Phase Noise Measurement Techniques Using Delta-Sigma TDC

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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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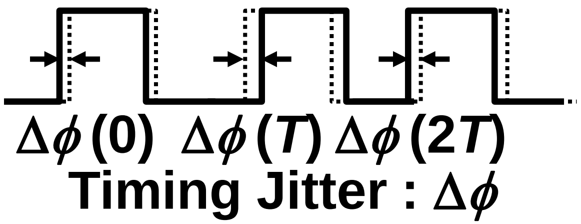
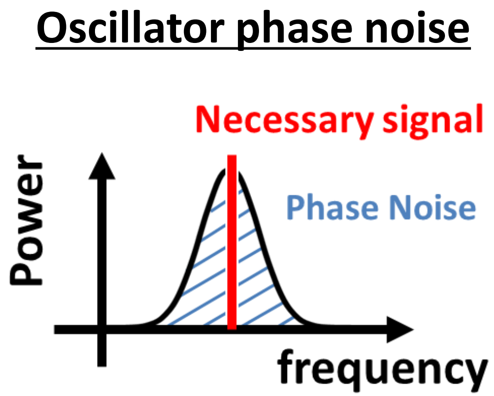
Research Background

Phase noise of clock can cause malfunctions of electronic systems





Electronic system performance degradation

- **RF circuit & system**
- **ADC**

Test & measurement for phase noise, jitter is important

Conventional Method Ⅰ

Conventional Phase Noise Measurement

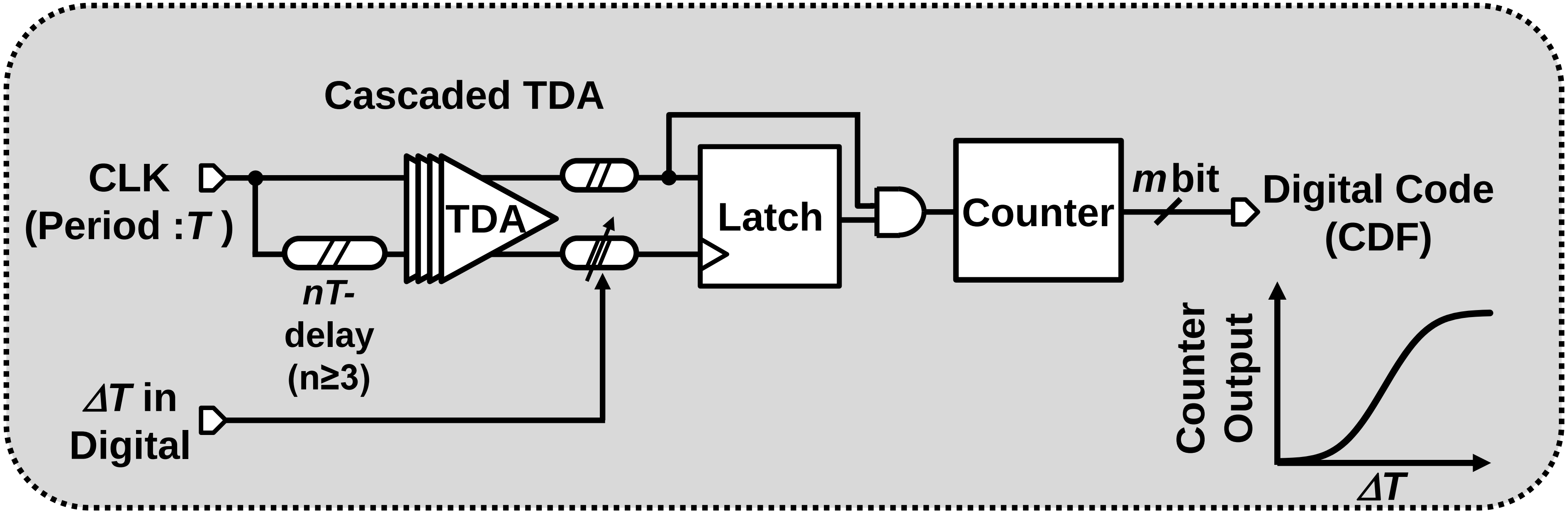
- **Expensive : Spectrum Analyzer**
- **Long testing time： ~10 seconds**

Mass production

Test cost → high

Conventional Method II

On-chip Jitter Measurement Circuit



Can NOT measure jitter power spectrum

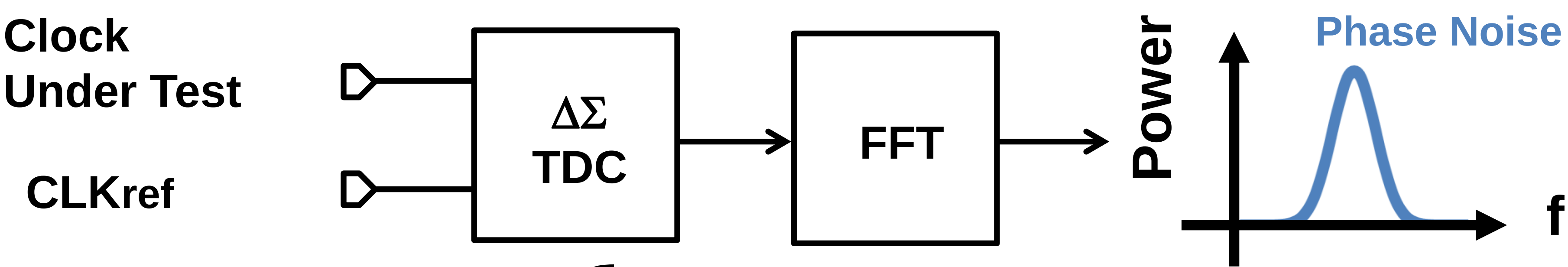
[1] K. Niitsu, et al., "CMOS Circuits to Measure Timing Jitter Using a Self-Referenced Clock and a Cascaded Time Difference Amplifier with Duty-Cycle Compensation," IEEE Journal of Solid-State Circuits, Nov. 2012.

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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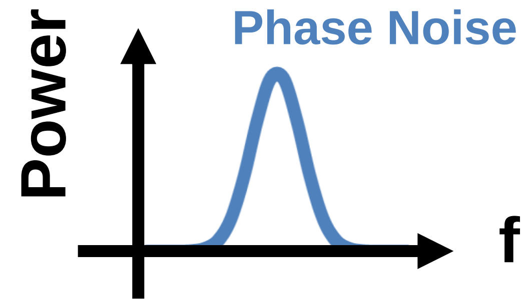
Phase Noise Measurement Flow

Phase noise : Frequency characteristics

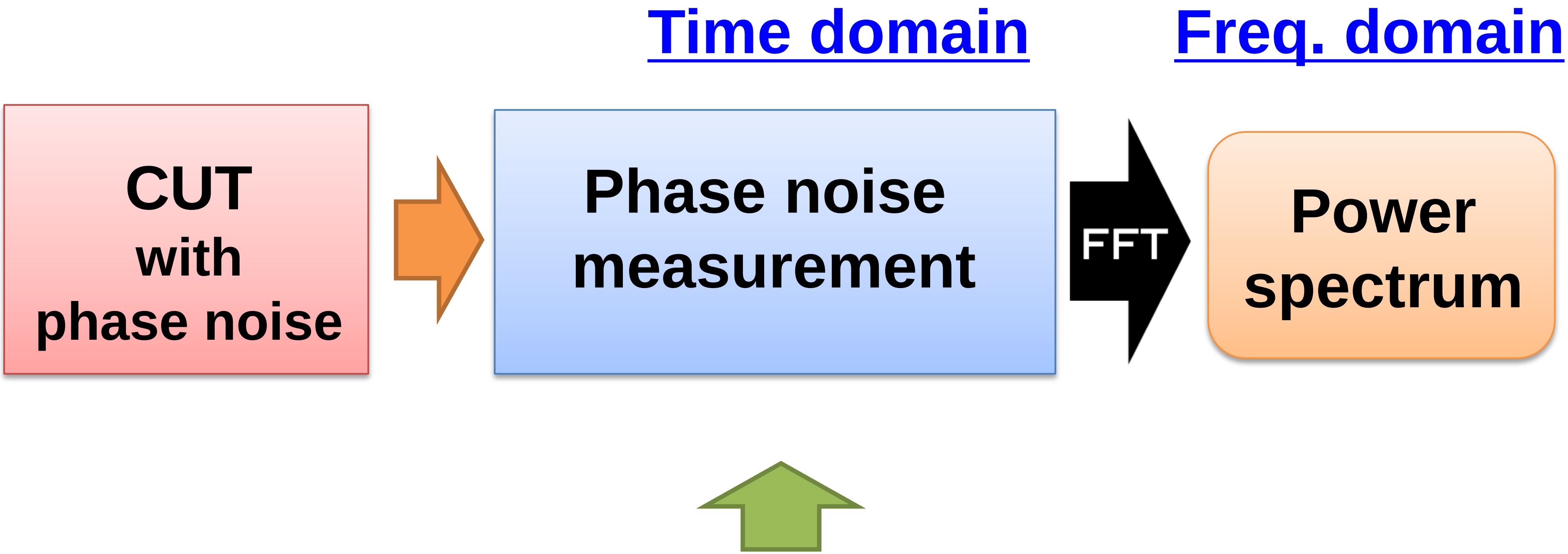


Time domain **Freq. domain**

CUT with phase noise → Phase noise measurement → FFT → Power spectrum

CUT : Clock Under Test

Proposed Method



Delta-Sigma TDC

TDC : Time-to-Digital Converter

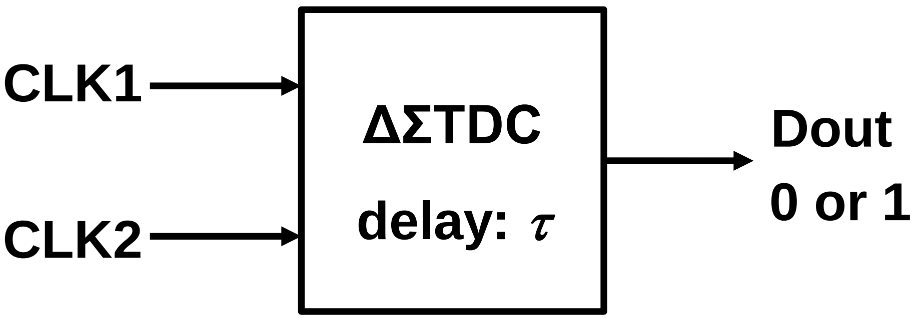
Time resolution improved
by longer measurement time

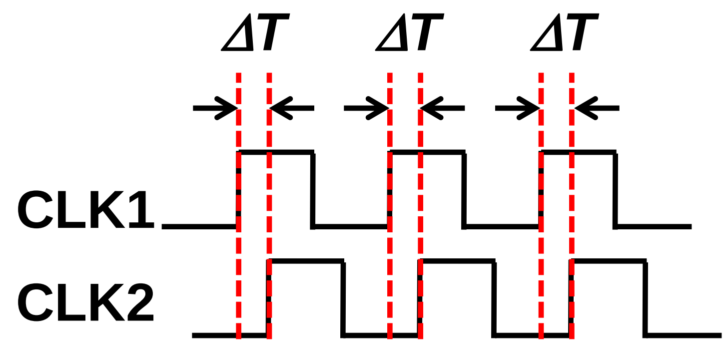
$$T\_resolution \propto \frac{2\tau}{time}$$

Ex: τ = 1ns, N_{DATA} =64K

→ T_resolution = 0.03ps

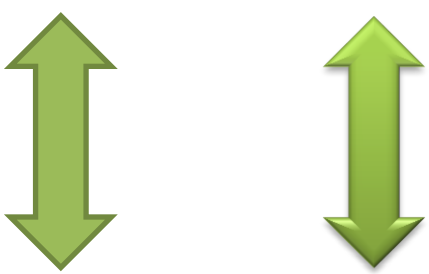
Principle of ΔΣTDC



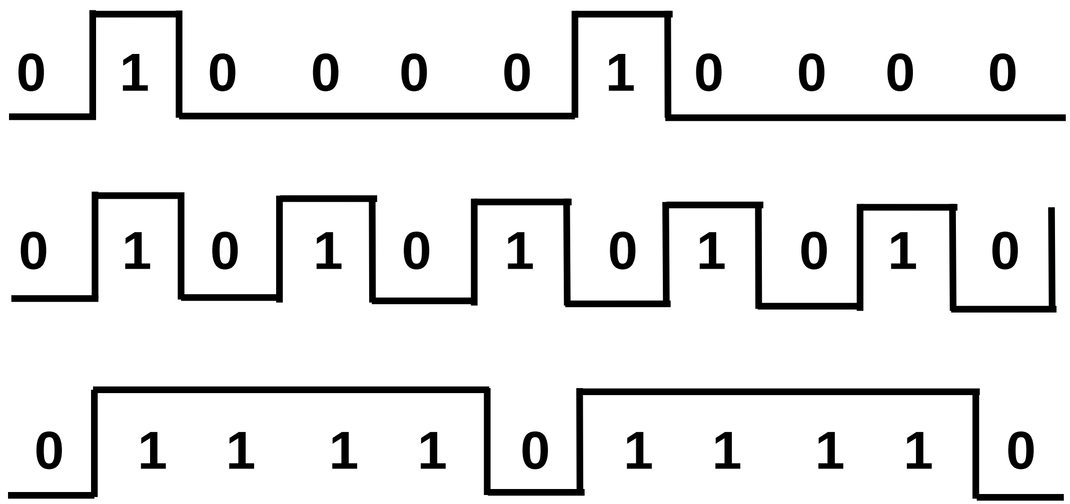


Dout # of 1's is proportional to ΔT

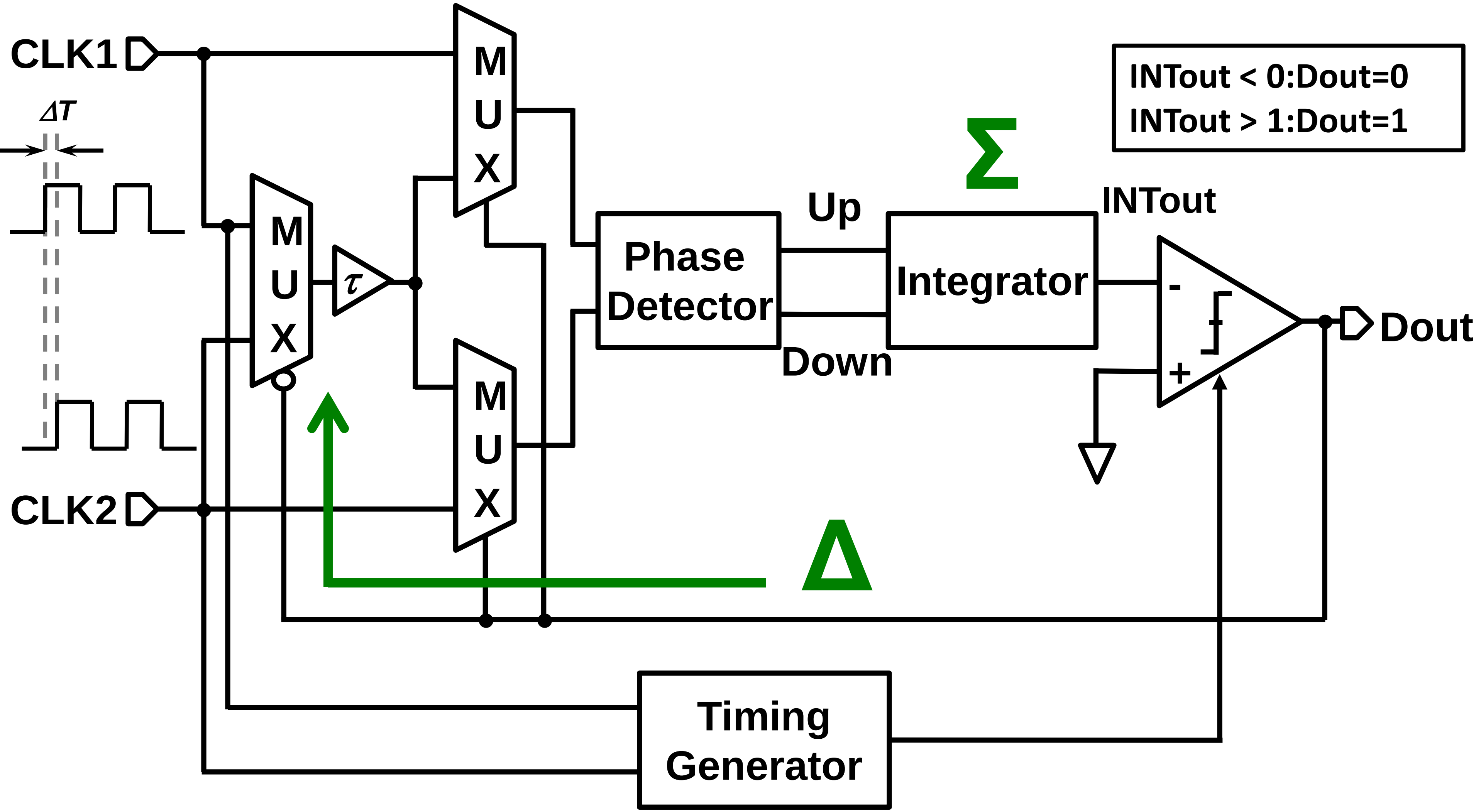
ΔT	# of 1's
short	few
long	many



Dout



ΔΣTDC Configuration



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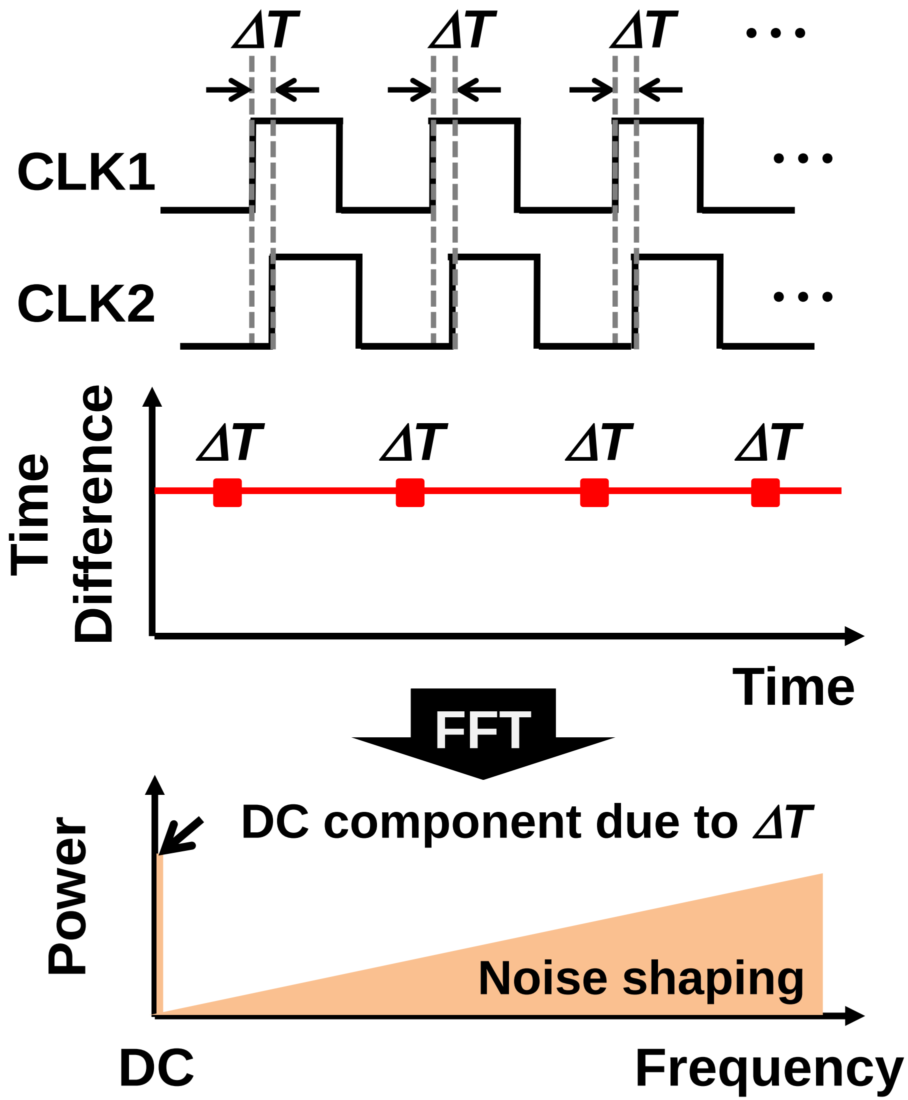
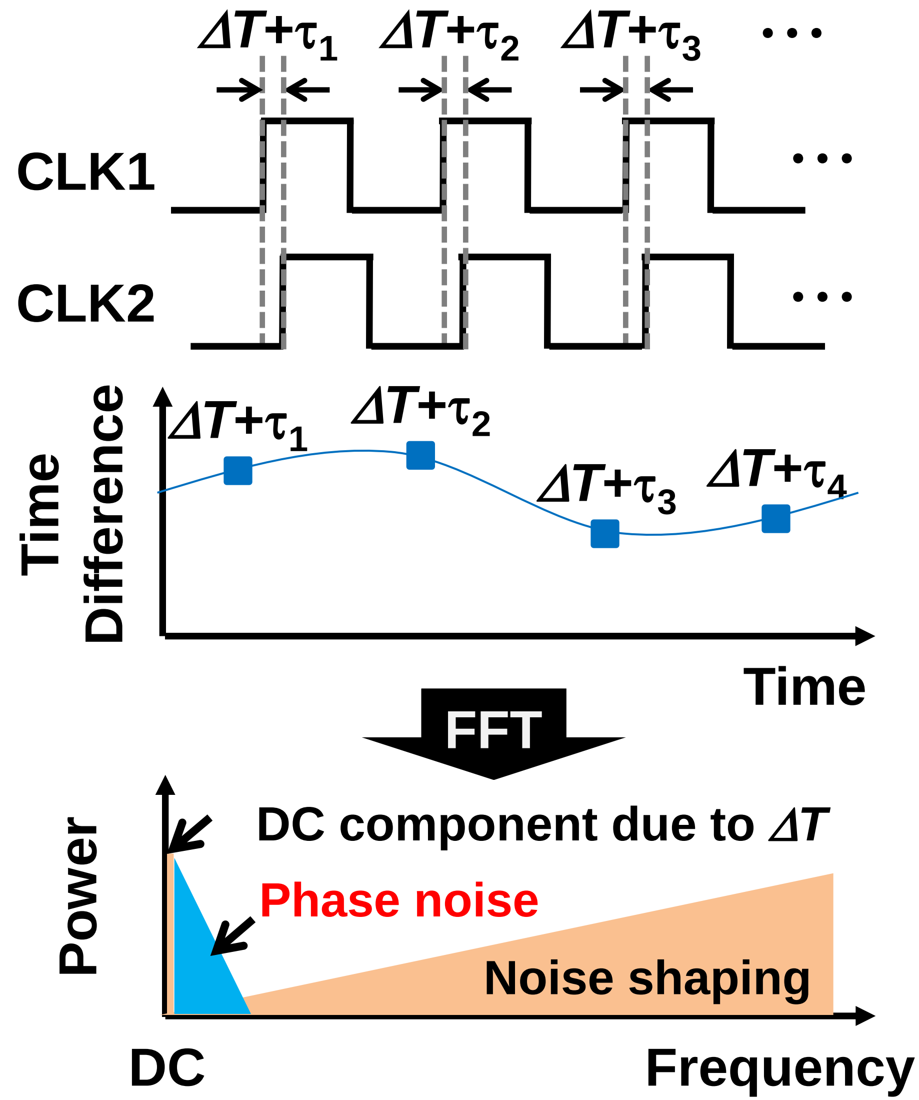
Principle of Phase Noise Measurement

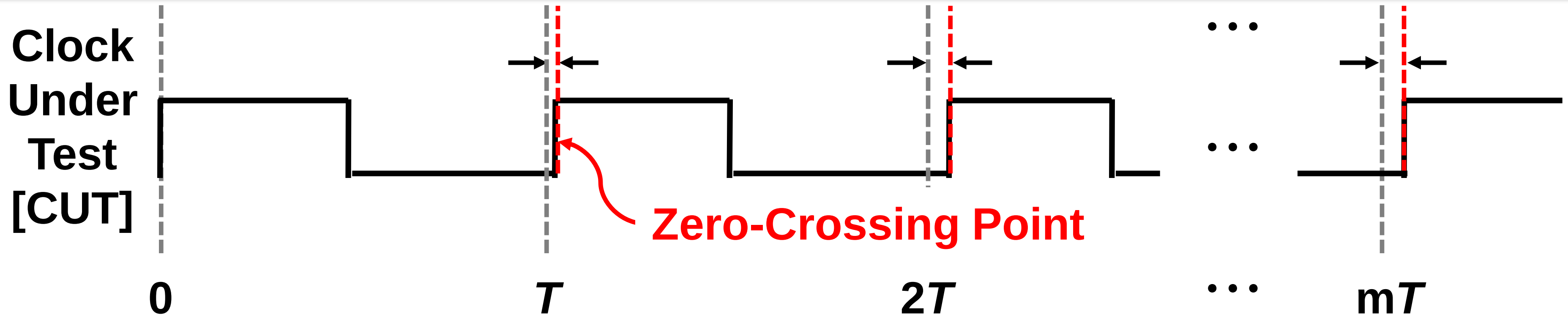
CLK1 without phase noise



CLK1 with phase noise



Mathematical Analysis



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

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

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

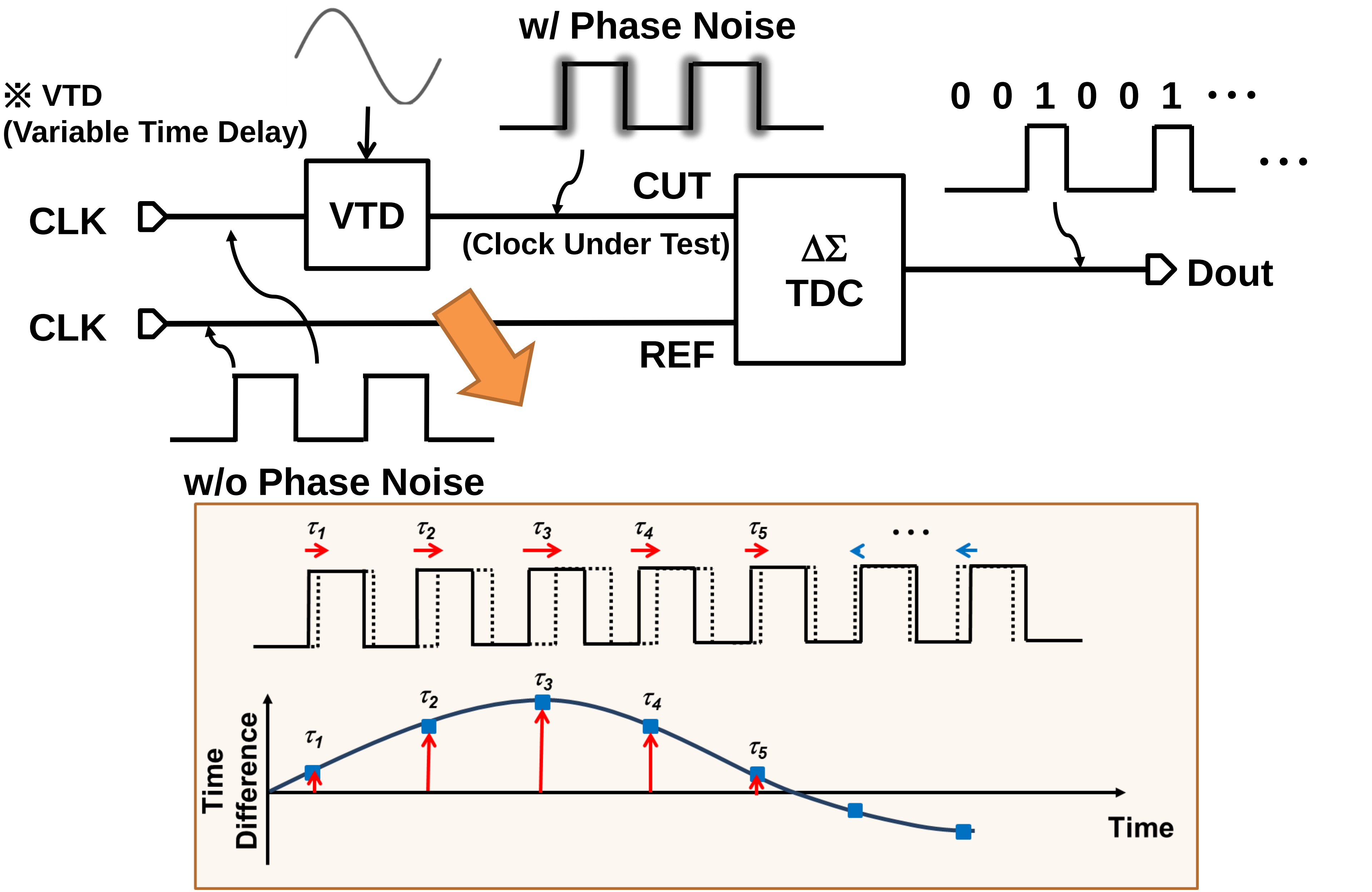
In case of sinusoidal phase fluctuation

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

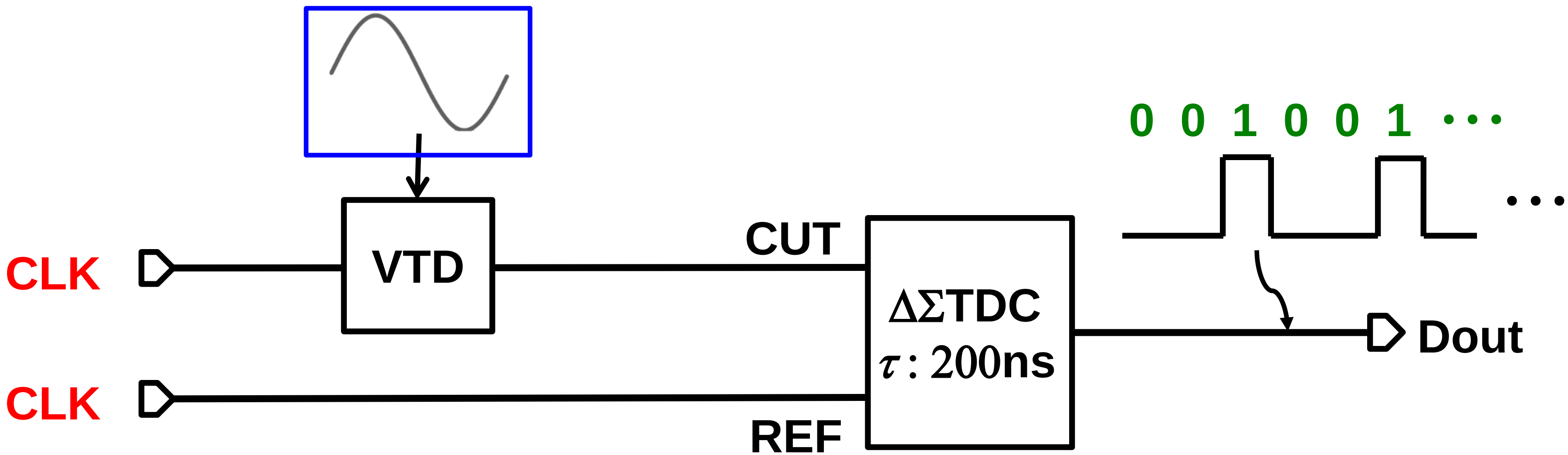
$$\phi(mT) = -2\pi\alpha_1 \cdot \sin(\omega_1 mT)$$: phase noise (time domain)

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

MATLAB Simulation



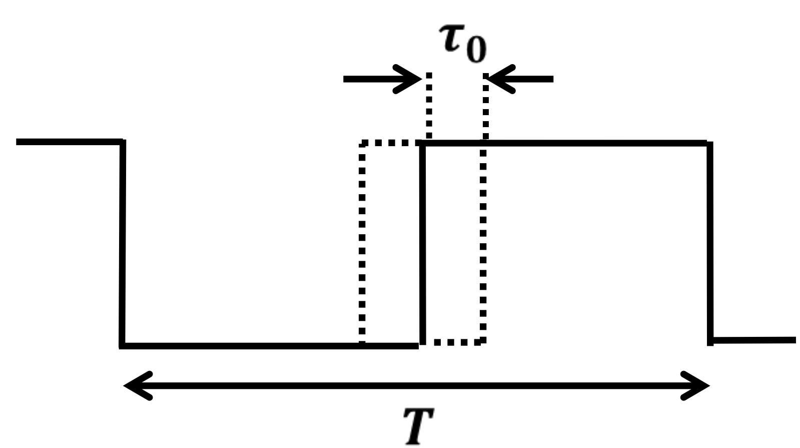
Simulation Conditions



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

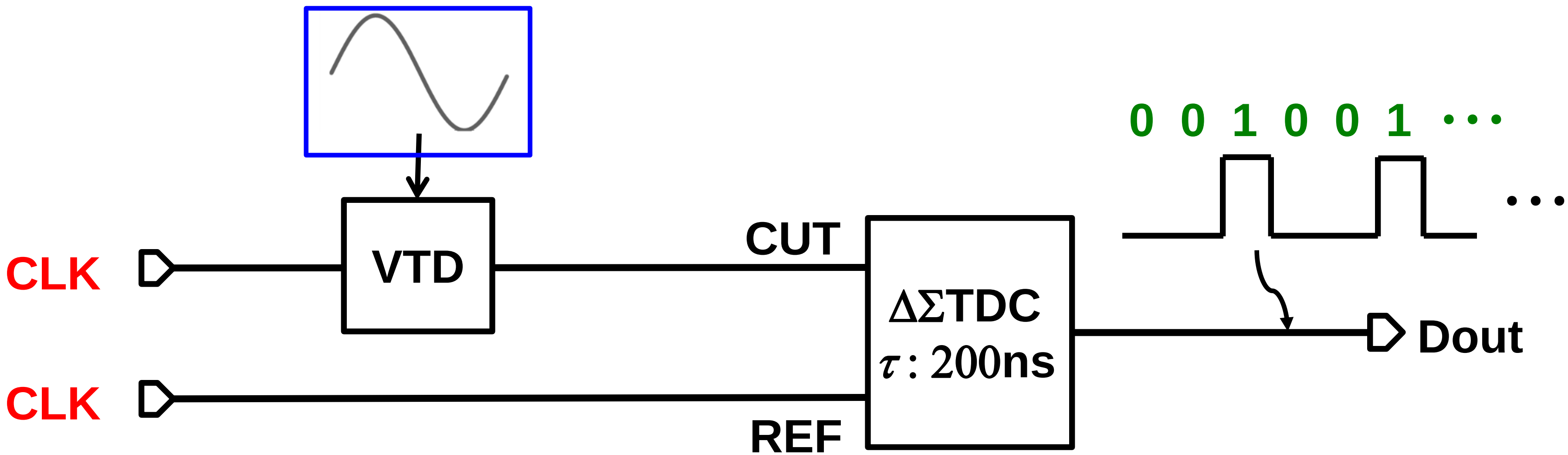
Phase variation（sinusoidal）

- **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 :**
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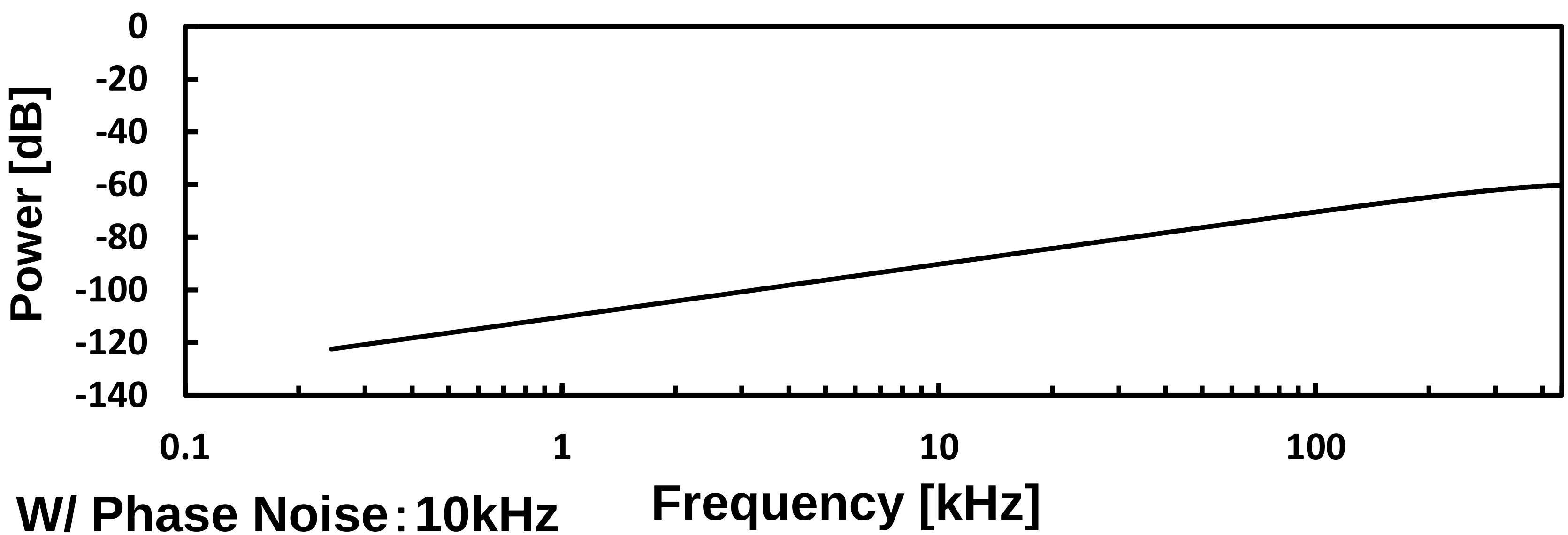
- **Number of data:**
  4096

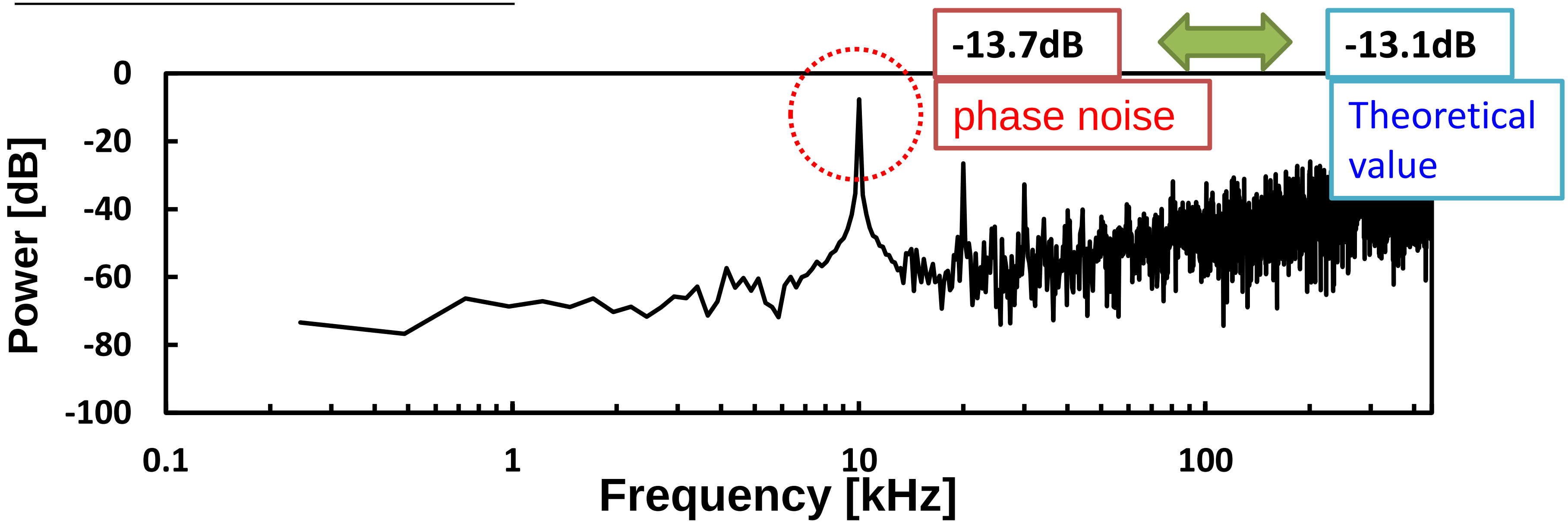
- **Single sine wave**
  ① $f_1 = 10$ kHz
  ② $f_1 = 50$ kHz
- **Multiple sine waves**
  ③ $f_1 = 10$ kHz
  $f_2 = 50$ kHz

Simulation Results ①

W/O Phase Noise

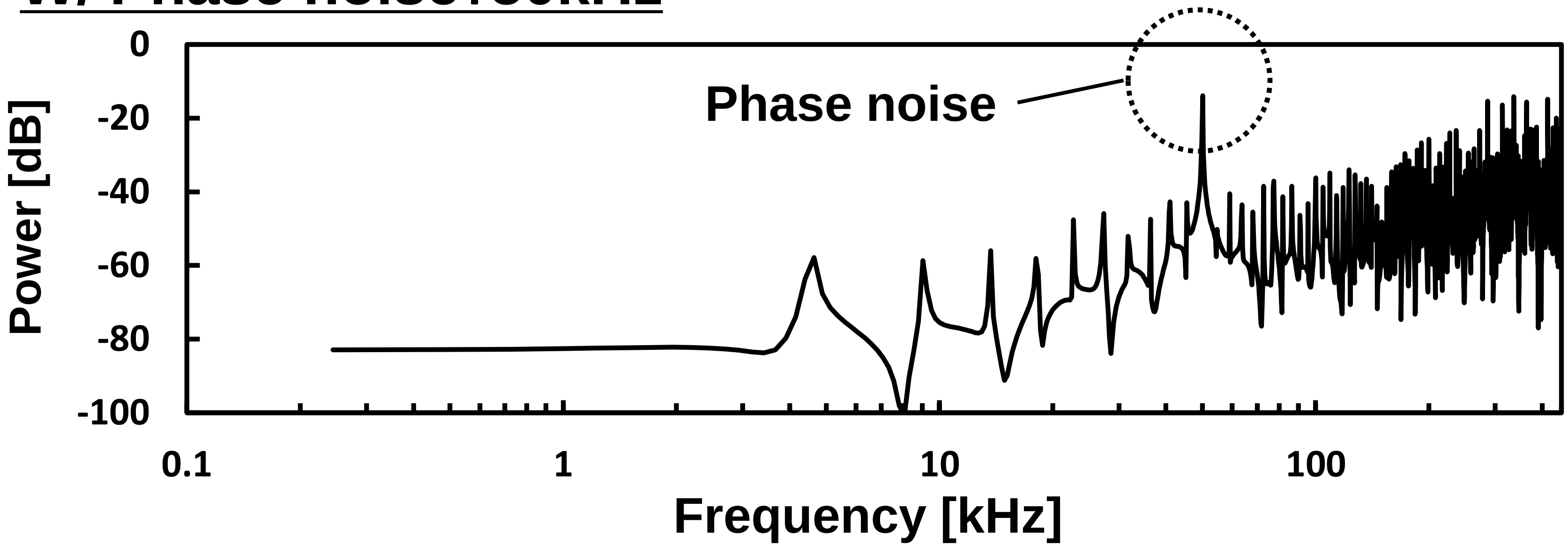


W/ Phase Noise：10kHz



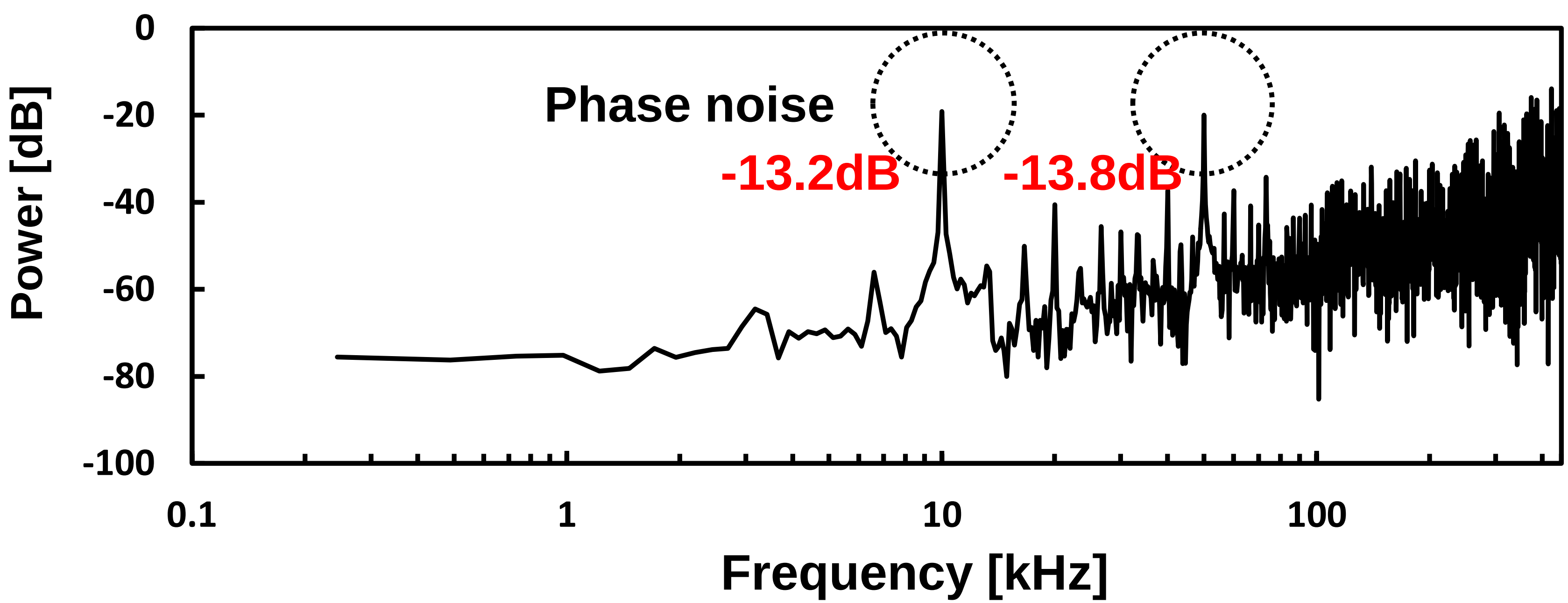
Simulation Results ②

W/ Phase noise：50kHz



Simulation Results ③

Phase noise：10kHz & 50kHz



Theoretical value

Power = -13.1[dB]

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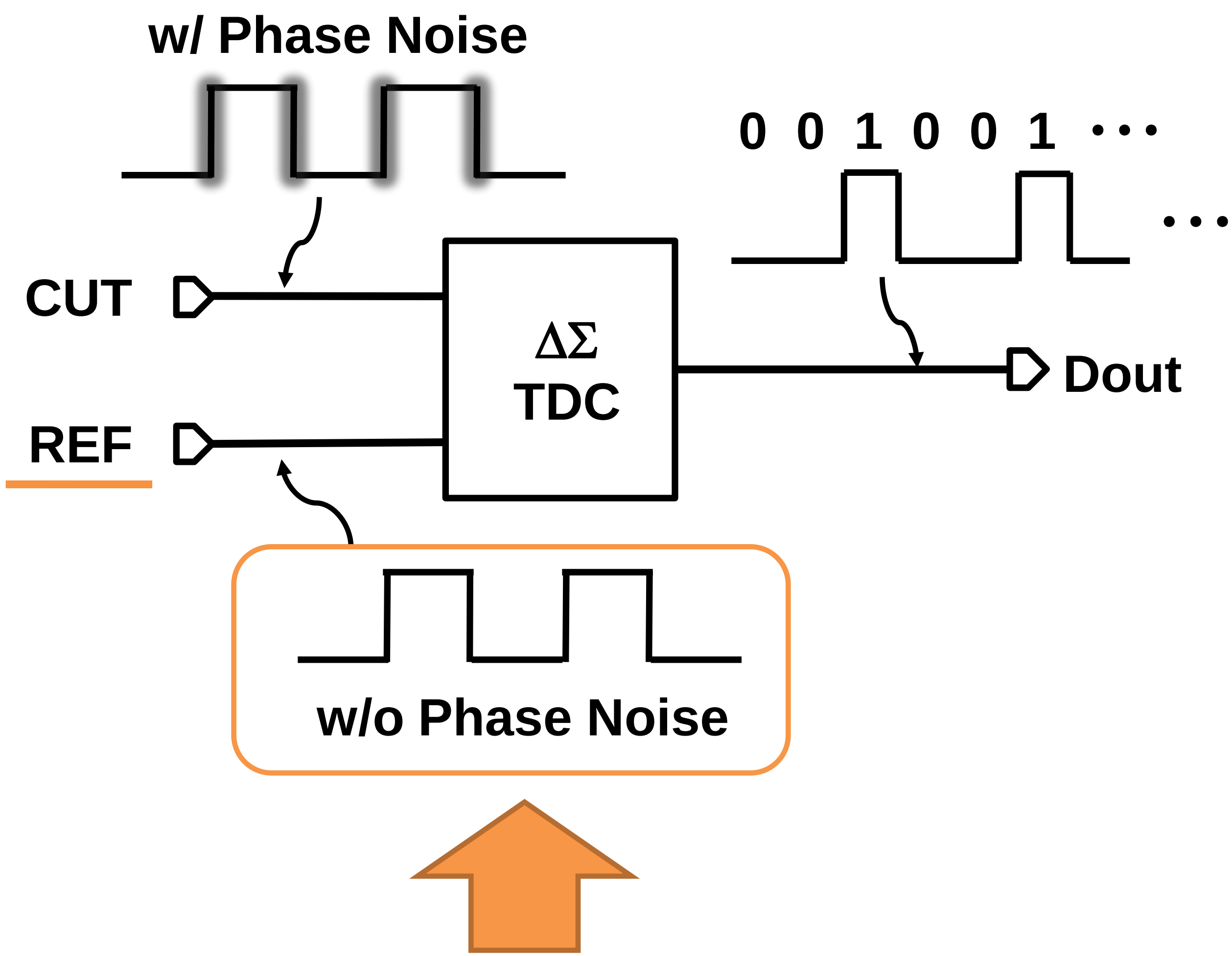
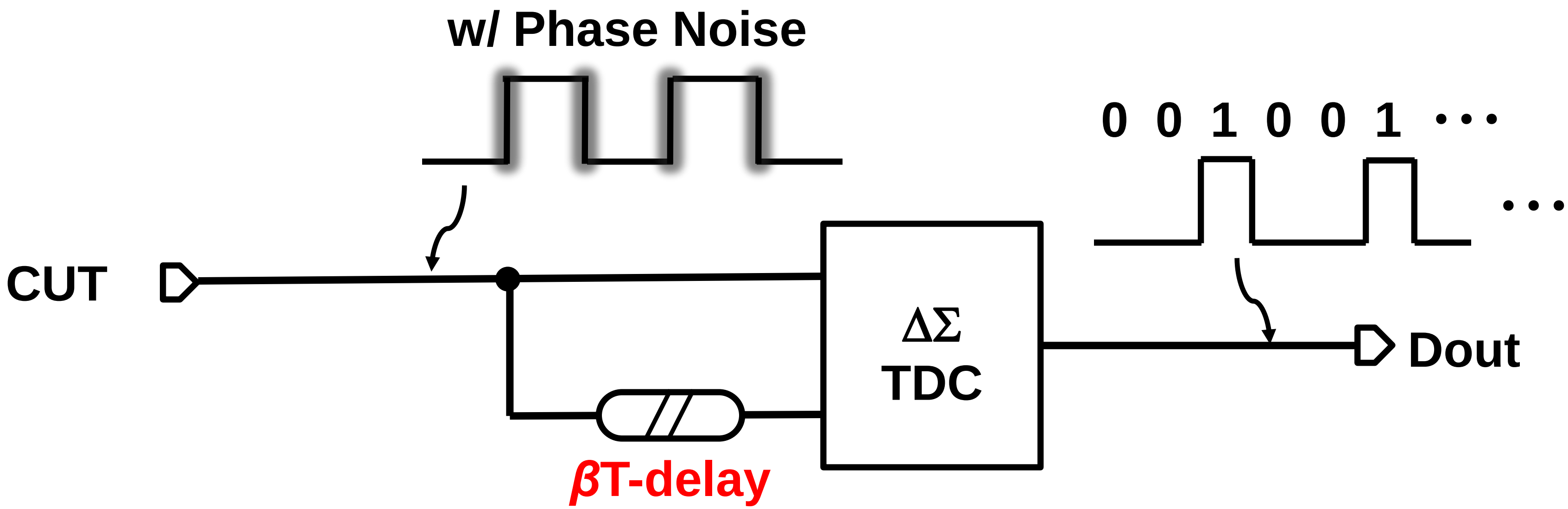
Problem of Proposed Method I



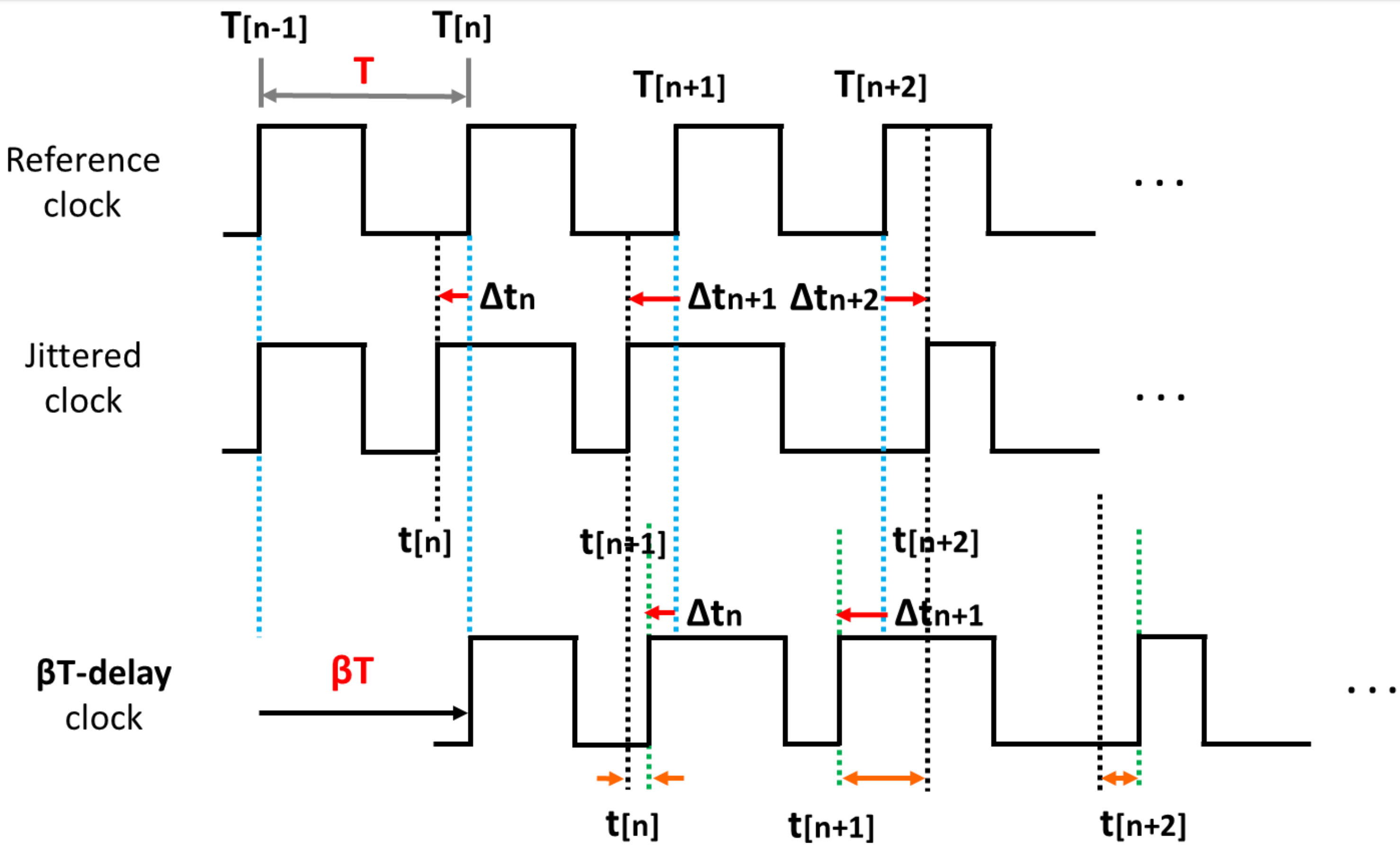
Difficult to implement

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

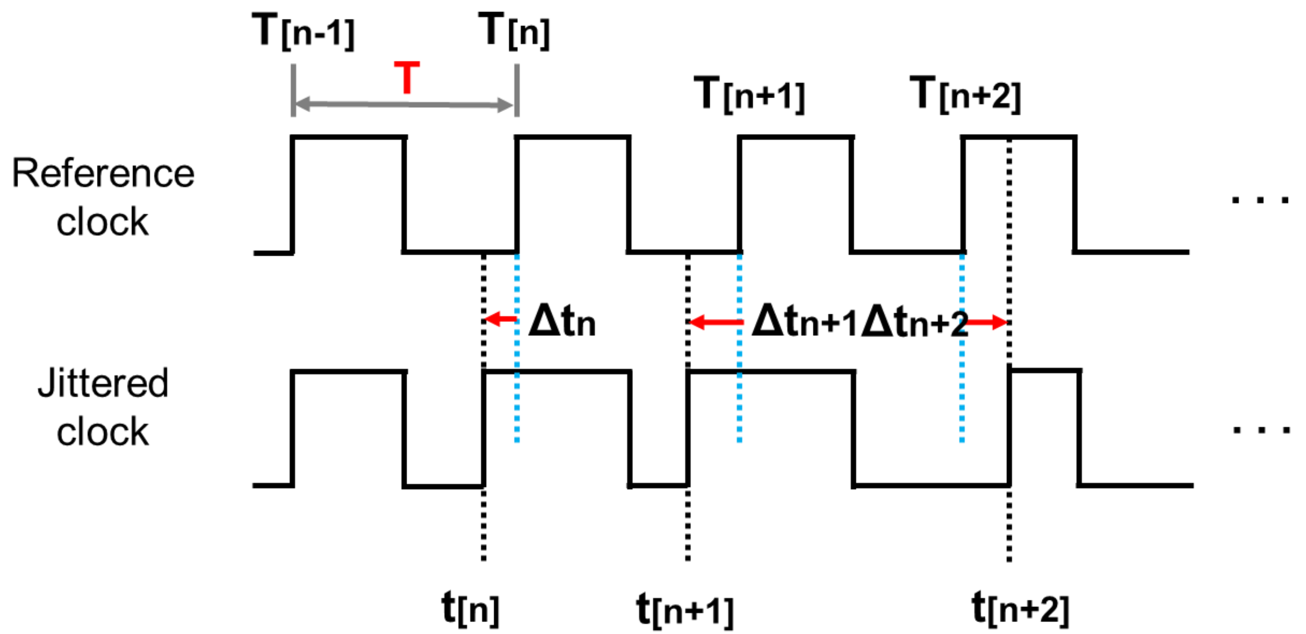
Method Ⅱ

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 $\tau(m) = T \cdot \alpha_j \cdot \sin(\omega_j m T)$ 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)

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

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

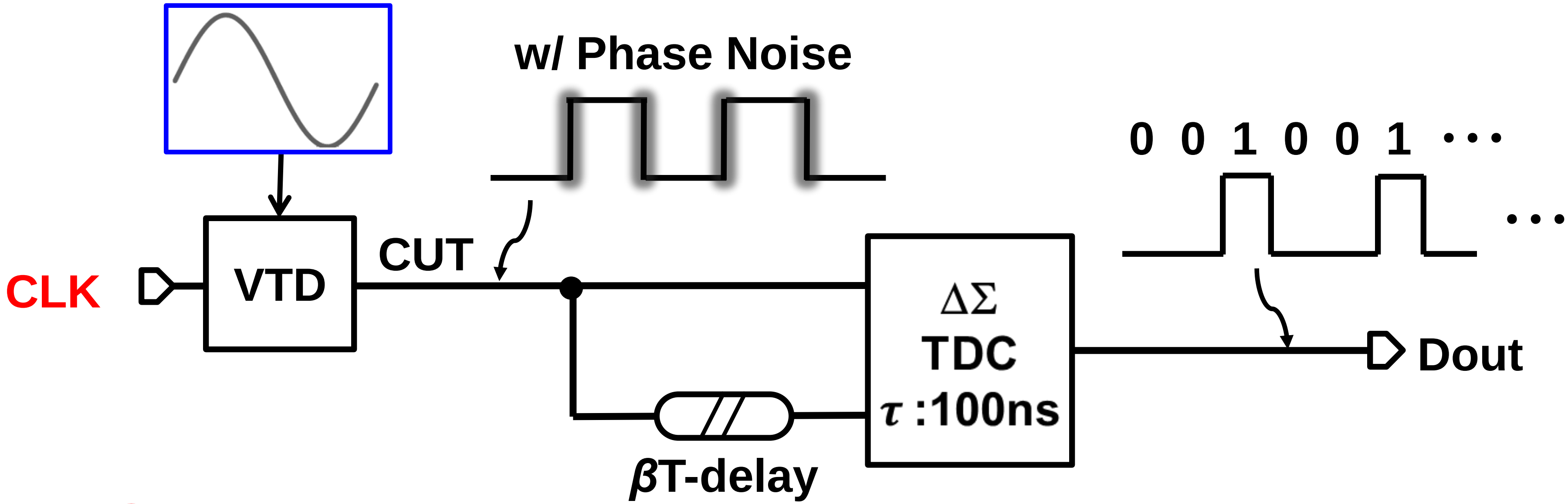
ω_1: phase noise freq. [low freq.]

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)

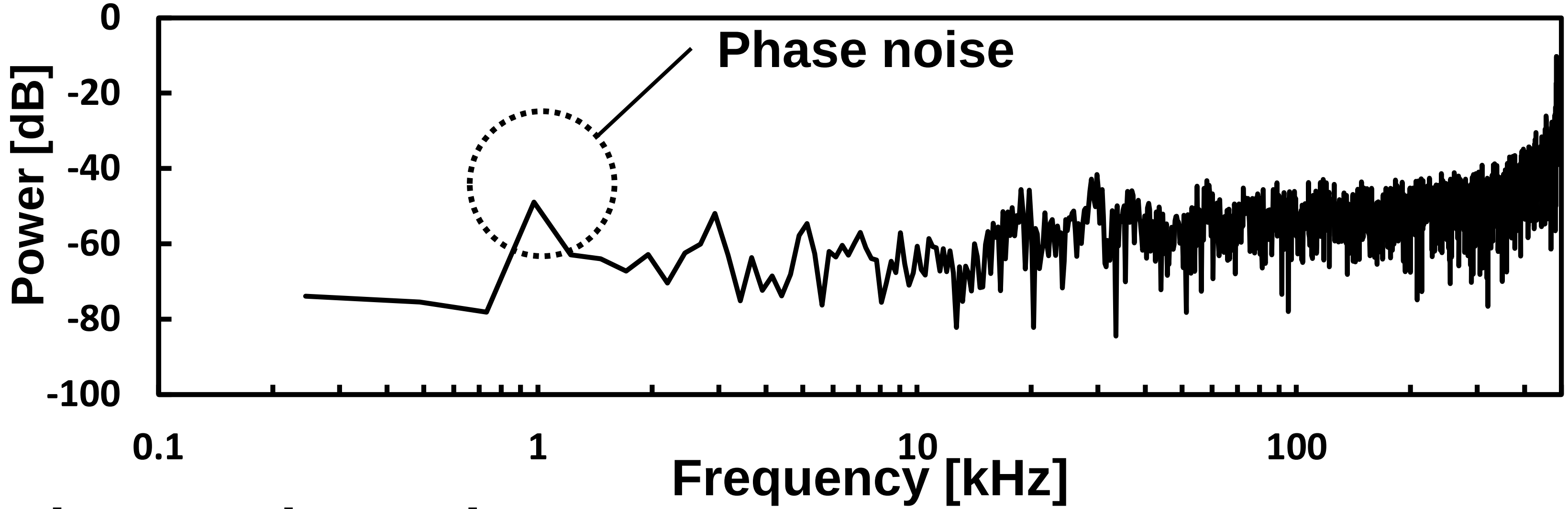
Phase variation (sinusoidal)

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

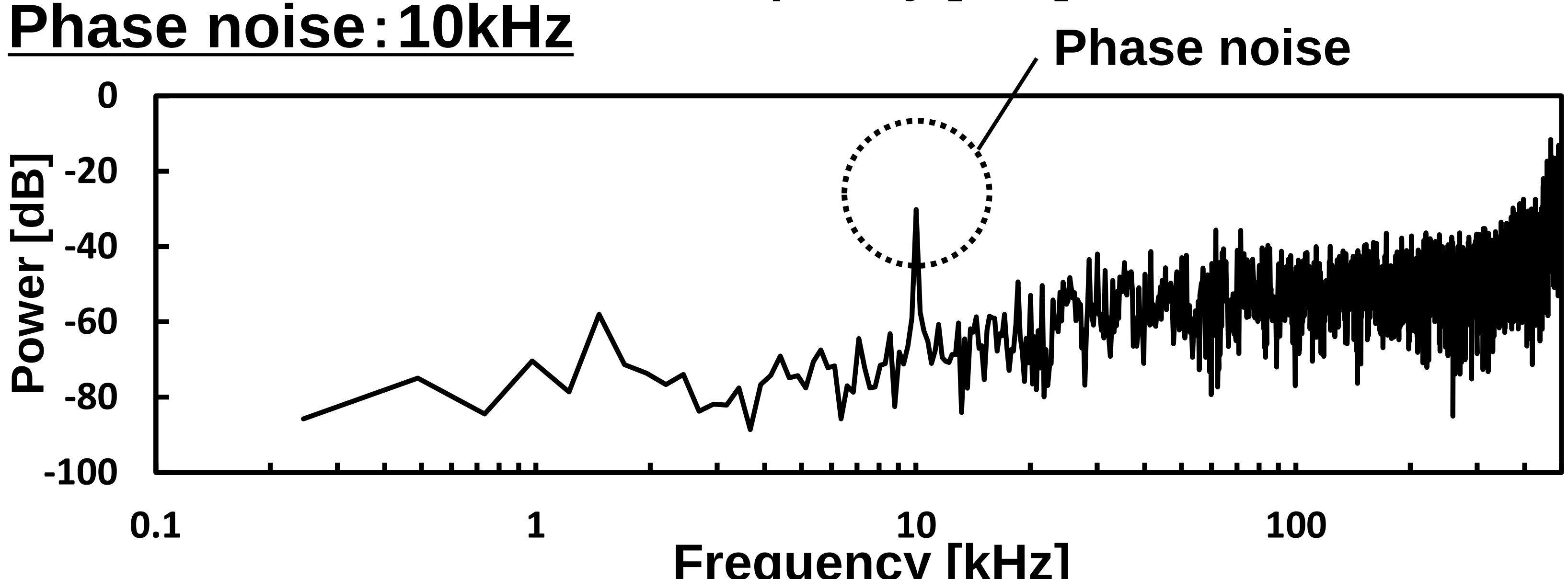
- **Single sinusoidal**
  ① $f_1 = 1$ kHz
  ② $f_1 = 10$ kHz
  ③ $f_1 = 100$ kHz
- **Multiple sinusoidal**
  ④ $f_1 = 10$ kHz
  $f_2 = 50$ kHz

Simulation Results ①&②

Phase noise：1kHz

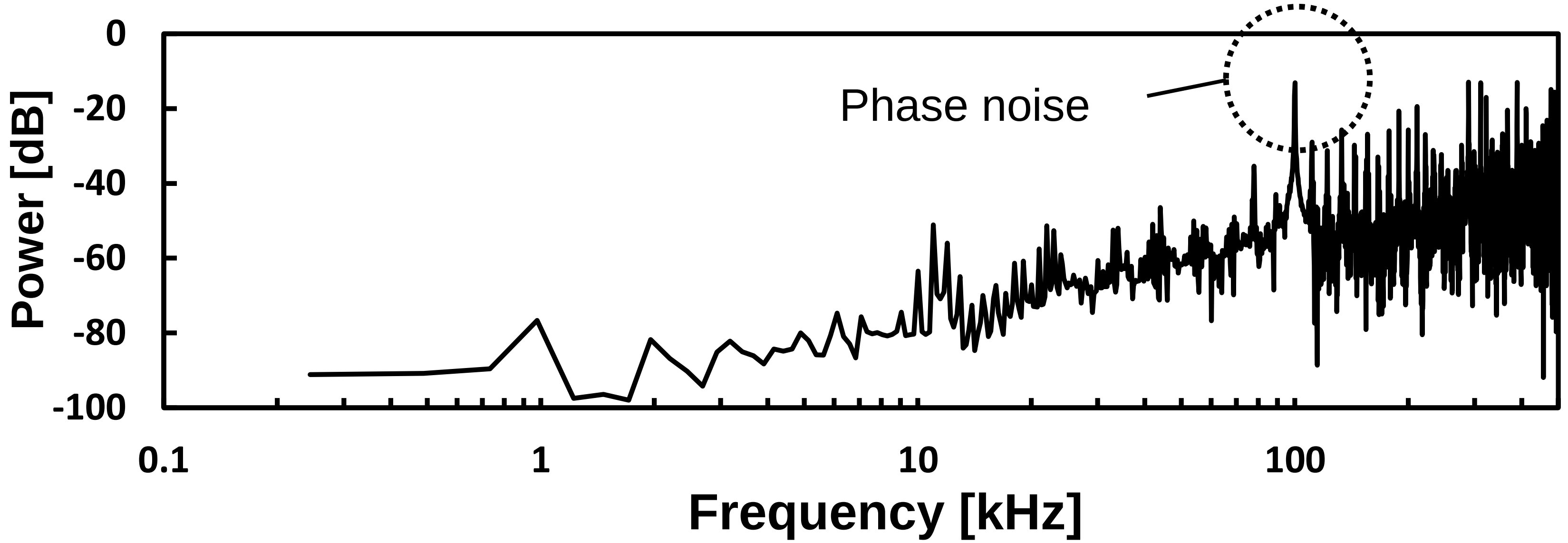


Phase noise：10kHz

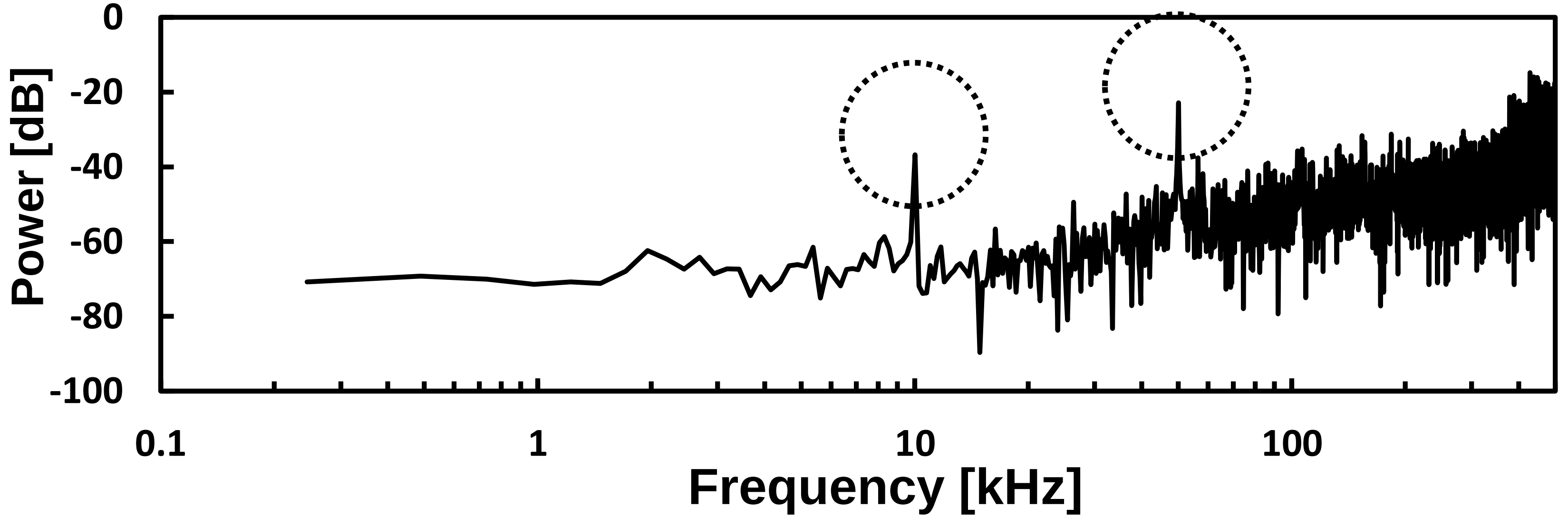


Simulation Results ③&④

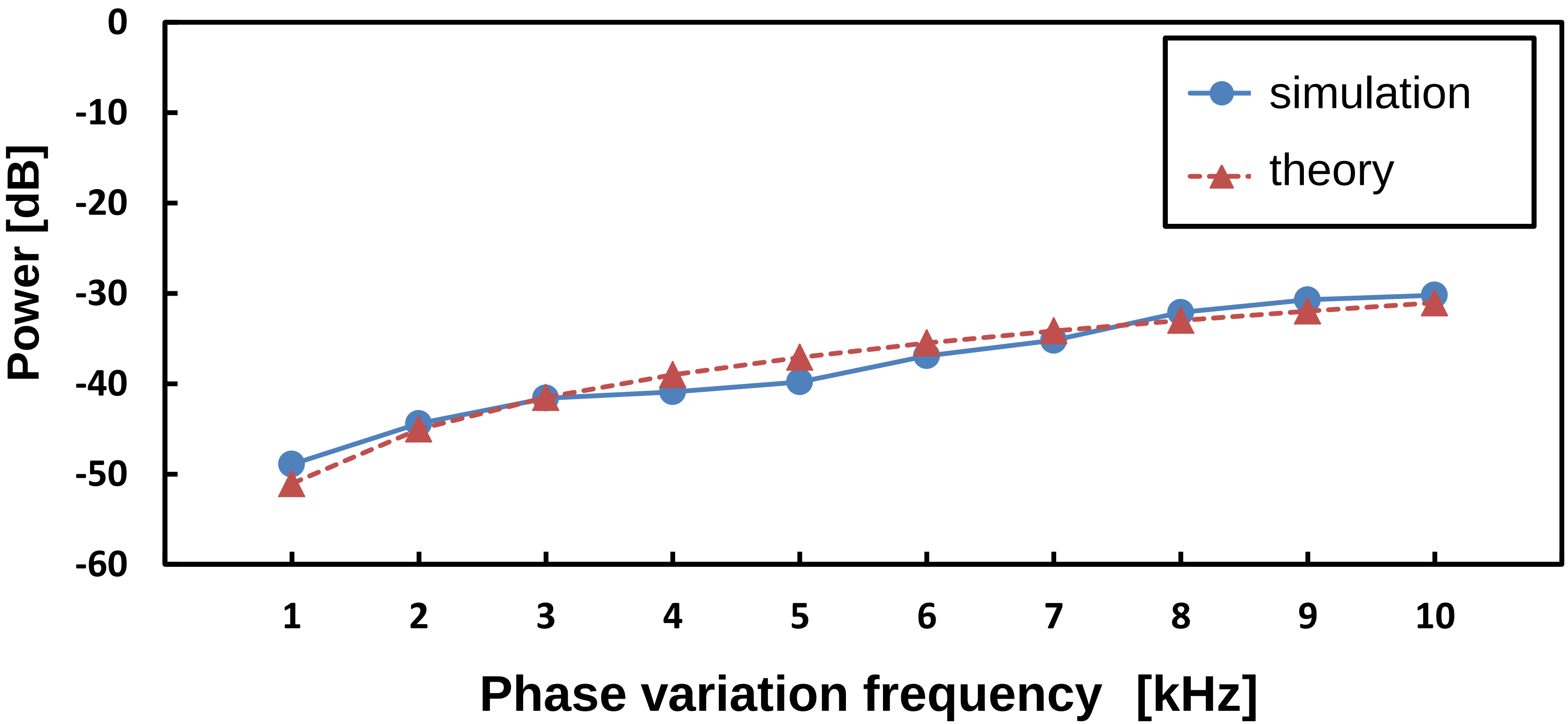
Phase noise：100kHz



Phase noise：10kHz＆50kHz



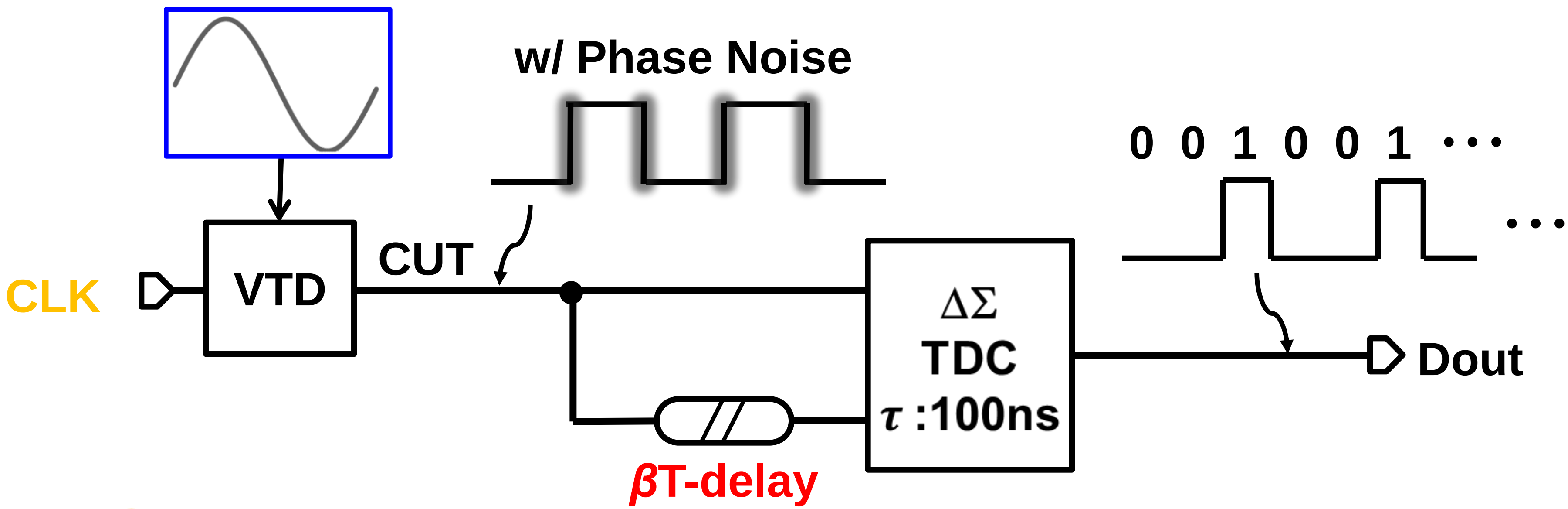
Comparison of Theory and Simulation Results



Theoretical expression

$$\boldsymbol{\Phi}'(\boldsymbol{\omega}_1) = \frac{1}{2}(2\pi\alpha_1)^2{\boldsymbol{\omega}_1}^2 T^2$$

Simulation Conditiions



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

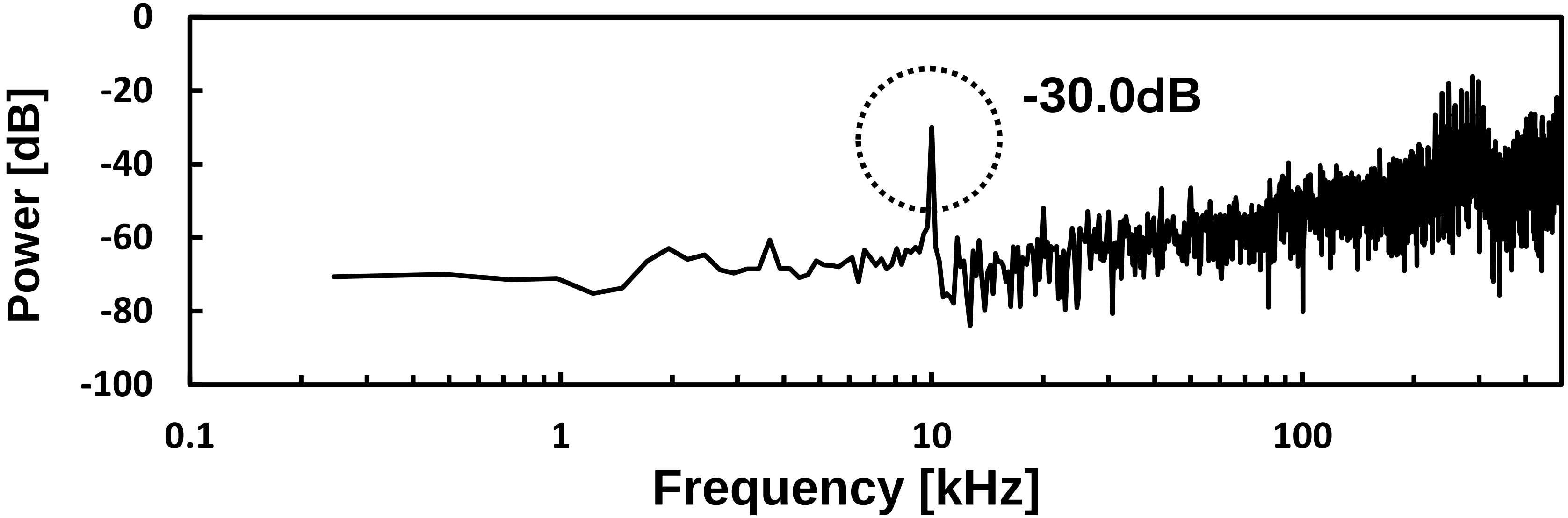
Phase variation (sinusoidal)

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

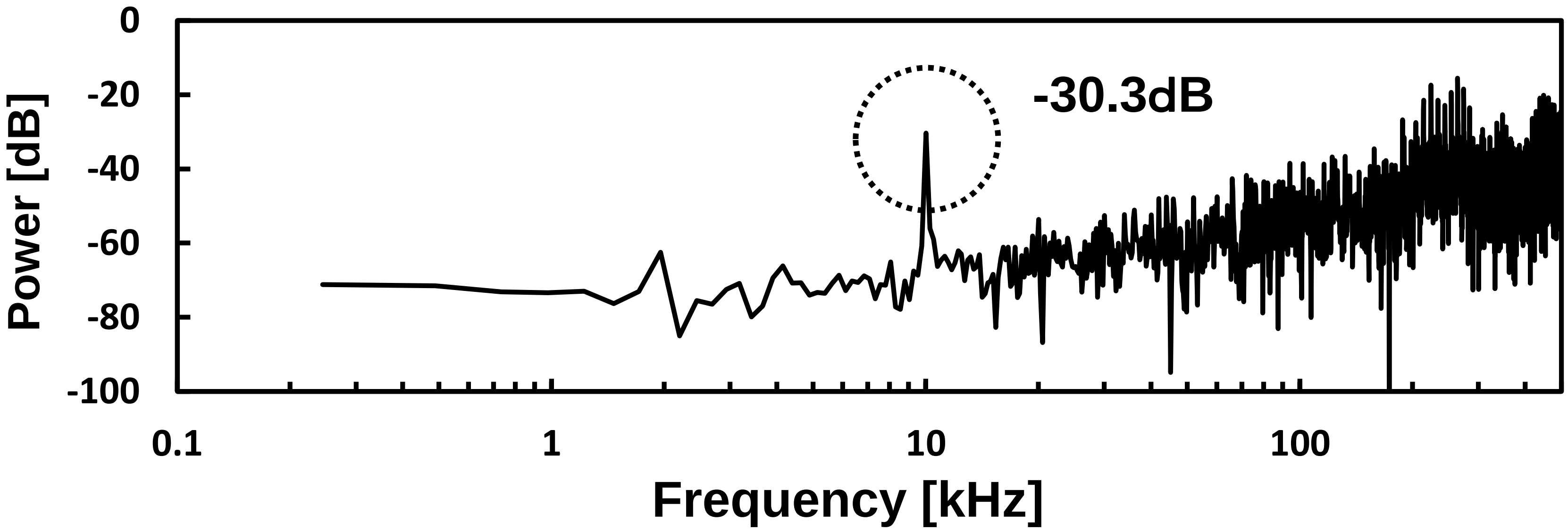
- **β value deviation by ±5% from 1.0**
  - **β=0.95**
  - **β=1.05**

Simulation Results（delay β variation）

β = 0.95（error -5%）



β = 1.05（error +5%）



Simulation Results（delay β variation）

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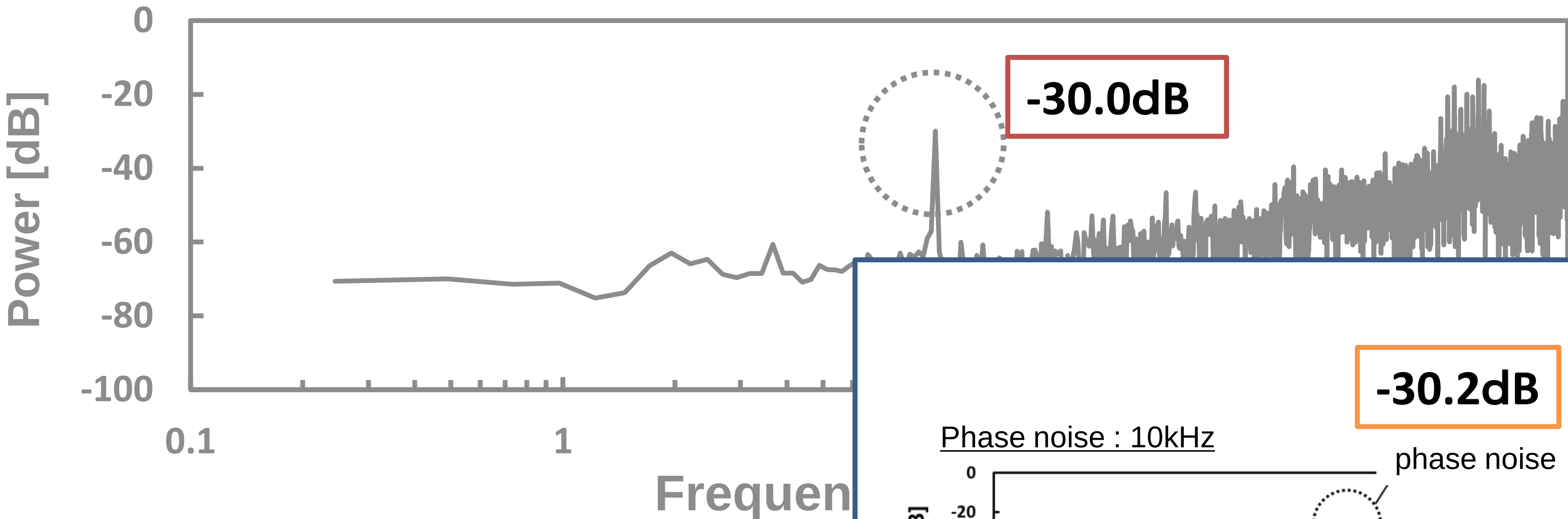

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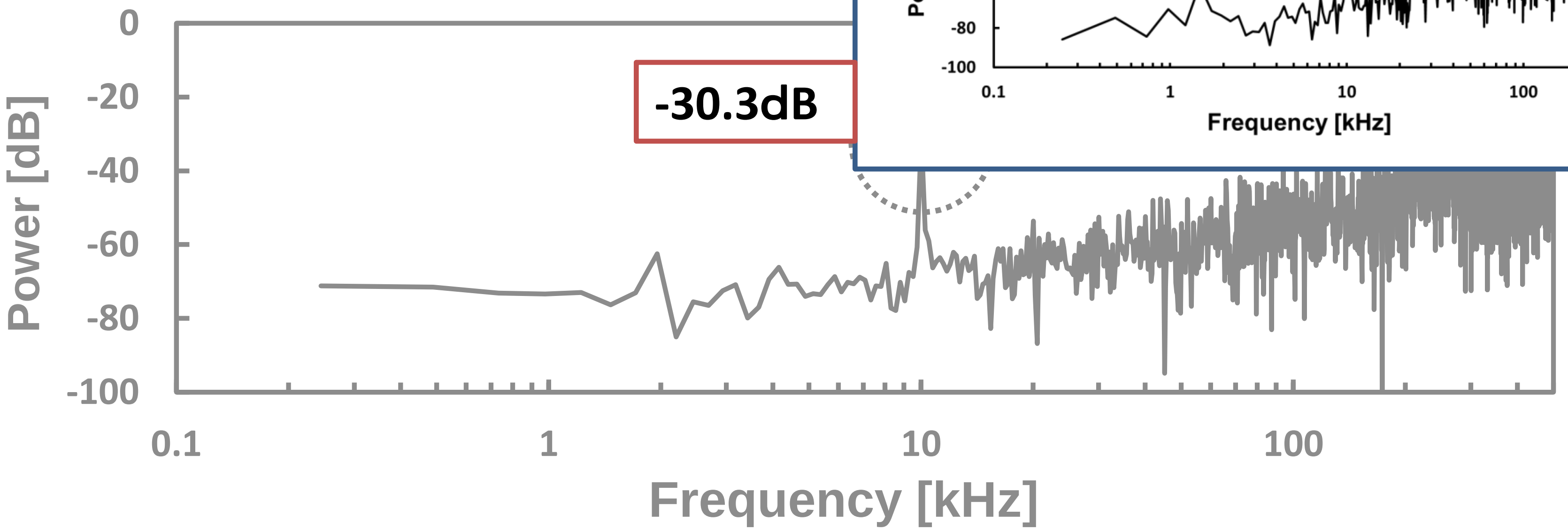

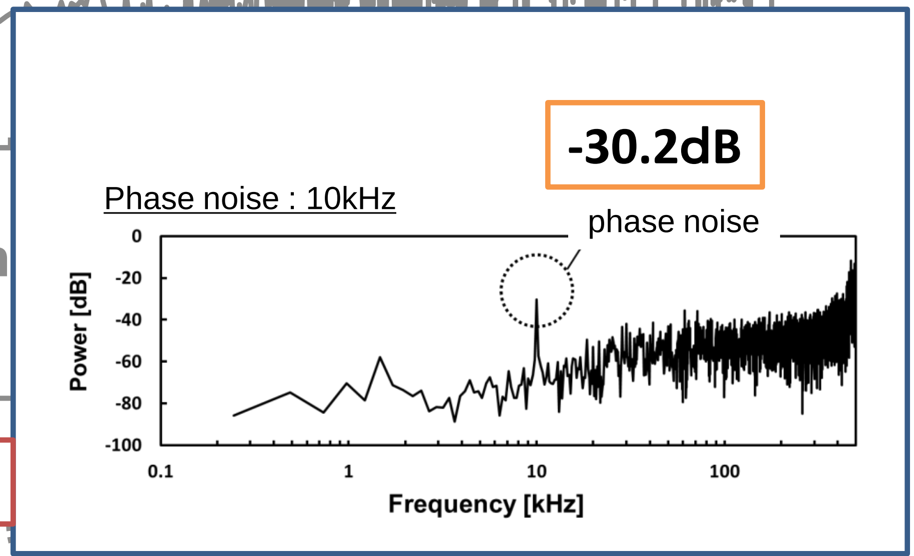

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Conclusion

■ 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

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Phase Noise Measurement Techniques
Using Delta-Sigma TDC
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