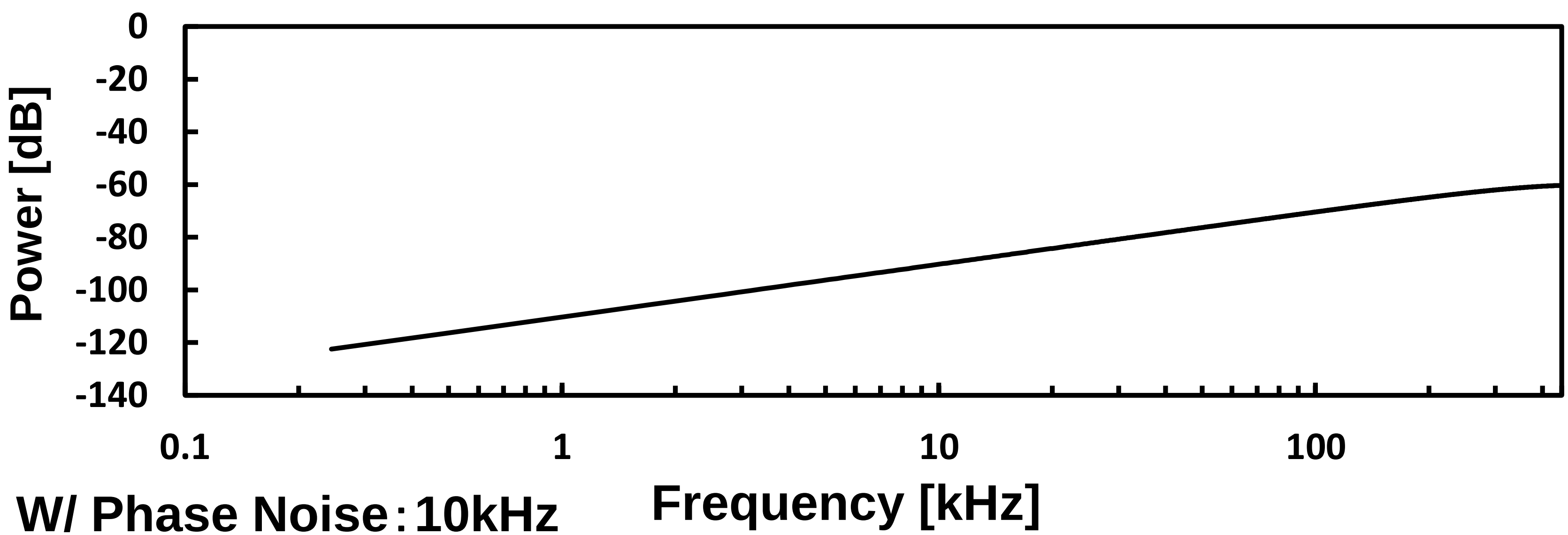
Phase variation（sinusoidal）

- Phase noise frequency :
  f_i = varied
- Jitter variation :
  $-0.1\mu s \leq \tau_0 \leq 0.1\mu s \; (= \frac{T}{10})$
- **Number of data:**
  4096

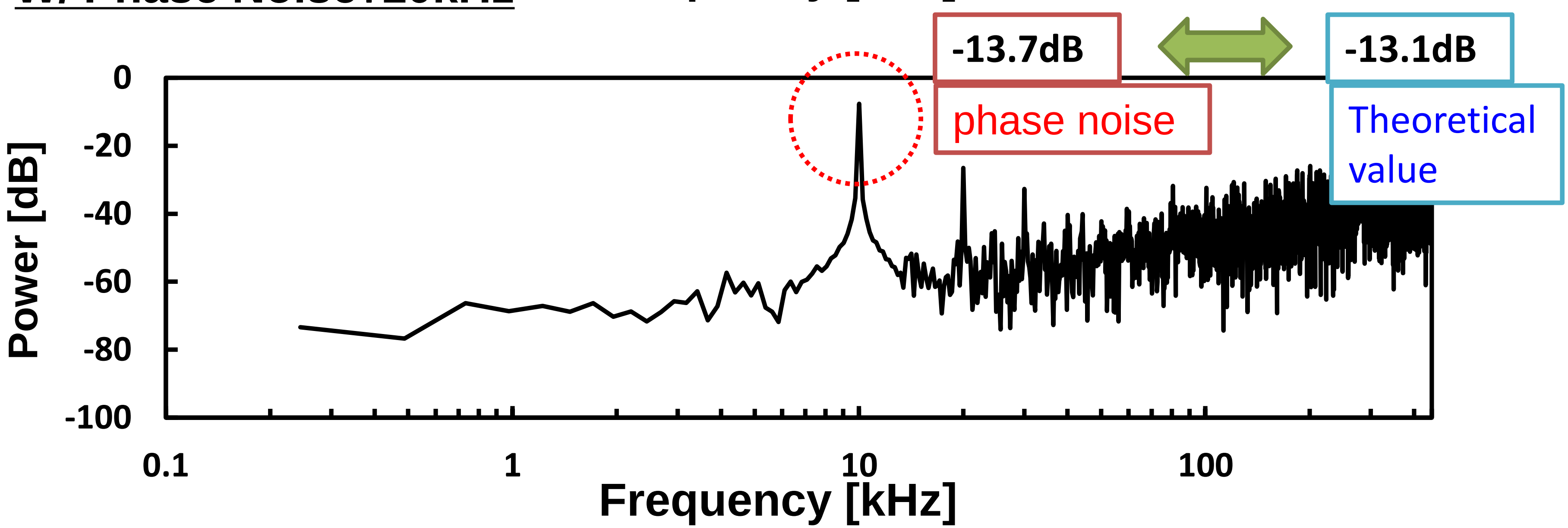
- Single sine wave
  ① $f_1 = 10$ kHz
  ② $f_1 = 50$ kHz
- Multiple sine waves
  ③ $f_1 = 10$ kHz
  $f_2 = 50$ kHz

Simulation Results ①

W/O Phase Noise

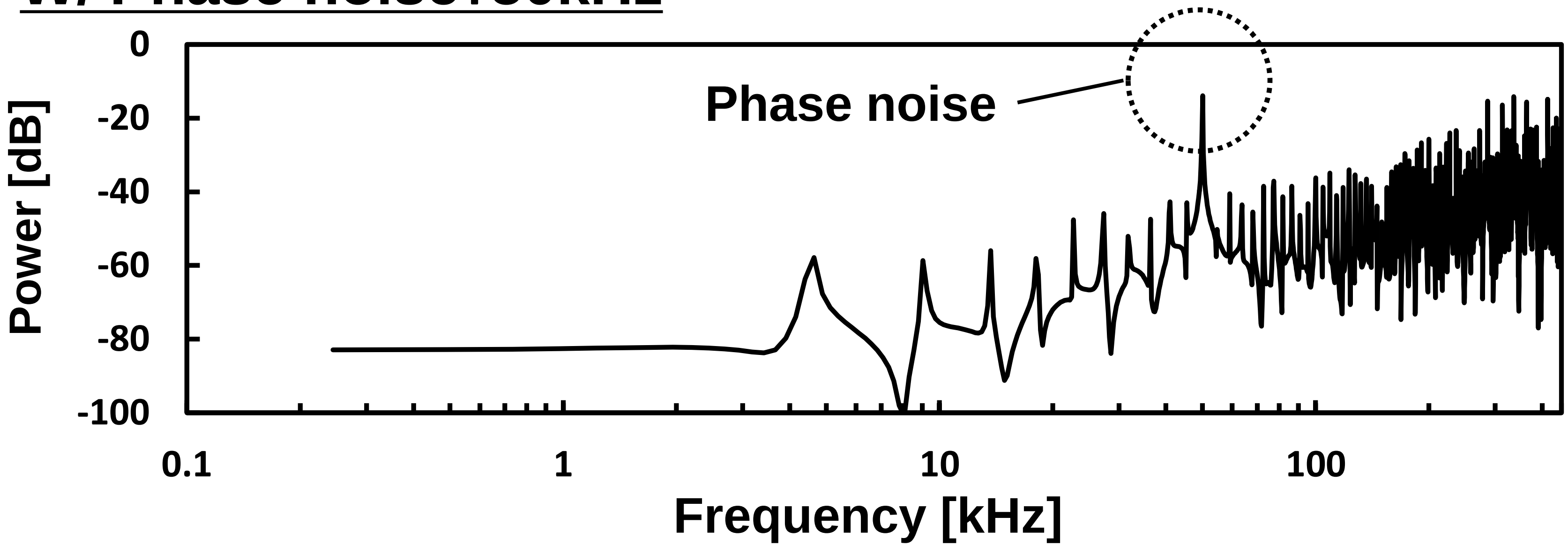


W/ Phase Noise：10kHz



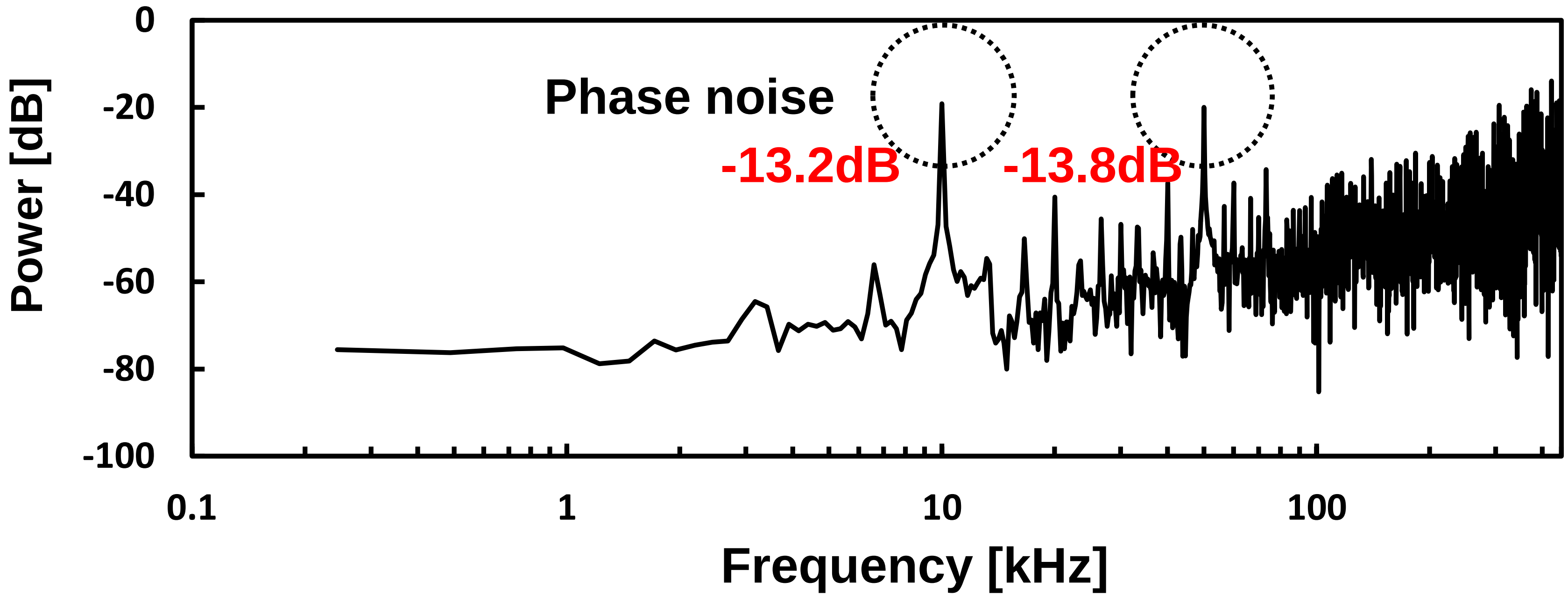
Simulation Results ②

W/ Phase noise：50kHz



Simulation Results ③

Phase noise：10kHz & 50kHz



Theoretical value

Power = -13.1[dB]

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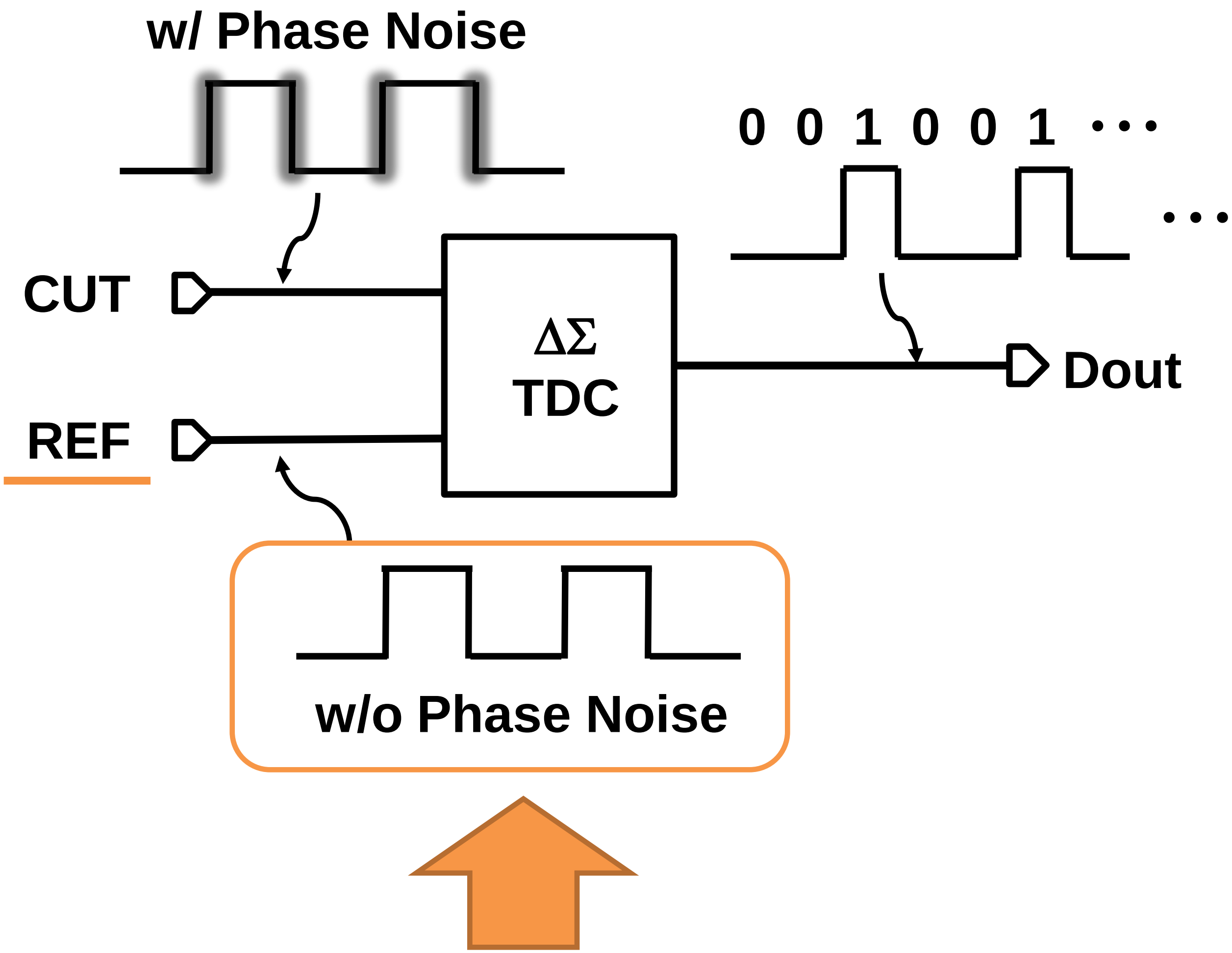
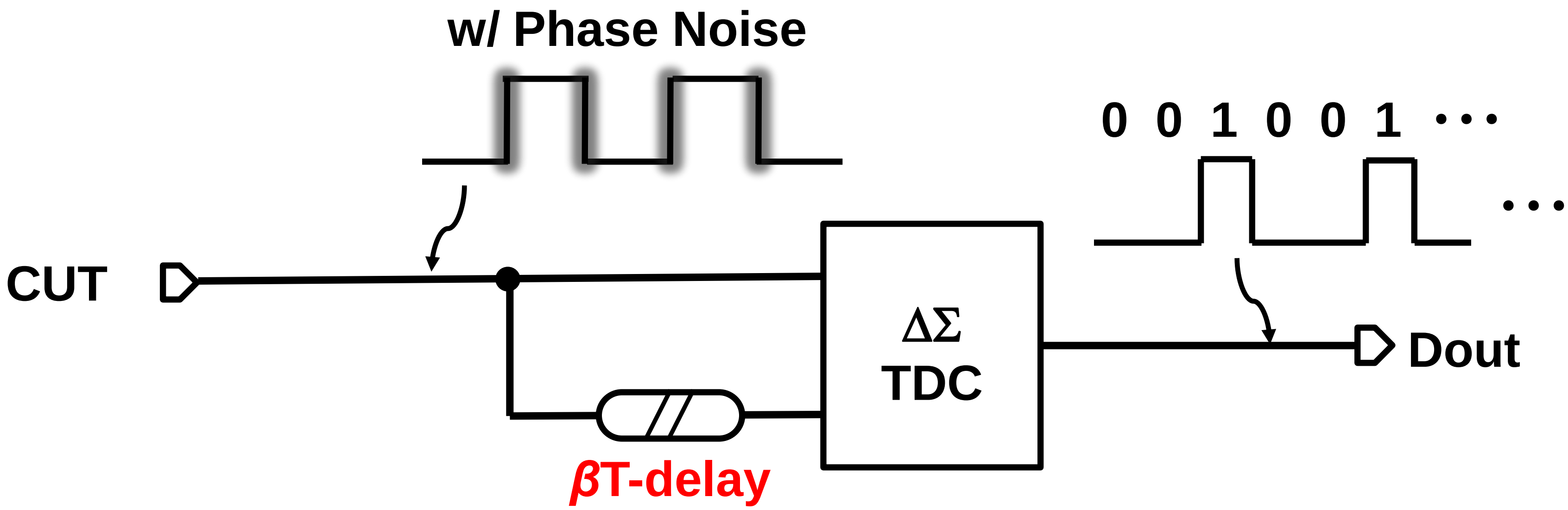
Problem of Proposed Method I



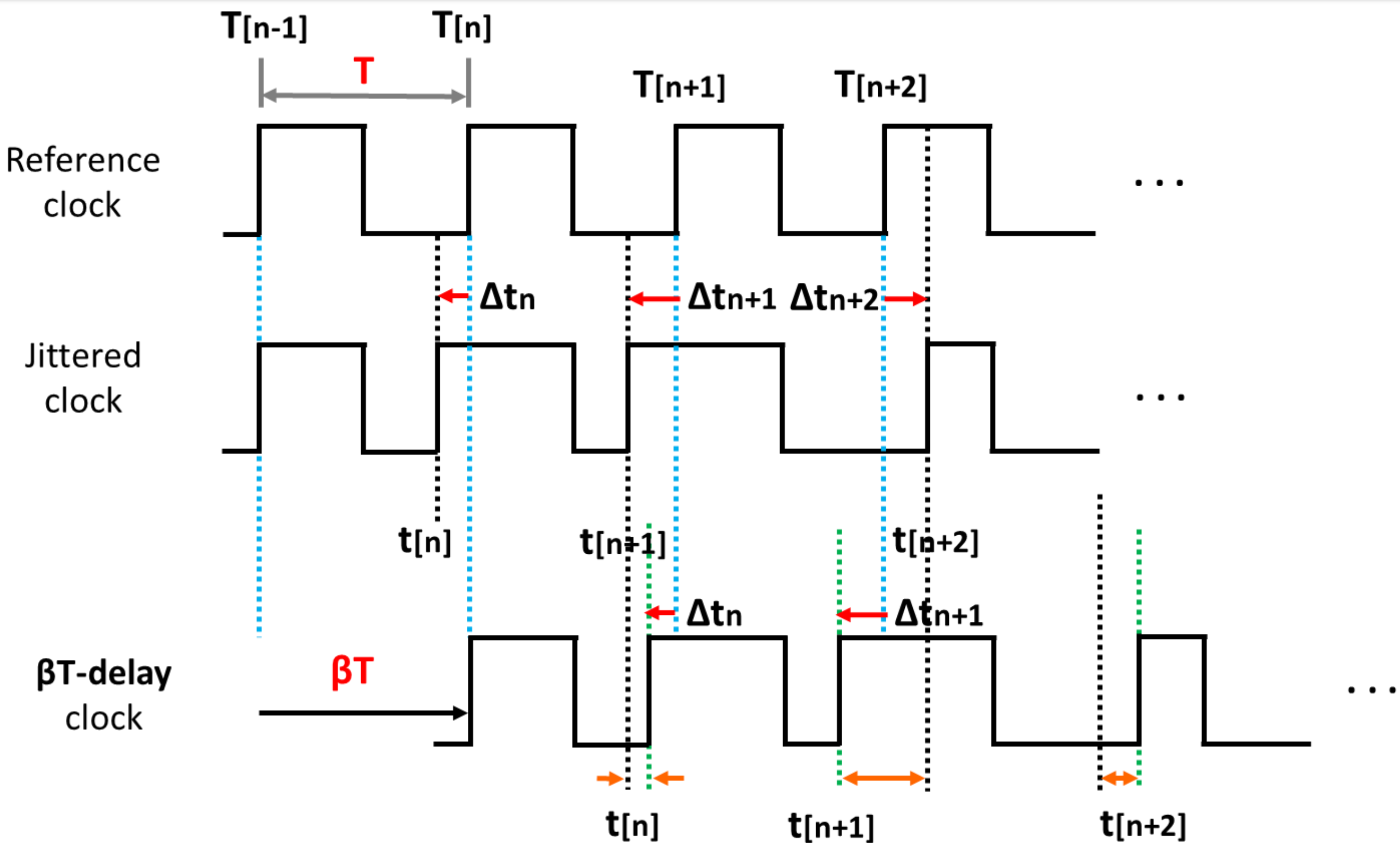
Difficult to implement

Self-Referenced Phase Noise Measurement Method



- No need for jitterless reference clock
- βT-delay: β is not required to be an integer.

Proposed Methods Ⅰ & Ⅱ



Method Ⅰ

Timing jitter measurement

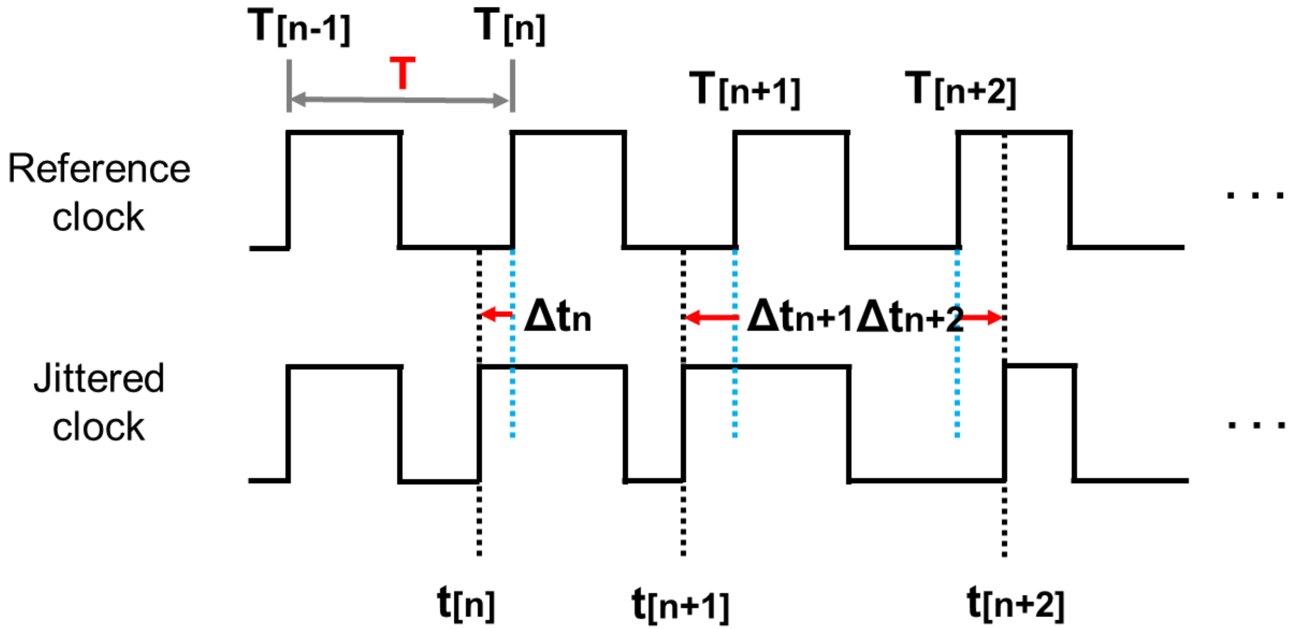
Method Ⅱ

Period jitter measurement

$$J_{PER}(n) = [\Delta t(n) - \Delta t(n-1)] - T_0$$

$$\therefore J_{PER}(n) = J(n) - J(n-1)$$

Mathematical Analysis



$\phi(mT) = -2\pi f_{in}\tau(m)$ **: phase noise (time domain)**

① $\tau(m) = T \cdot \alpha_j \cdot \sin(\omega_j mT)$ In case of sinusoidal phase variation $0 \leq \alpha_j \leq 1$

Measurement of each period

$$\tau(m+1) - \tau(m) + (\beta - 1)T$$
$$= T \cdot \alpha_1 [sin(\omega_1 (m+1)T) - sin(\omega_1 \cdot mT)] + (\beta - 1)T$$
$$= 2T \cdot \alpha_1 \, sin(\omega_1 T/2) \, cos(\omega_1 (m + 1/2)T) + (\beta - 1)T$$

Mathematical Analysis

① $\tau(m) = T \cdot \alpha_j \cdot \sin(\omega_j mT)$ In case of sinusoidal phase variation $0 \le \alpha_j \le 1$

phase noise (time domain)

$$\therefore \phi'(mT) = 2T \cdot \alpha_1 \, sin(\omega_1 T/2) \, cos(\omega_1 (m + 1/2)T)$$

phase noise (frequency domain)

$$\therefore \Phi'(\omega_1) = \frac{1}{2}(2\pi\alpha_1)^2 \, [2 \sin 2(\omega_1 T/2)]^2$$

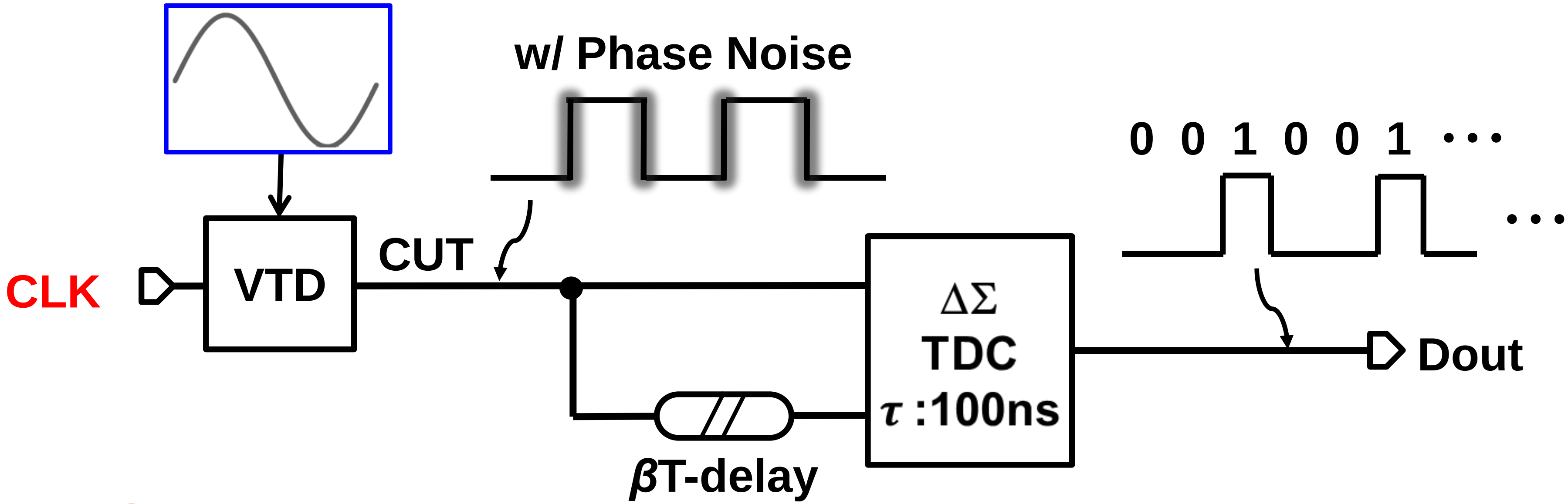
$$\cong \frac{1}{2}(2\pi\alpha_1)^2 {\omega_1}^2 T^2 \qquad (\because \omega_1 T/2 \ll 1)$$

ω_1: phase noise freq. [low freq.]
T : input CLK period (=1/f)

phase noise power at ω_1

$$\Phi(\omega_1) = \frac{1}{2}(2\pi\alpha_1)^2$$

Simulation Conditions



- **CLK:**
  Input freq. = 1 MHz (T = 1 μs)

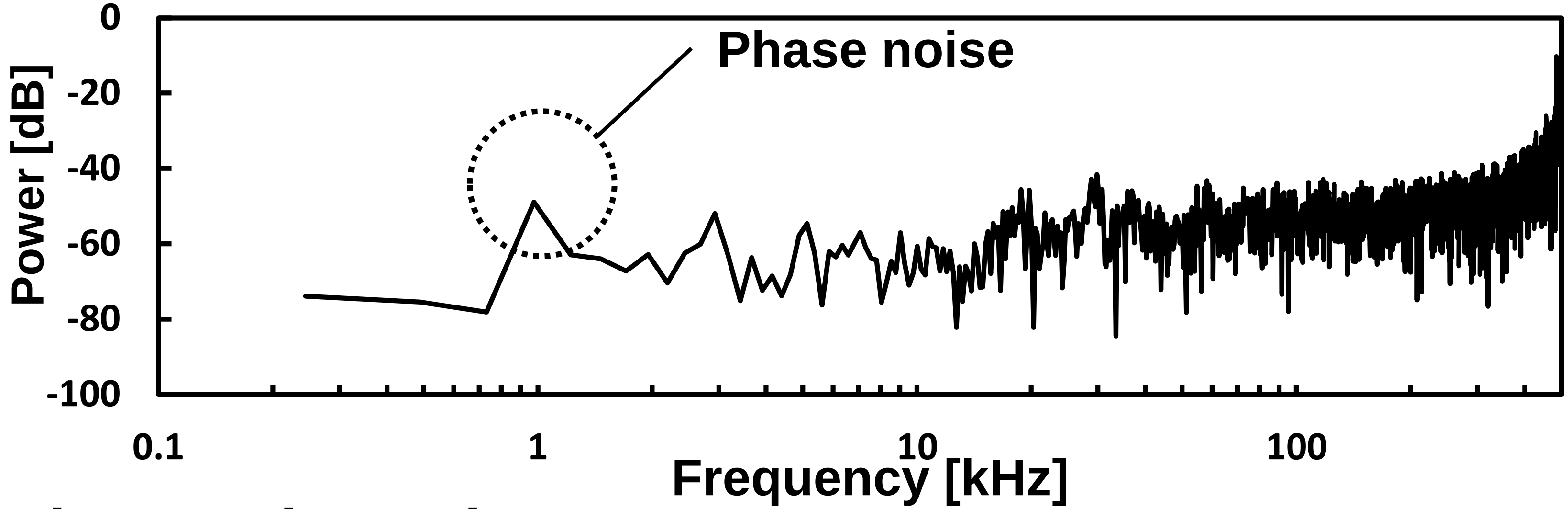
Phase variation (sinusoidal)

- Phase noise frequency :
  f_i = varied
- Jitter variation :
  $$-0.1\mu s \le \tau_0 \le 0.1\mu s \left(= \frac{T}{10}\right)$$
- **Number of data:**
  4096

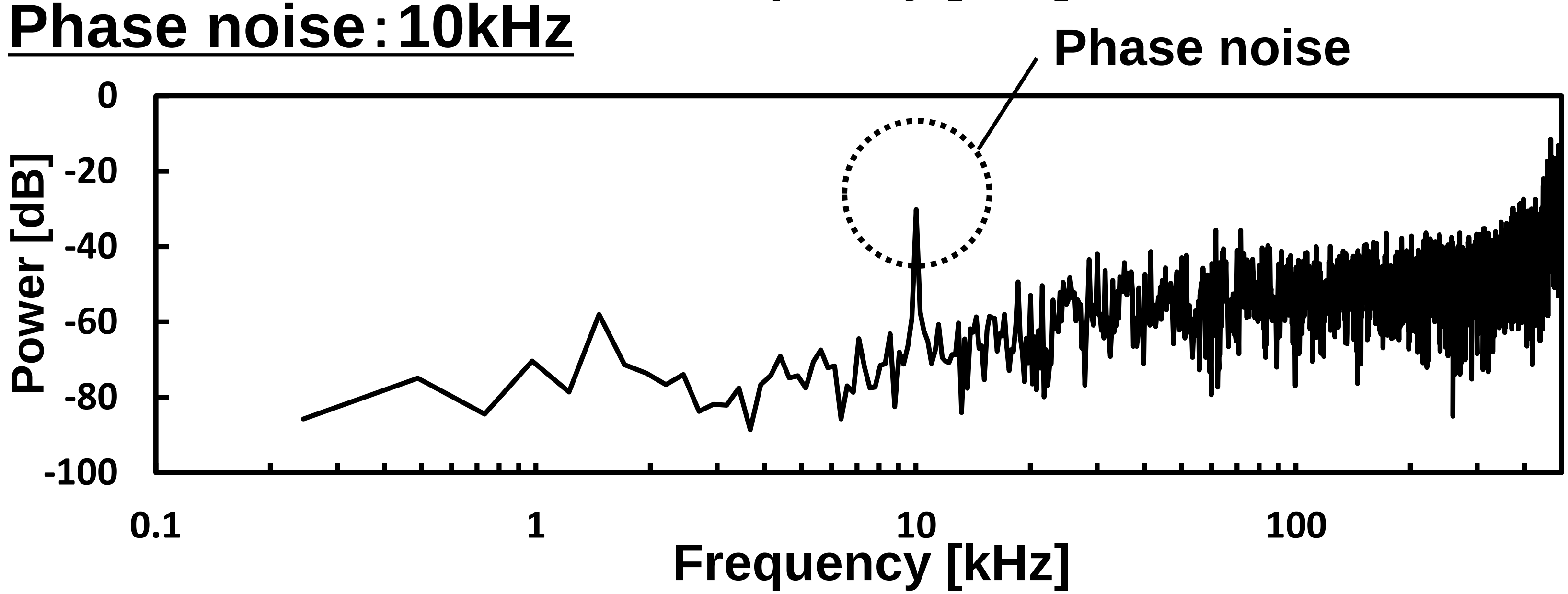
- Single sinusoidal
  ① $f_1 = 1$ kHz
  ② $f_1 = 10$ kHz
  ③ $f_1 = 100$ kHz
- Multiple sinusoidal
  ④ $f_1 = 10$ kHz
  $f_2 = 50$ kHz

Simulation Results ①&②

Phase noise：1kHz

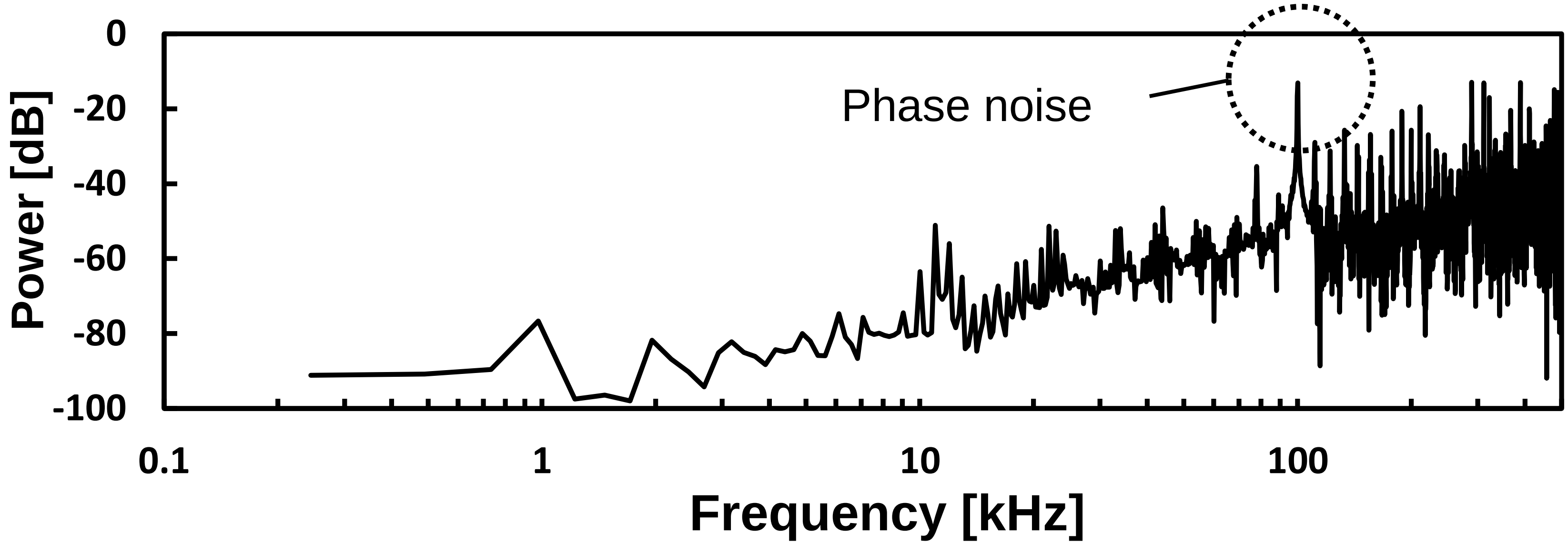


Phase noise：10kHz

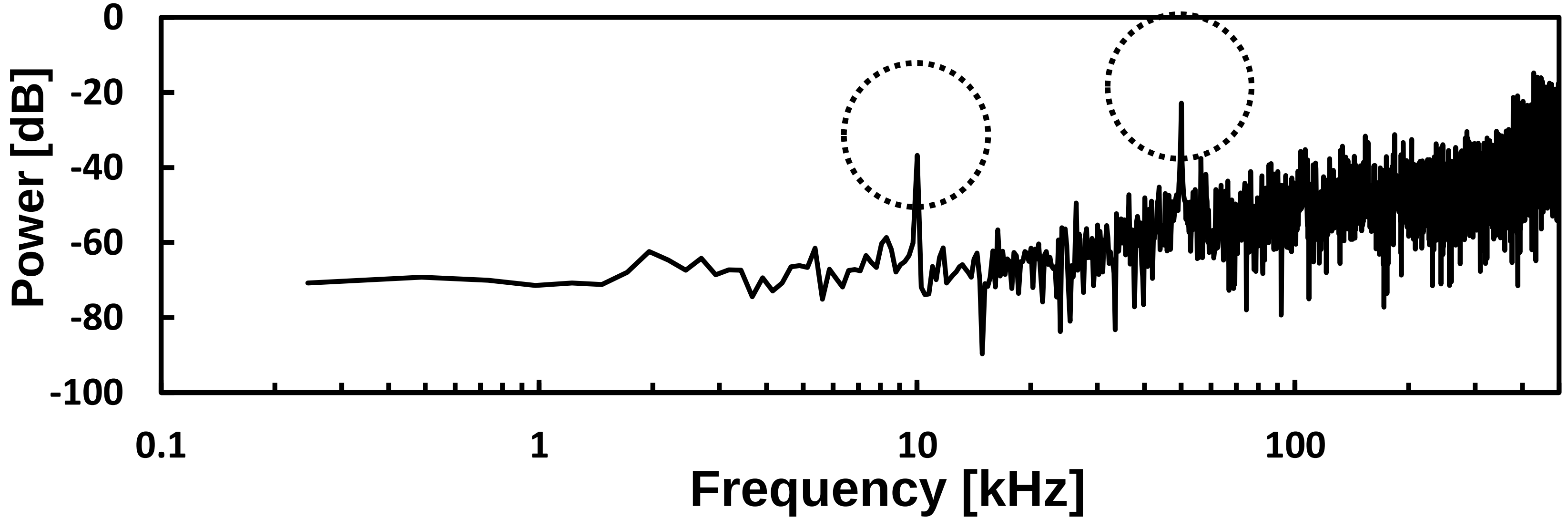


Simulation Results ③&④

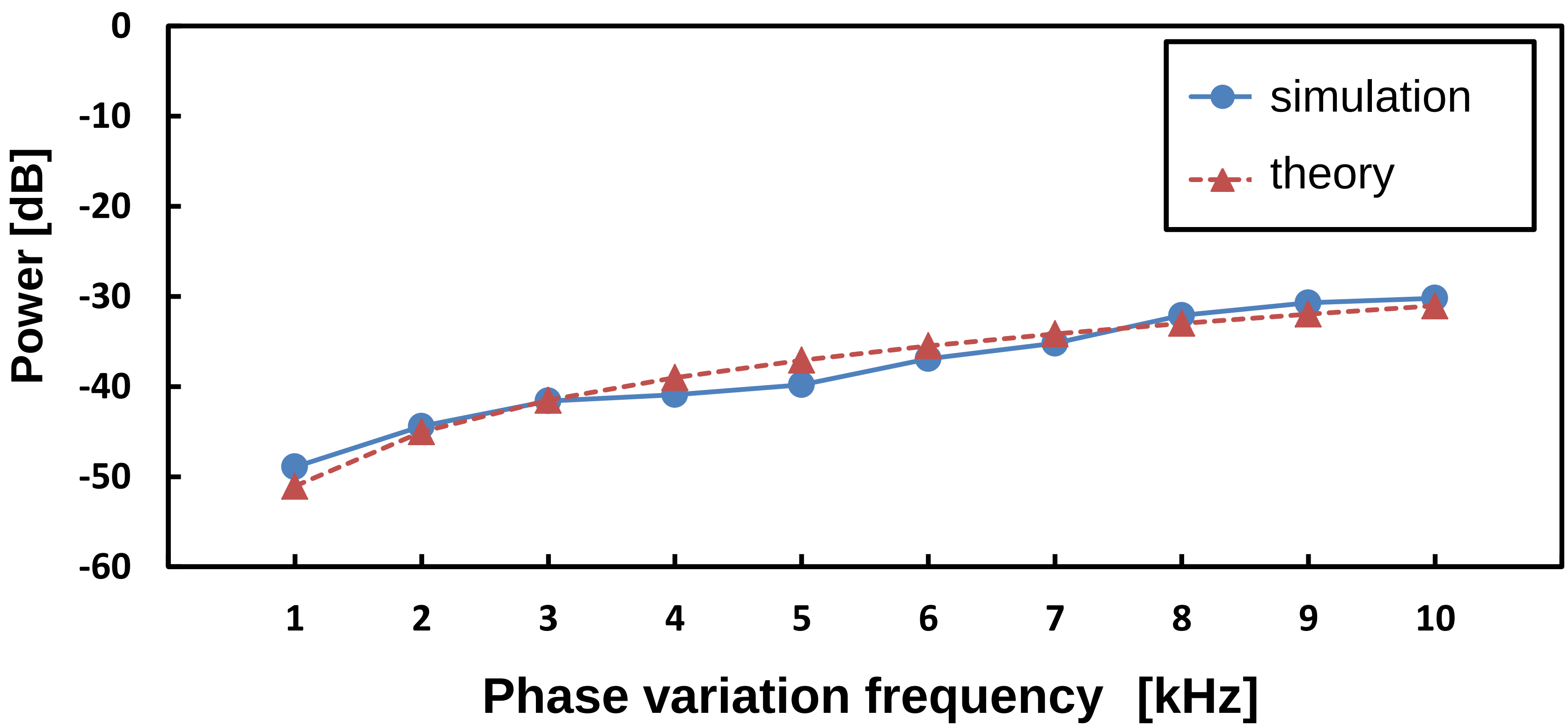
Phase noise：100kHz



Phase noise：10kHz＆50kHz



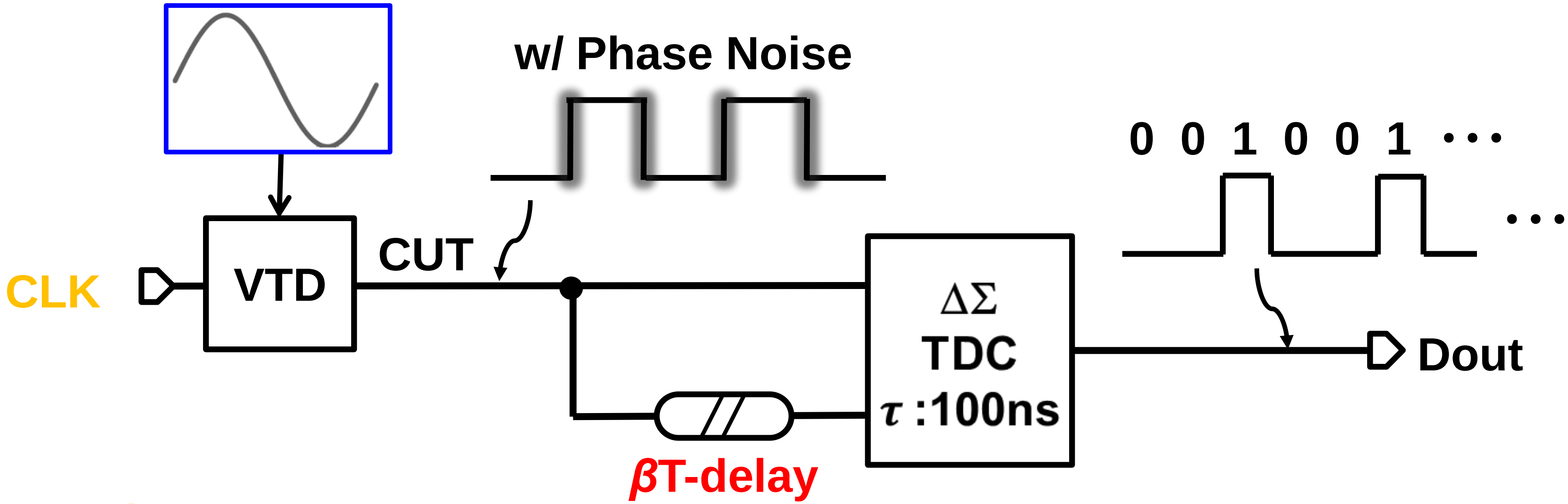
Comparison of Theory and Simulation Results



Theoretical expression

$$\Phi'(\omega_1) = \frac{1}{2}(2\pi\alpha_1)^2{\omega_1}^2T^2$$

Simulation Conditiions



- CLK:
  Input freq. = 1 MHz （T = 1 μs)

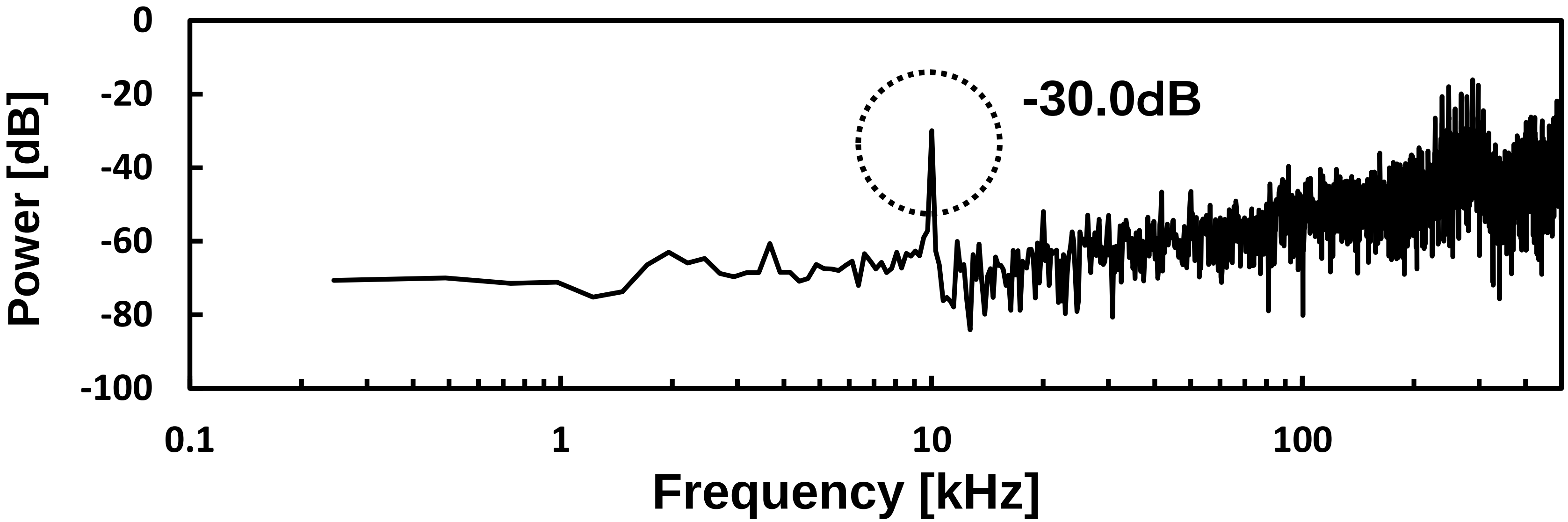
Phase variation（sinusoidal）

- Phase noise frequency :
  $f_i = 10\text{kHz}$
- Jitter variation :
  $-0.1\mu s \le \tau_0 \le 0.1\mu s \; (= \frac{T}{10})$
- Number of data:
  4096

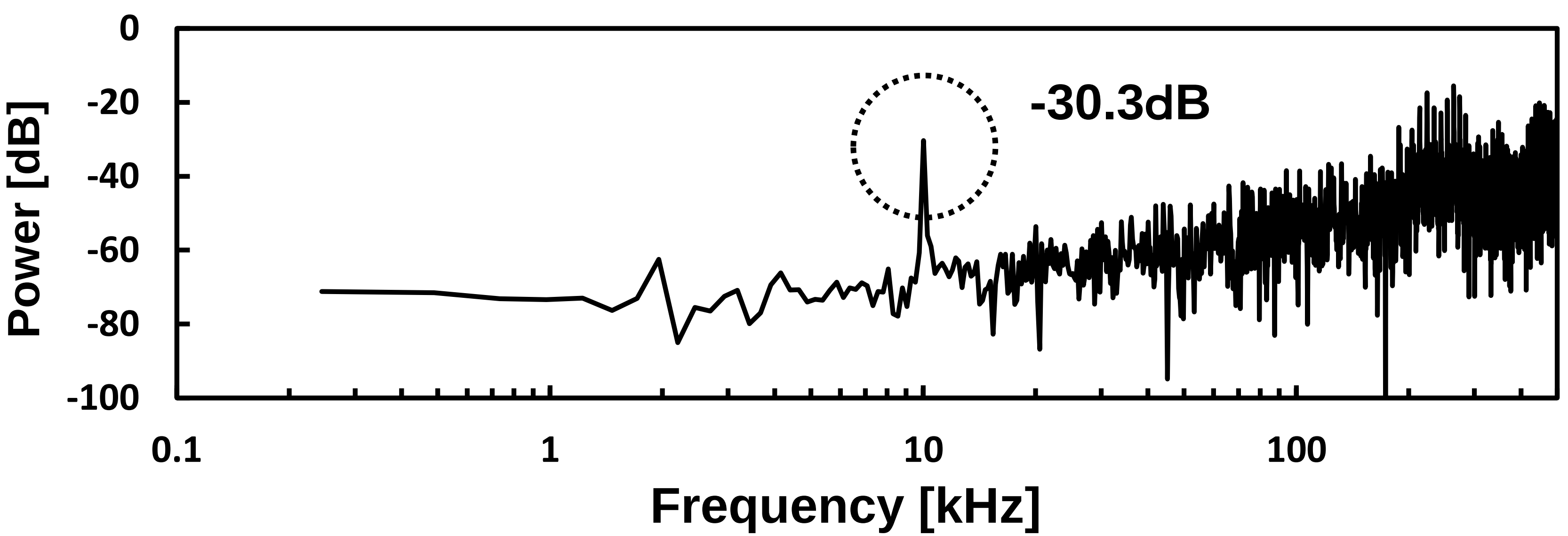
- β value deviation by ±5% from 1.0
  - β＝0.95
  - β＝1.05

Simulation Results（delay β variation）

β = 0.95（error -5%）

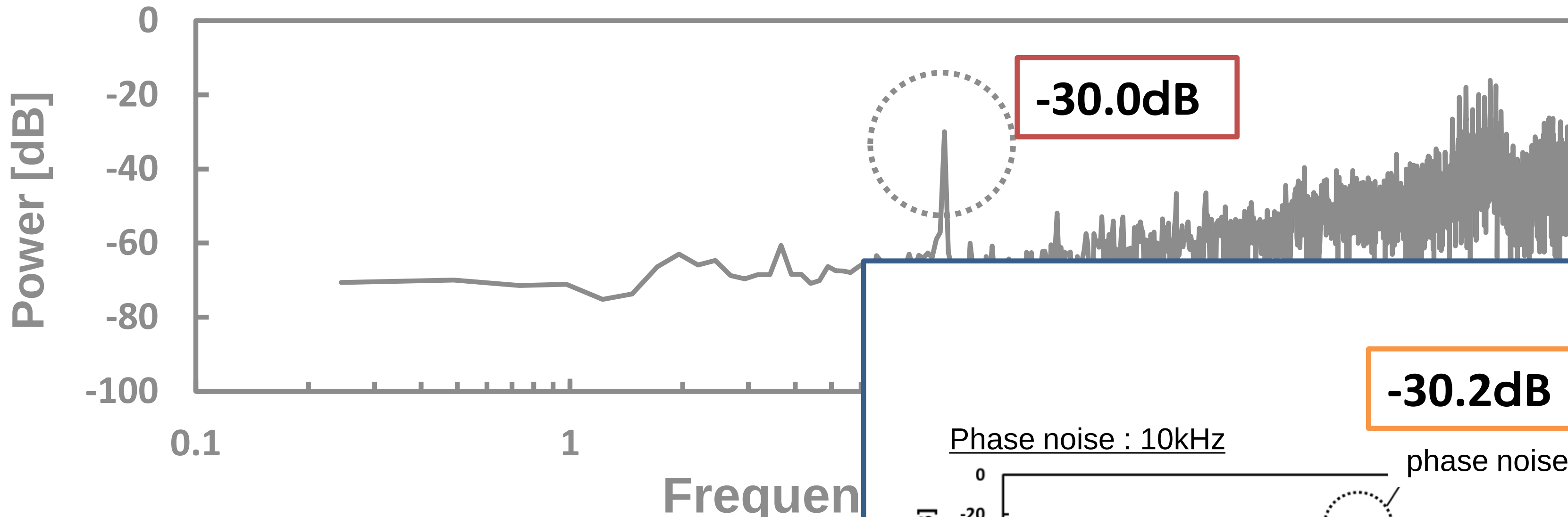


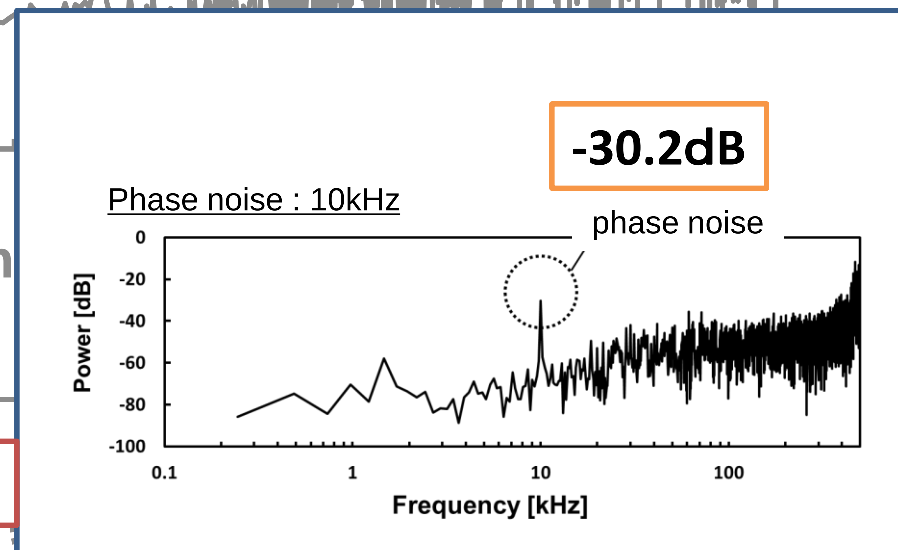
β = 1.05（error +5%）



Simulation Results（delay β variation）

β = 0.95（error -5%）





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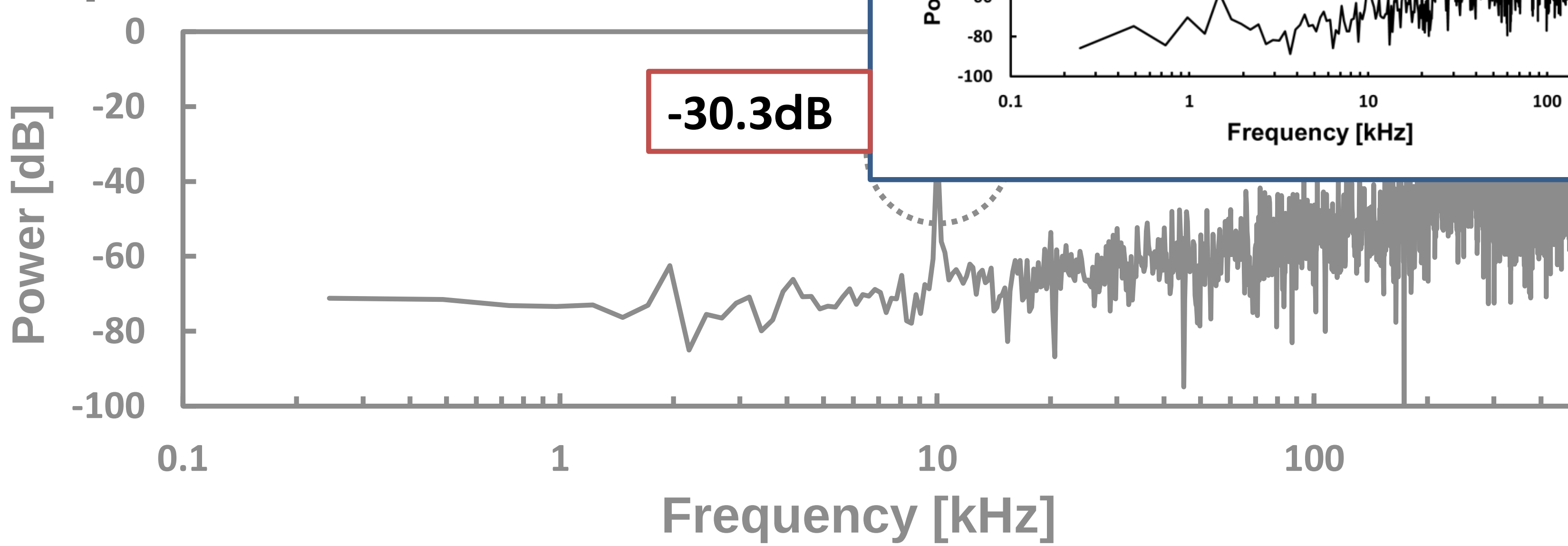

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- <u>Conclusions</u>

Conclusion

■ Proposal of two phase measurement techniques with ΔΣTDC

- Low cost testing without requiring spectrum analyzer
- On-chip high-precision phase noise measurement
- Fine time resolution measurement possible with ΔΣTDC
- Phase noise power spectrum obtained by FFT of TDC digital output

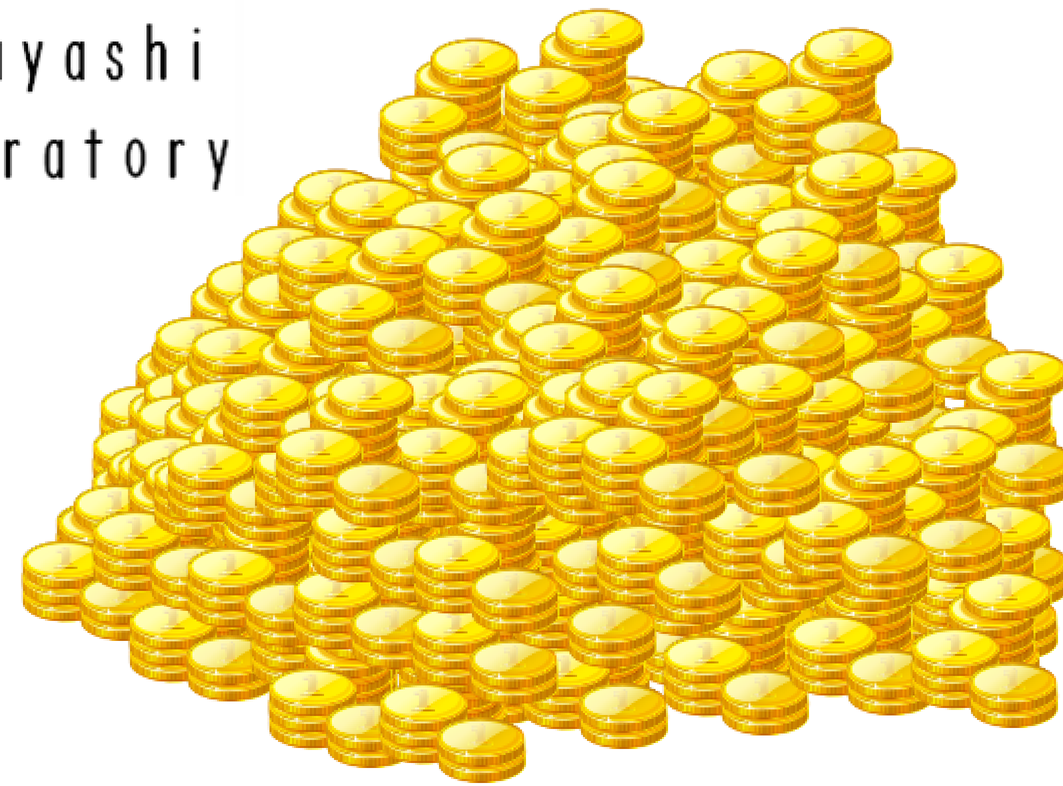
1MHz carrier (clock), 64K TDC output data

➡ Phase noise power spectrum of 0 to 0.5MHz away from 1MHz with 15.2Hz resolution.

■ MATLAB simulation verification

- Verified by superimposing several sinusoidal phase variation components
- Compared theoretical analysis and simulation results
- Self-referenced clock method with several β delay coefficient values

Kobayashi Laboratory



Time is GOLD !!

ΔΣTDC is the key.

Acknowledgement

We would like to thank

Semiconductor Technology Academic Research Center (STARC) for kind support of this project.