ICSICT-2018
2018 IEEE 14th International Conference on Solid-State and Integrated Circuit Technology
Oct. 31- Nov. 3, 2018
Huangdao Sheraton Hotel, Qingdao, China

Nov. 3
S56-2

Low-Distortion Signal Generation for Analog/Mixed-Signal IC Testing Using Digital ATE Output Pin and BOST

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Research Objectives

Objective

Low-Distortion Signal Generation

- For analog/mixed signal IC Testing
- High quality test signal

Approach

- Rectangular add/subtract method
- Proposed phase control method

Digital ATE ＋ Simple analog circuit & BOST

↓

No need expensive signal generator

ATE: Automatic Test Equipment

BOST: Built-Out Self-Test

Outline

- **Research Background**
- **Signal Generation Method**
- **Phase Shift Technique**
- **Circuit Configuration & Simulation**
- **Conclusion**

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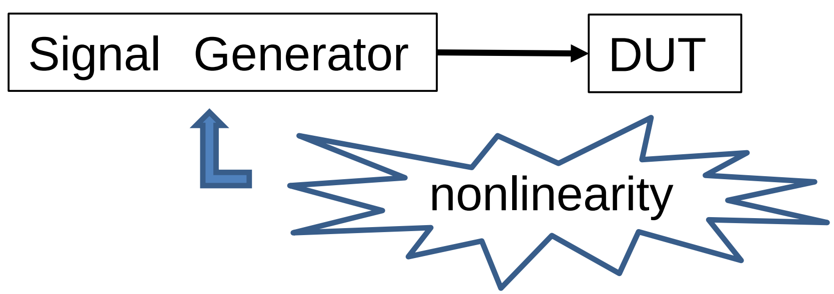
Research Background

- Testing analog ICs requires low distortion sinusoidal

Signal generator has nonlinearity

▪Harmonic distortion caused
▪Test accuracy deterioration



Objective

Low-Distortion Signal Generation at Low Cost

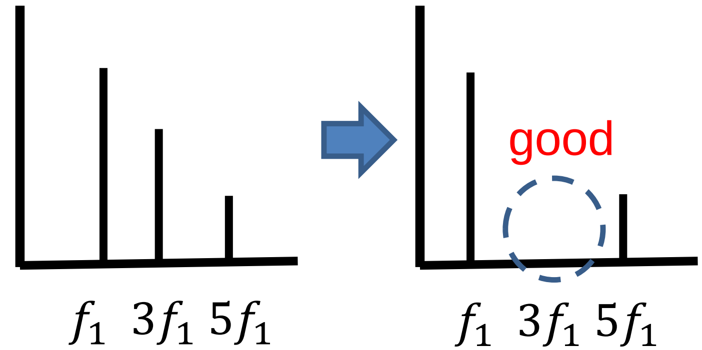
Problem of Our Previous Method

3rd harmonics suppression

Phase parameters

$$\varphi_1 = 2\pi \frac{\tau_1}{T}$$

3 rectangular add/subtract



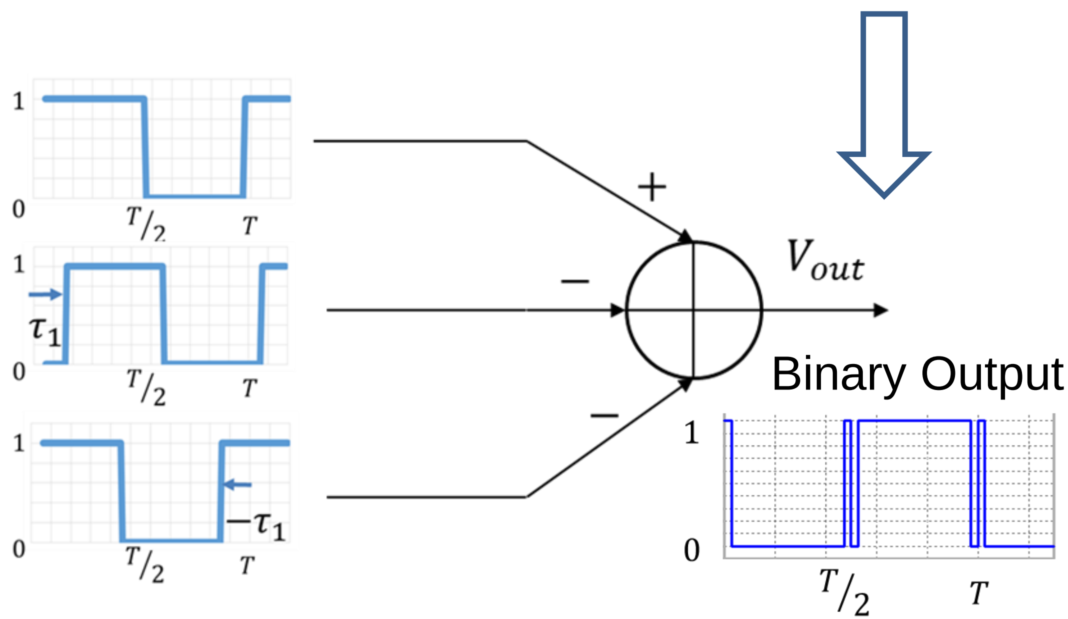
Phase shift parameter

$$\tau_1 = \pm \frac{T}{6k}$$

Phase shift parameter is simple

High resolution is not needed

Digital phase shift



[1] M. Kawabata, et. al., "Low-Distortion Signal Generation for Analog/Mixed-Signal Circuit Testing Using Digital ATE", International Test Conference in Asia (Sept. 2017).

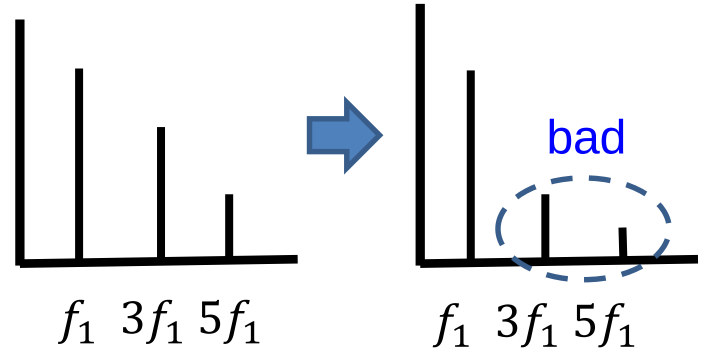
Problem of Conventional Method

3rd & 5th harmonics suppression

Phase parameters

$$\varphi_1 = 2\pi\frac{\tau_1}{T}, \varphi_2 = 2\pi\frac{\tau_2}{T}$$

5 rectangular add/subtract



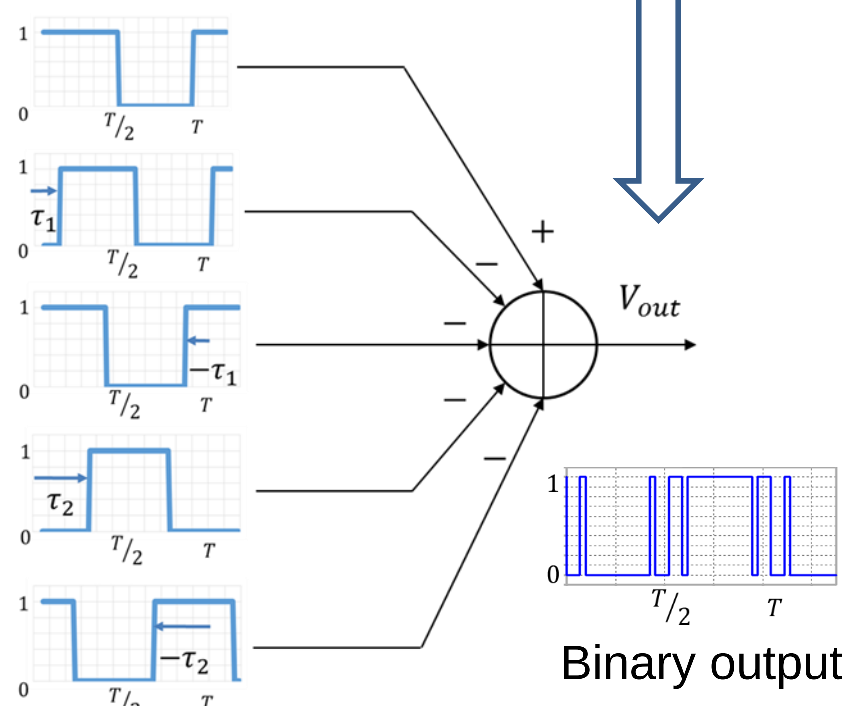
Phase shift parameter

$$\tau_1 = \frac{T}{2k\pi}\left(\cos^{-1}\left(\frac{1}{2}\left\{1 - 2\cos\left(\frac{2k\pi}{T}\tau_2\right)\right\}\right)\right)$$

Phase shift parameter is complex

High resolution is needed

Analog phase shift



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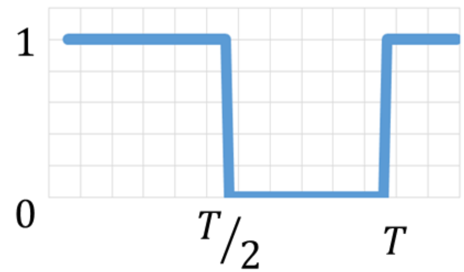
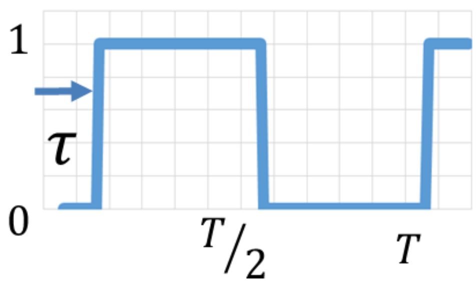
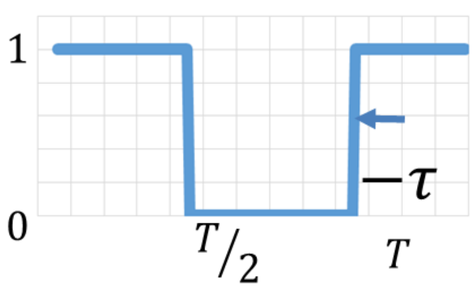
Fourier Series Expansion

Duty 50% rectangular wave

$$f(\mathrm{t}) = \begin{cases} 1 \cdots \mathrm{nT} \le t \le (2n+1)T/2 \\ 0 \cdots (2n+1)T/2 < t \le (n+1)T \end{cases}$$
$$(n = 0, 1, 2, \cdots)$$







Fourier Series Expansion

$$f(\mathrm{t}) = \frac{1}{2} + \sum_{m=1}^{\infty} \frac{2}{k\pi} \sin\left(\frac{2\pi}{T} kt\right)$$
$$(\mathrm{k} = 2\mathrm{m} - 1,\ \mathrm{m} = 1,\ 2,\ \ldots)$$

$$\mathrm{f}(\mathrm{t} - \tau) = \frac{1}{2} + \sum_{m=1}^{\infty} \frac{2}{k\pi} \sin\left\{\frac{2\pi}{T} k(t - \tau)\right\}$$

$$\mathrm{f}(\mathrm{t} + \tau) = \frac{1}{2} + \sum_{m=1}^{\infty} \frac{2}{k\pi} \sin\left\{\frac{2\pi}{T} k(t + \tau)\right\}$$

Single Harmonic Suppression Method

- Three rectangular waveforms add/subtract

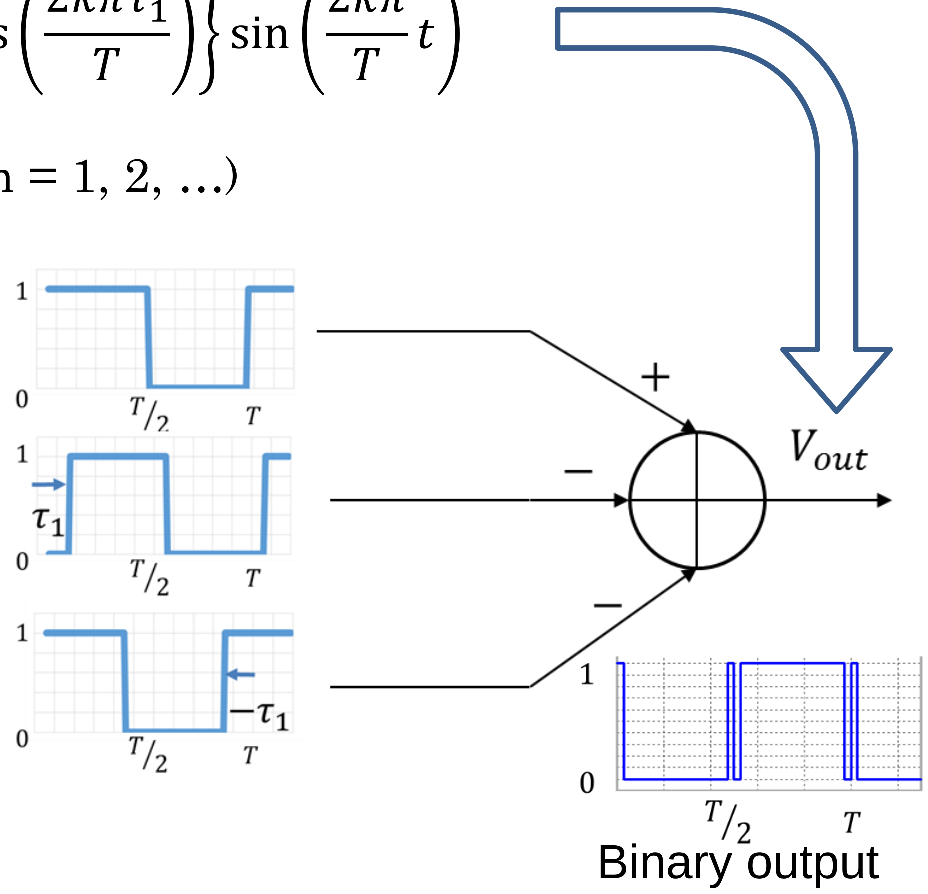
$$V_{out} = f(\mathrm{t}) - \{f(t-\tau_1) + f(t+\tau_1)\}$$
$$= -\frac{1}{2} + \sum_{m=1}^{\infty} \frac{2}{k\pi}\left\{1 - 2\cos\left(\frac{2k\pi\tau_1}{T}\right)\right\}\sin\left(\frac{2k\pi}{T}t\right)$$

$$(\mathrm{k} = 2\mathrm{m} - 1,\ \mathrm{m} = 1, 2, \ldots)$$

- K-th HD suppression parameter

$$\frac{2}{k\pi}\left\{1 - 2\cos\left(\frac{2k\pi\tau_1}{T}\right)\right\}\sin\left(\frac{2k\pi}{T}t\right) = 0$$

$$\tau_1 = \pm\frac{T}{6k}$$



Multiple Harmonics Suppression Method

- Five rectangular waveforms add/subtract

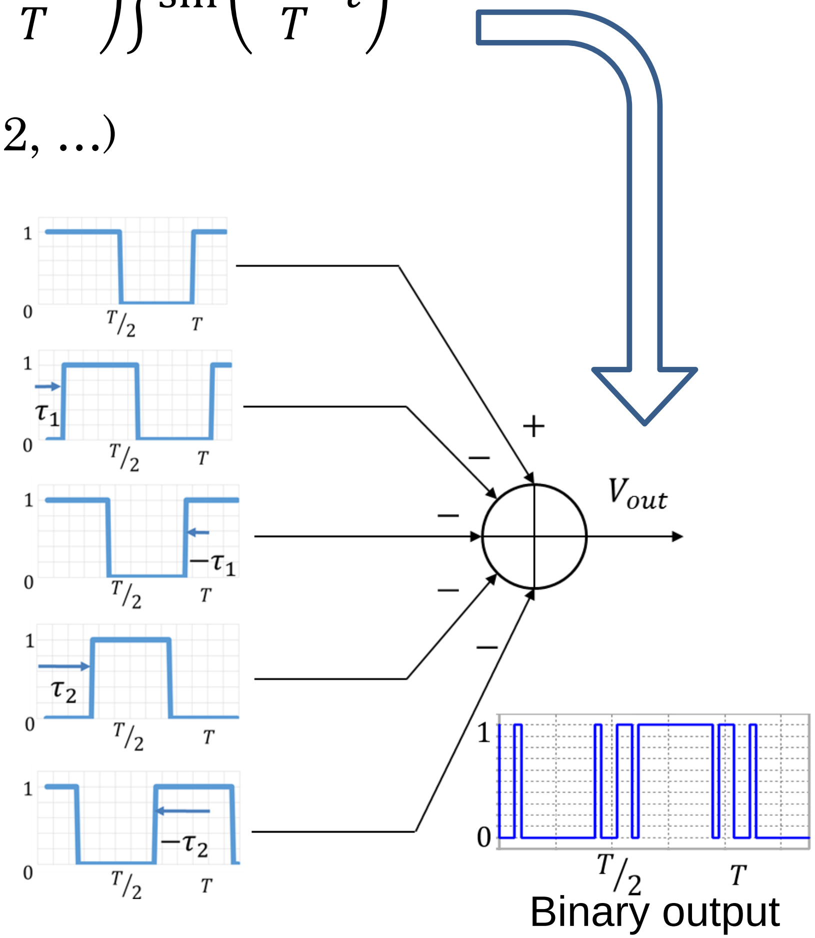
$$V_{out} = f(\mathrm{t}) - \{f(t-\tau_1) + f(t+\tau_1)\} - \{f(t-\tau_2) + f(t+\tau_2)\}$$
$$= -\frac{3}{2} + \sum_{m=1}^{\infty} \frac{2}{k\pi}\left\{1 - 2\cos\left(\frac{2k\pi\tau_1}{T}\right) - 2\cos\left(\frac{2k\pi\tau_2}{T}\right)\right\}\sin\left(\frac{2k\pi}{T}t\right)$$

$$(\mathrm{k} = 2\mathrm{m} - 1,\ \mathrm{m} = 1, 2, \ldots)$$

- K-th HD suppression parameter

$$\frac{2}{k\pi}\left\{1 - 2\cos\left(\frac{2k\pi\tau_1}{T}\right) - 2\cos\left(\frac{2k\pi\tau_2}{T}\right)\right\}\sin\left(\frac{2k\pi}{T}t\right) = 0$$

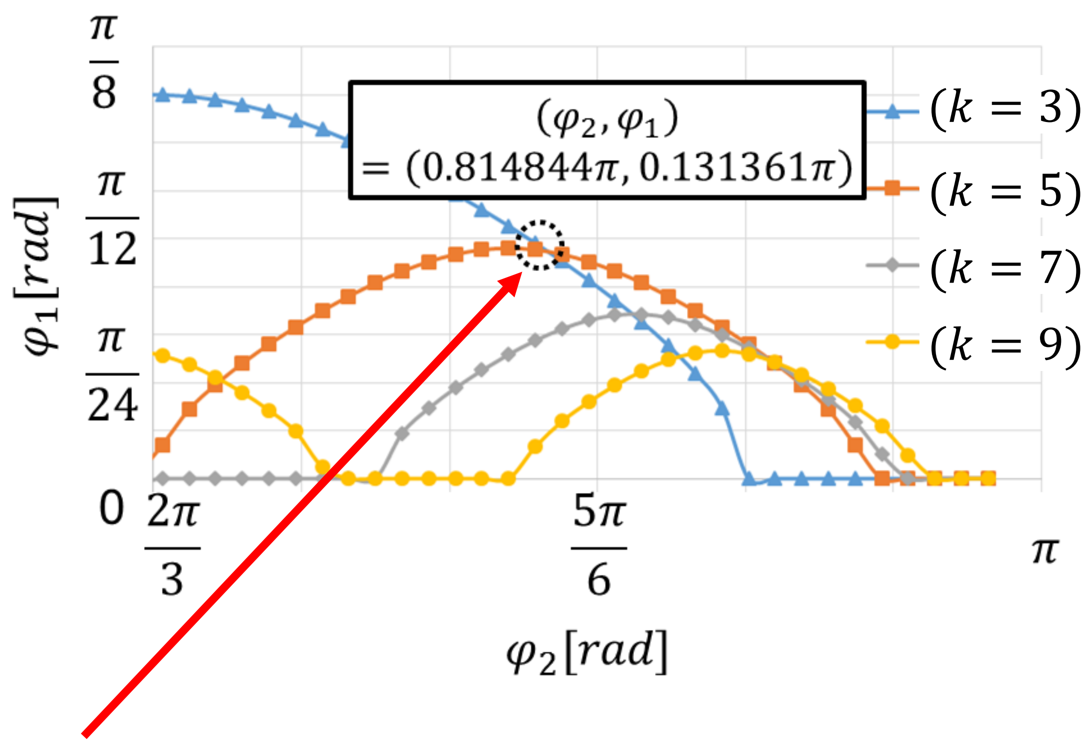
$$\tau_1 = \frac{T}{2k\pi}\left(\cos^{-1}\left(\frac{1}{2}\left\{1 - 2\cos\left(\frac{2k\pi}{T}\tau_2\right)\right\}\right)\right)$$



Multiple Harmonics Suppression Parameter

$$\tau_1 = \frac{T}{2k\pi}\left(\cos^{-1}\left(\frac{1}{2}\left\{1 - 2\cos\left(\frac{2k\pi}{T}\tau_2\right)\right\}\right)\right)$$

$$\varphi = 2\pi\frac{\tau}{T}[rad]$$



Cross point ➡ multi harmonics suppression parameter

➡ High quality needed

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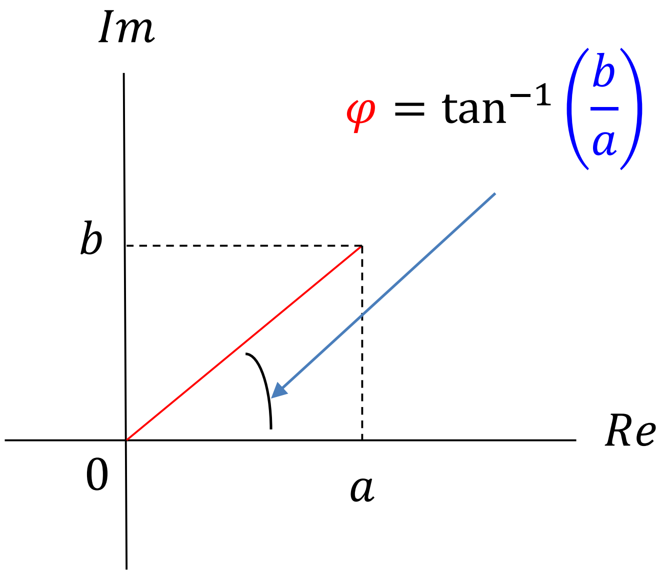
Principle of Analog Phase Shift Technique

Formula of trigonometric function

$$a\sin(\omega t) + b\cos(\omega t) = \sqrt{a^2 + b^2}\sin(\omega t + \varphi)$$

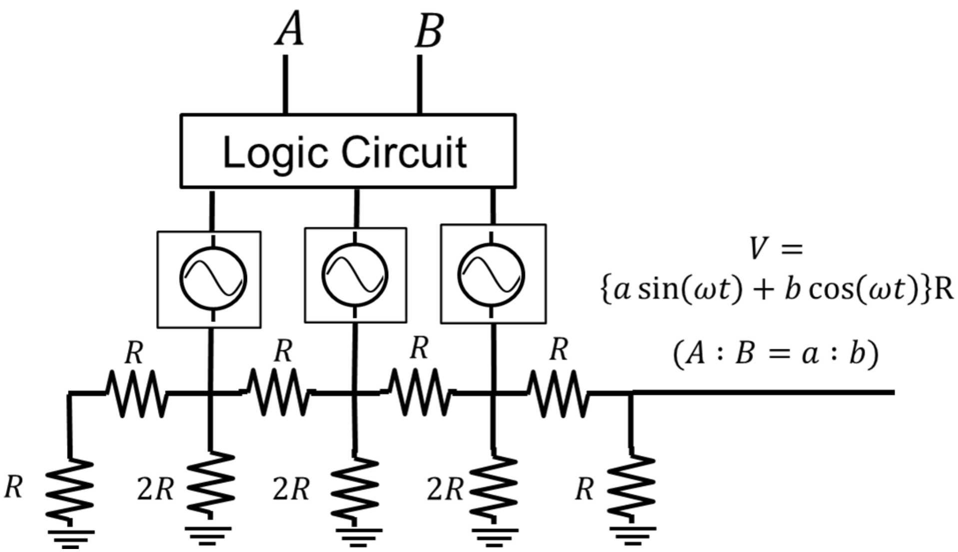
$$\varphi = \tan^{-1}\left(\frac{b}{a}\right)$$

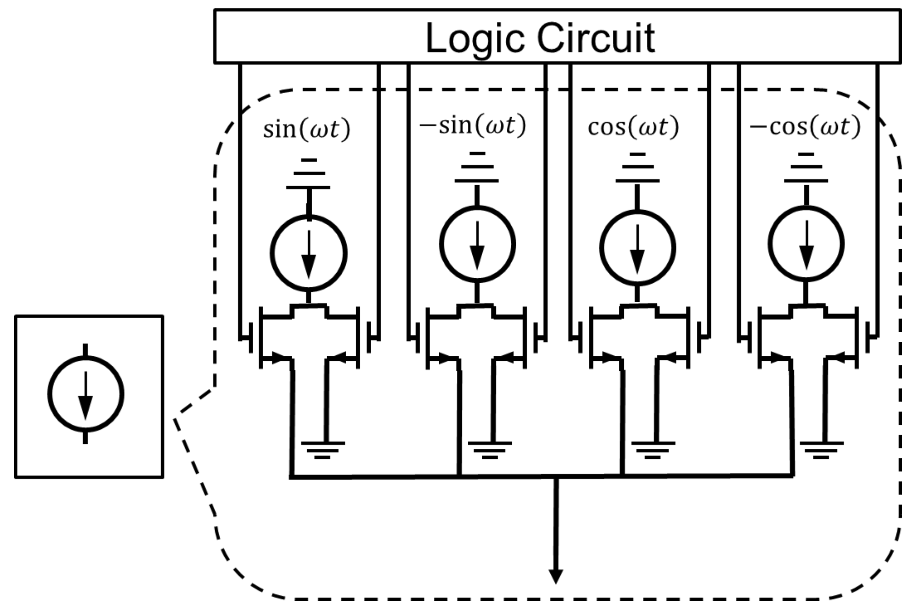


Control amplitude ratio $\frac{b}{a}$

Control phase φ

Phase Control Circuit





R – 2R Ladder register
+
AC current source

Control current source by NMOS switch

Realize amplitude ratio A : B

Fractional Approximation Method

- Amplitude ratio $\dfrac{\mathrm{B}}{\mathrm{A}}$ of phase φ

$$\tan(20°) = 0.363970\ldots \approx \frac{99}{273} = \frac{B}{A}$$

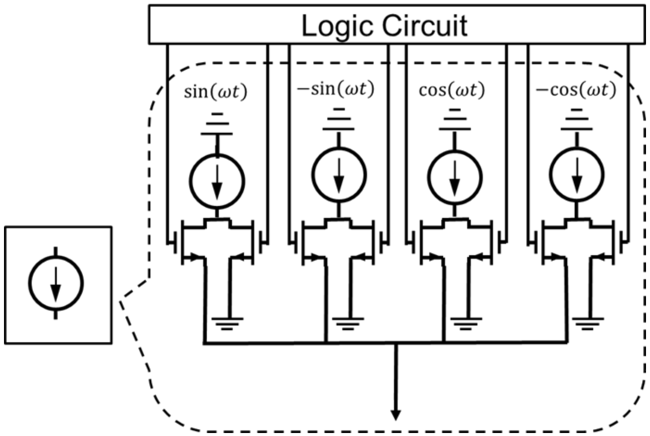
Fractional Approximation Method

$$3.14\cdots = 3 + \frac{1}{7.0625159} \approx 3 + \frac{1}{7} = \frac{22}{7}$$

$$3.14\cdots = 3 + \frac{1}{7 + \frac{1}{15.99593}} \approx 3 + \frac{1}{7 + \frac{1}{16}} = \frac{355}{113}$$

Using continued fraction ➡ accurate amplitude ratio

Current Source Nonlinearity

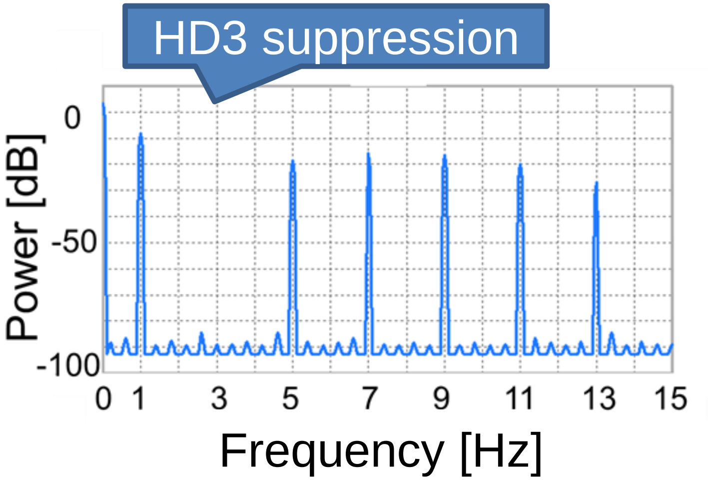


$$I = c_1 \sin\theta + c_3 \sin^3\theta$$

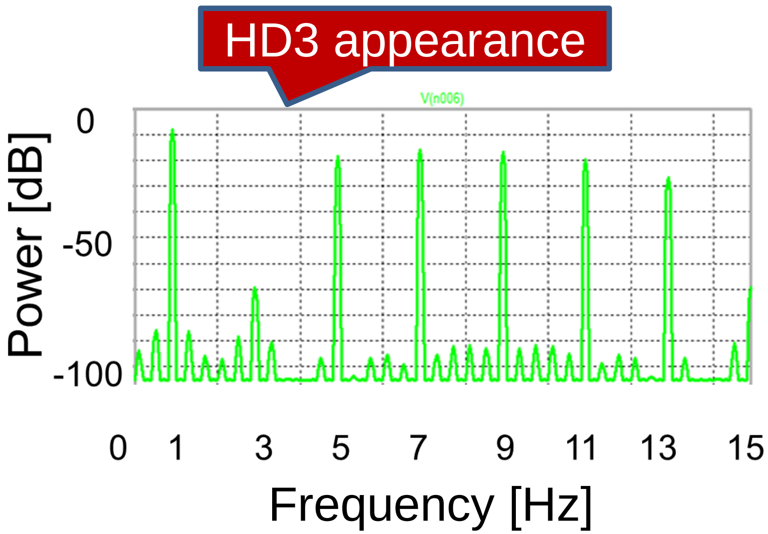
$$c_1 = 1, c_3 = -0.01$$

HD3 suppression case

linear



nonlinear



Amplitude Ratio Calculation

$$\frac{b}{a} = -\frac{c_1 \sin(2\pi f_1 t + \theta) + c_3 \sin^3(2\pi f_1 t + \theta)}{c_1 \cos(2\pi f_1 t + \theta) + c_3 \cos^3(2\pi f_1 t + \theta)}$$

$$= -\frac{c_1 + c_3 \sin^2(2\pi f_1 t + \theta)}{c_1 + c_3 \cos^2(2\pi f_1 t + \theta)} \tan(2\pi f_1 t + \theta)$$

$$a_1 = 1, a_3 = -0.01, t = \frac{1}{9}[s], f_1 = 1[Hz], \theta = 0[°]$$

$$\frac{b}{a} = -\frac{1 - 0.01 \times \sin^2\left(\pm\frac{\pi}{9}\right)}{1 - 0.01 \times \cos^2\left(\pm\frac{\pi}{9}\right)} \tan\left(\pm\frac{\pi}{9}\right) = \mp 2.299560241 = \frac{\mp 522}{227}$$

Obtain appropriate amplitude ratio

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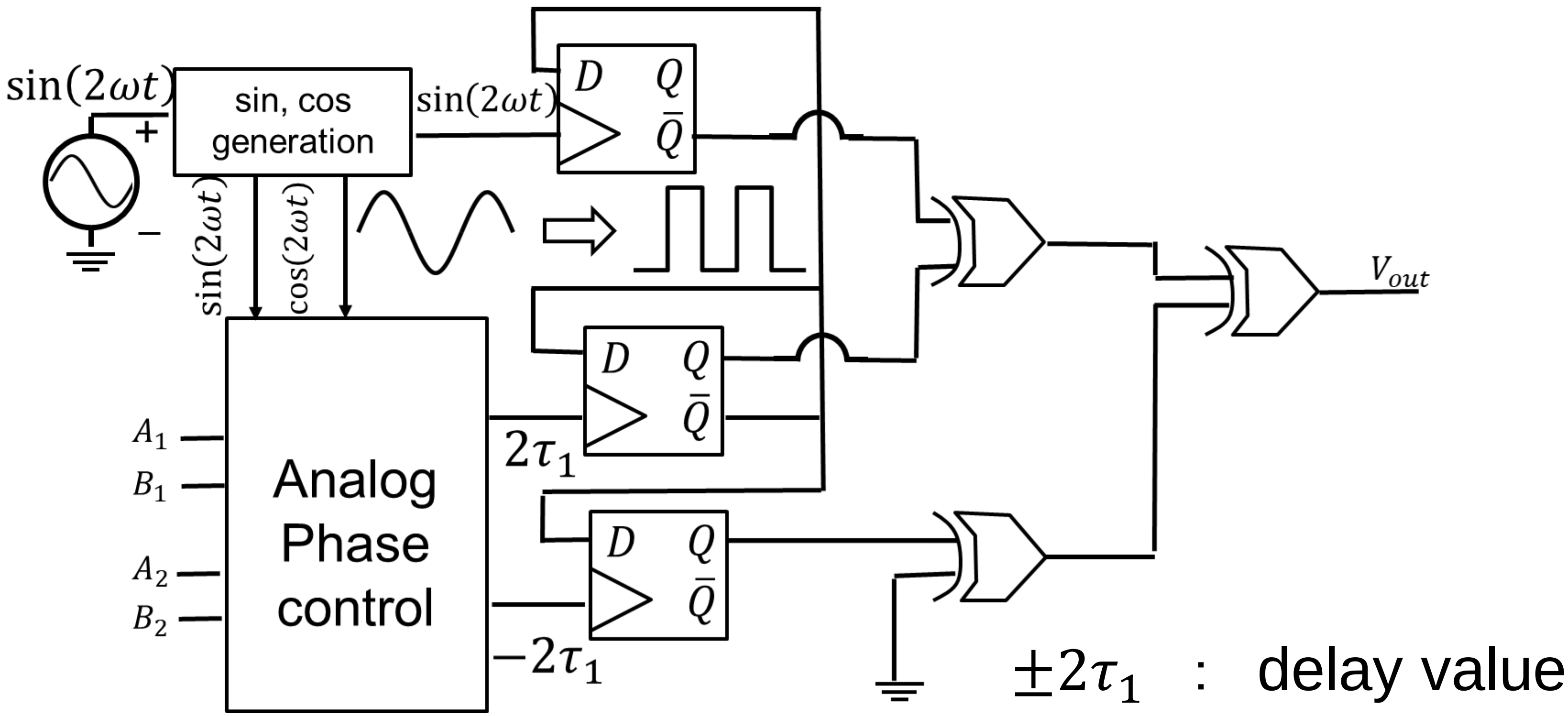
Duty50% Circuit Configuration

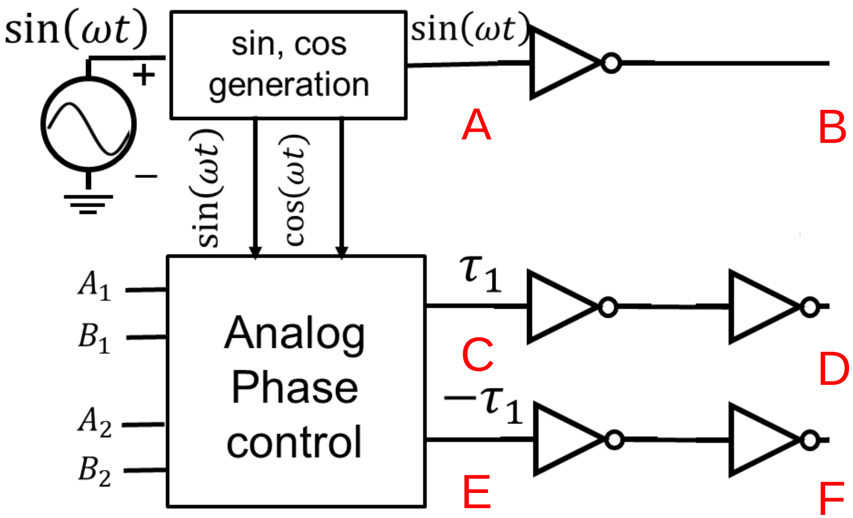


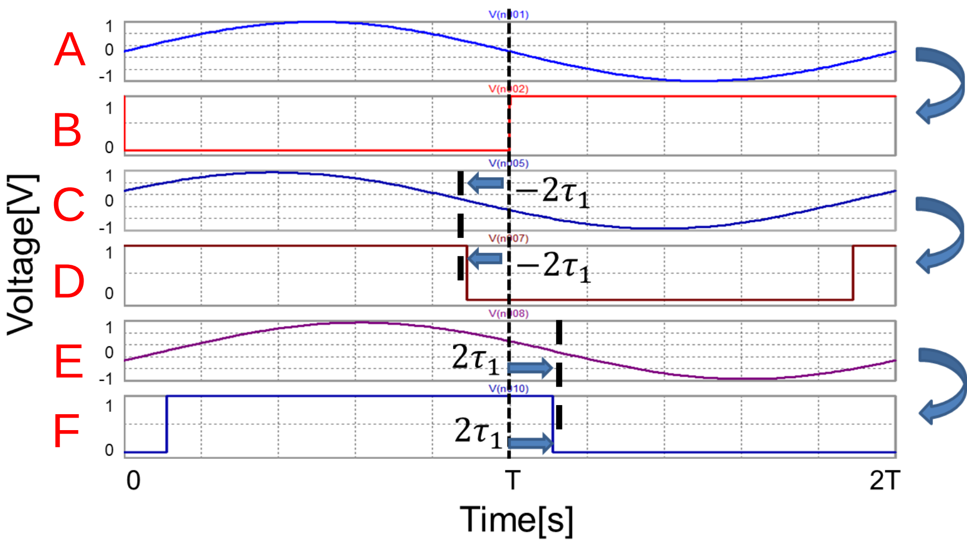
- Use a frequency divider
  - Guaranteed Duty 50%
  - Doubled phase and frequency
- Use XOR instead of opamp

From Sine to Rectangular Waveforms

Sin wave → inverter → rectangular wave

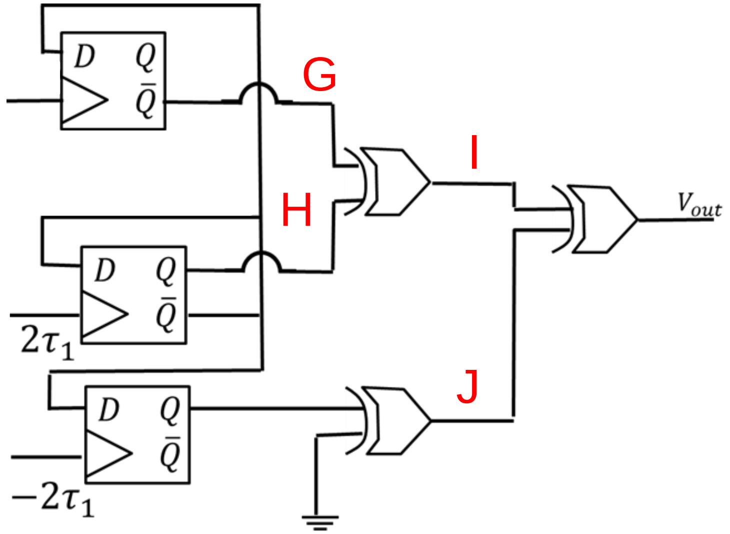
Phase φ — Binary change — Phase φ

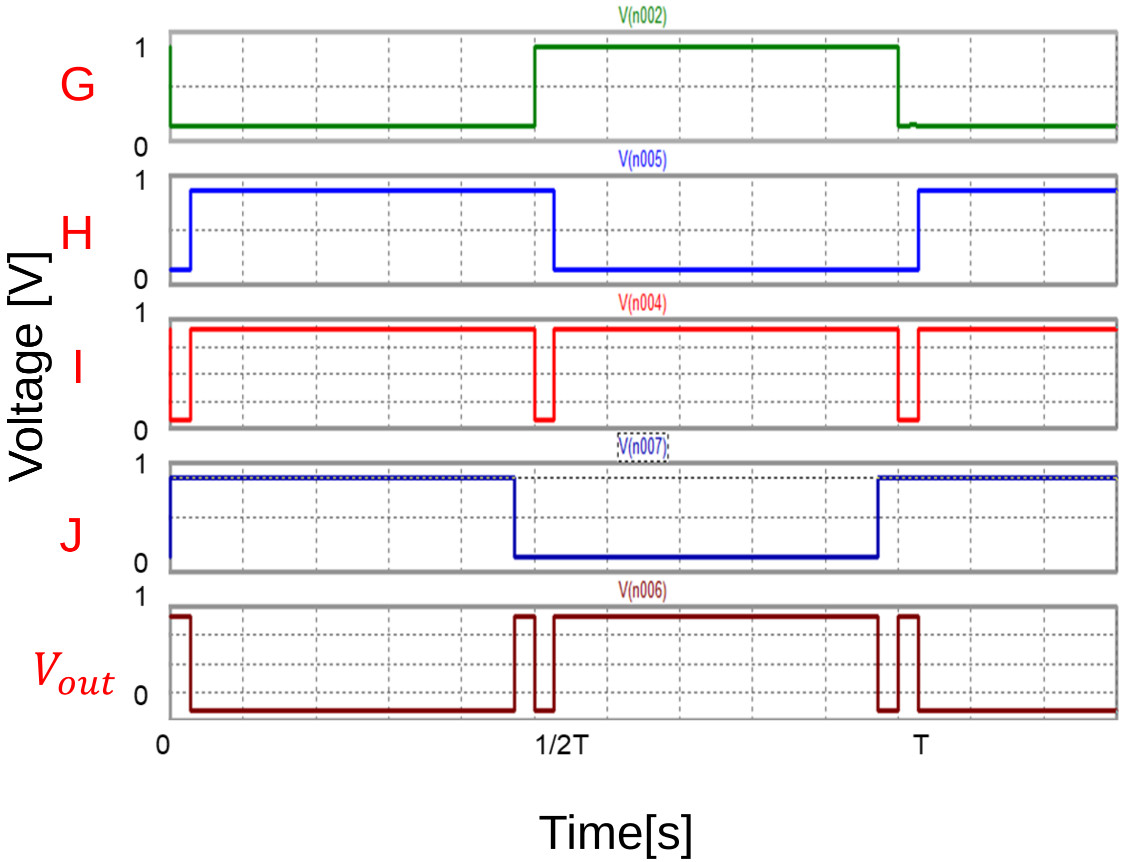




XOR Behavior

Binary output ➡ Express with logic circuit



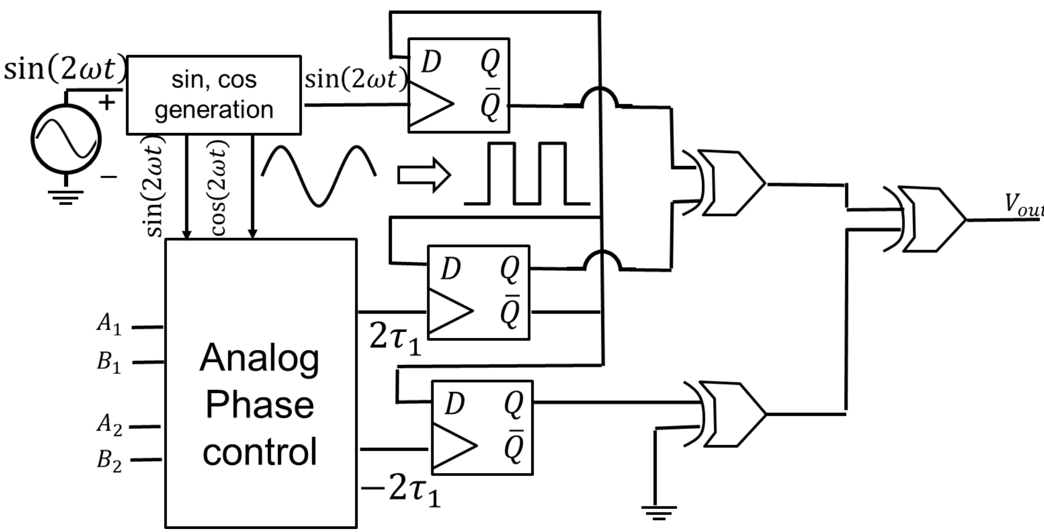


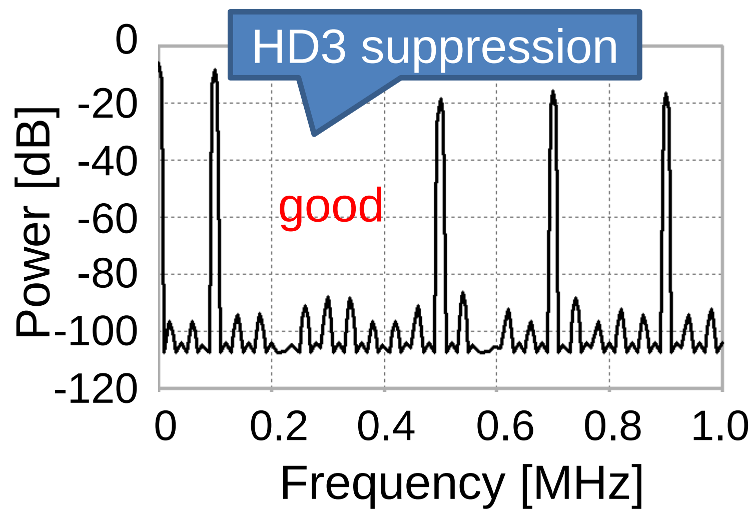
HD3 Suppression Simulation

Parameters

$$T/2 = 5\ [\mu s], c_1 = 1, c_2 = -0.1, c_3 = -0.01$$

$$2\tau_1 = \frac{10}{9}\ [\mu s], \frac{b_1}{a_1} = \frac{587}{689}, \frac{b_2}{a_2} = \frac{350}{361}$$





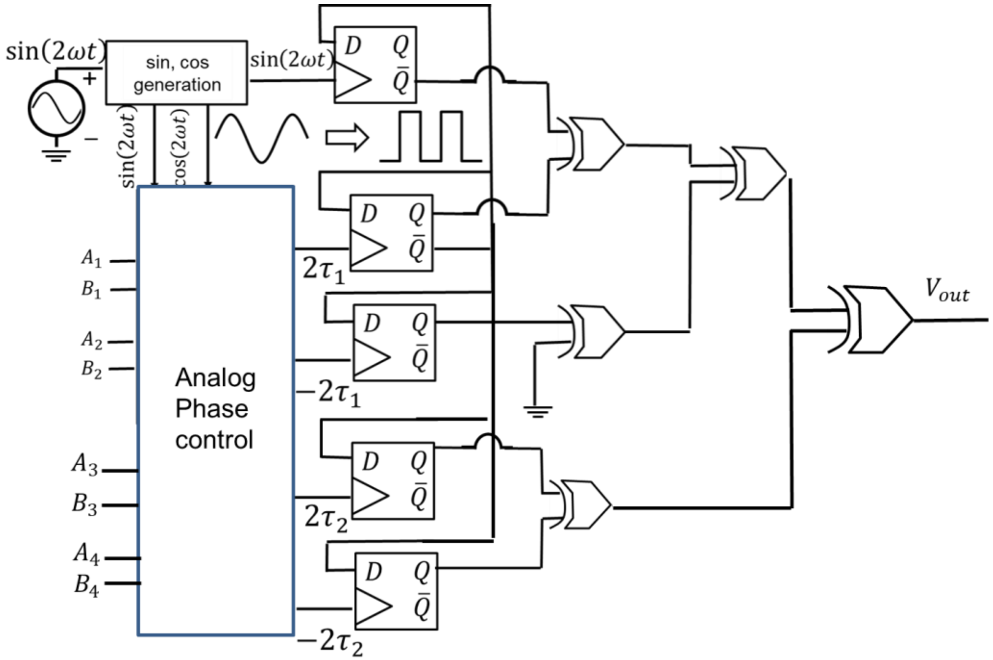
HD3 & HD5 Suppression Simulation

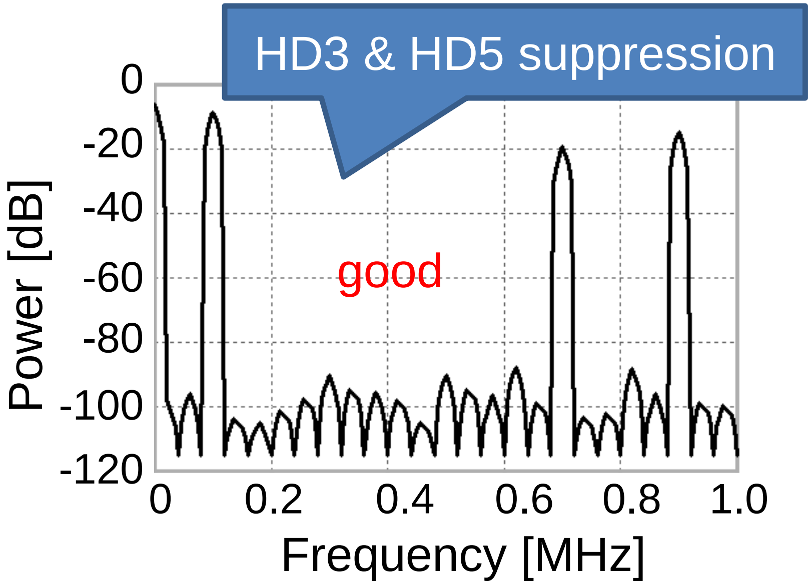
Parameters

$$T/2 = 5\ [\mu s], 2\tau_1 = 0.92578\ [\mu s], 2\tau_2 = 0.656805\ [\mu s]$$

$$c_1 = 1, c_2 = -0.1, c_3 = -0.05, c_4 = -0.01, c_5 = -0.005$$

$$\frac{b_1}{a_1} = \frac{489}{235}, \frac{b_2}{a_2} = \frac{313}{122}, \frac{b_3}{a_3} = \frac{938}{868}, \frac{b_4}{a_4} = \frac{929}{868}$$





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Conclusion

Summary

- We proposed low-distortion signal method using analog phase shift & rectangular.

Digital ATE ＋ Simple analog circuit & BOST

⇩

No need expensive signal generator

Future task

- Consideration of delay time & threshold voltage of Flip-Flop
- It is necessary to verify with the actual circuit