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# Low-Distortion Signal Generation for ADC Testing

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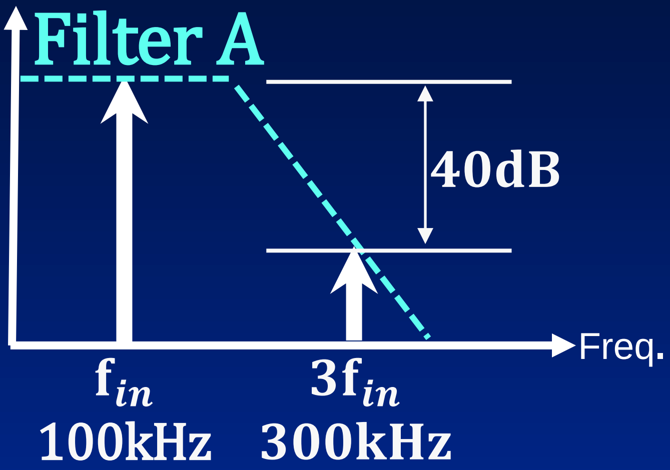
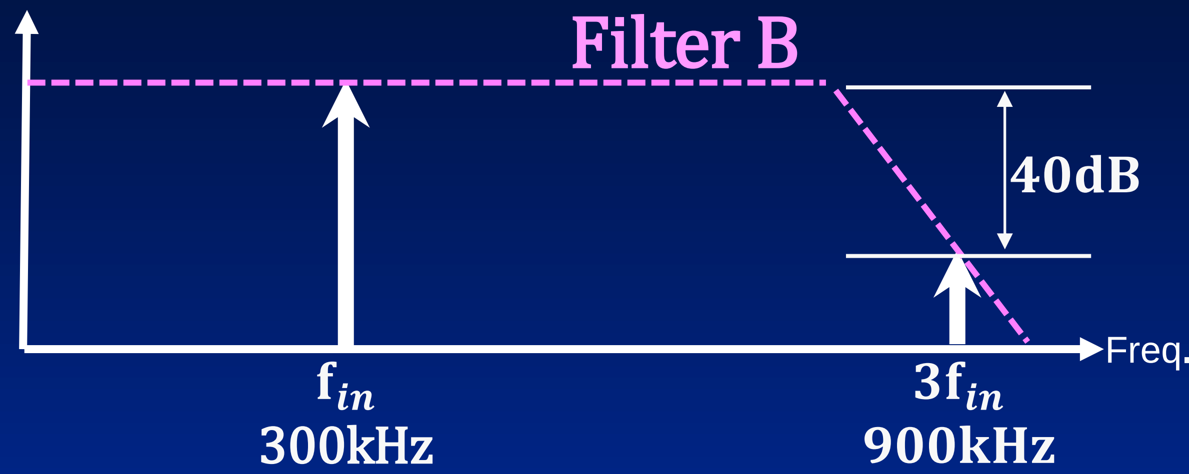
# Research Objectives

- Use an Arbitrary Waveform Generator (AWG) as low-cost low-distortion signal source for ADC testing
- Validate our 3rd-harmonic-cancelling phase-switching signal generation technique
- Perform analysis, simulation, and experiments using AWGs  for ADC testing

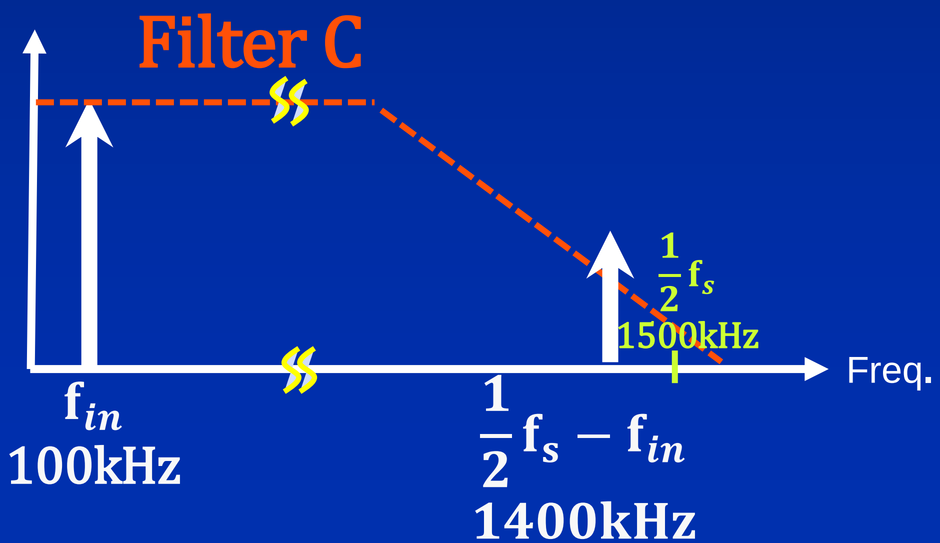
# Expected Advantage of Our Solution

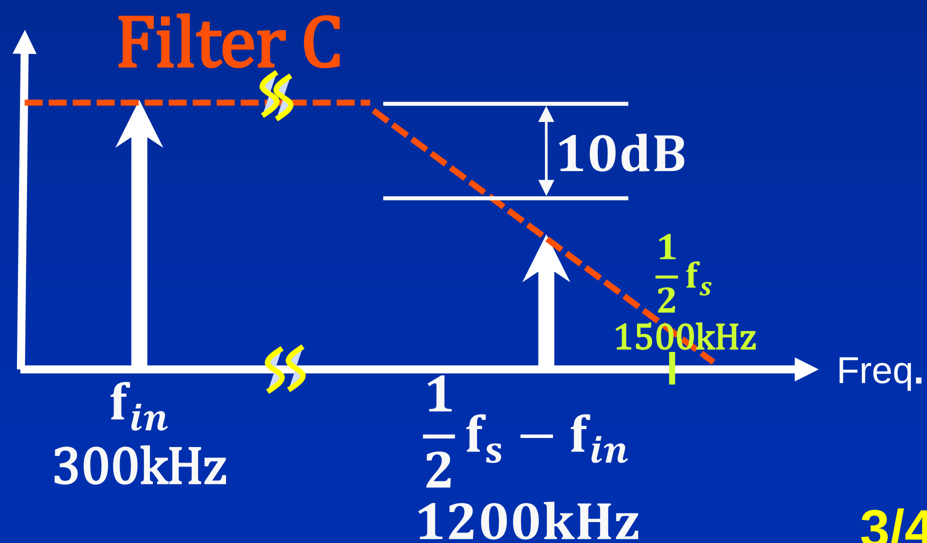
## Conventional Method　Tough LPF requirements




## Our Method　Relaxed LPF requirements



# Outline

- Background to this research
- Proposed solution
- Problems with proposed solution
- Remedy 1
- Remedy 2
- Experimental results
- Conclusions

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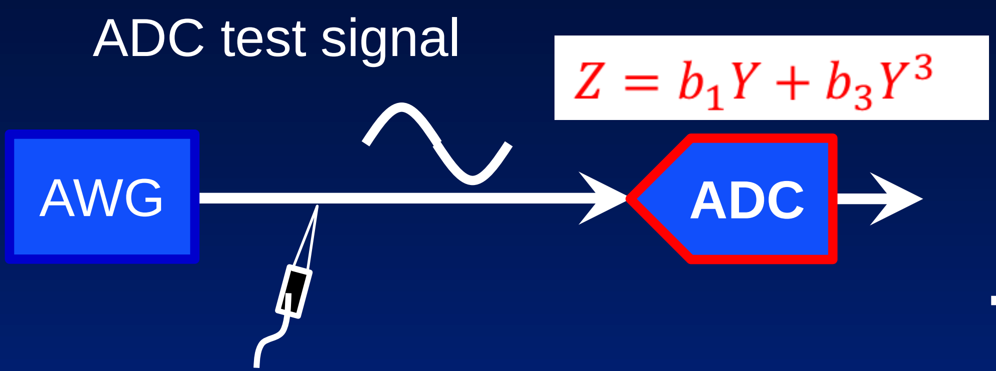
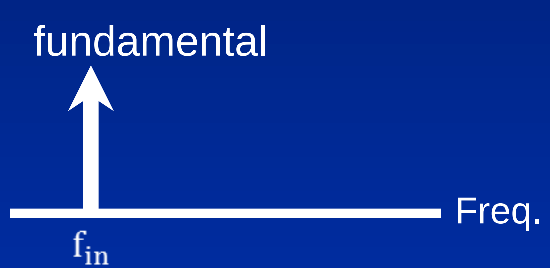
# Background to this Research

- ADCs are important part of mixed-signal SOCs.
- Need a low-cost, low-distortion signal source for ADC linearity testing.
- #1: Use existing AWGs in testers → low cost
- # 2: Develop a technique that doesn’t require identification of AWG nonlinearity, just a DSP program change.

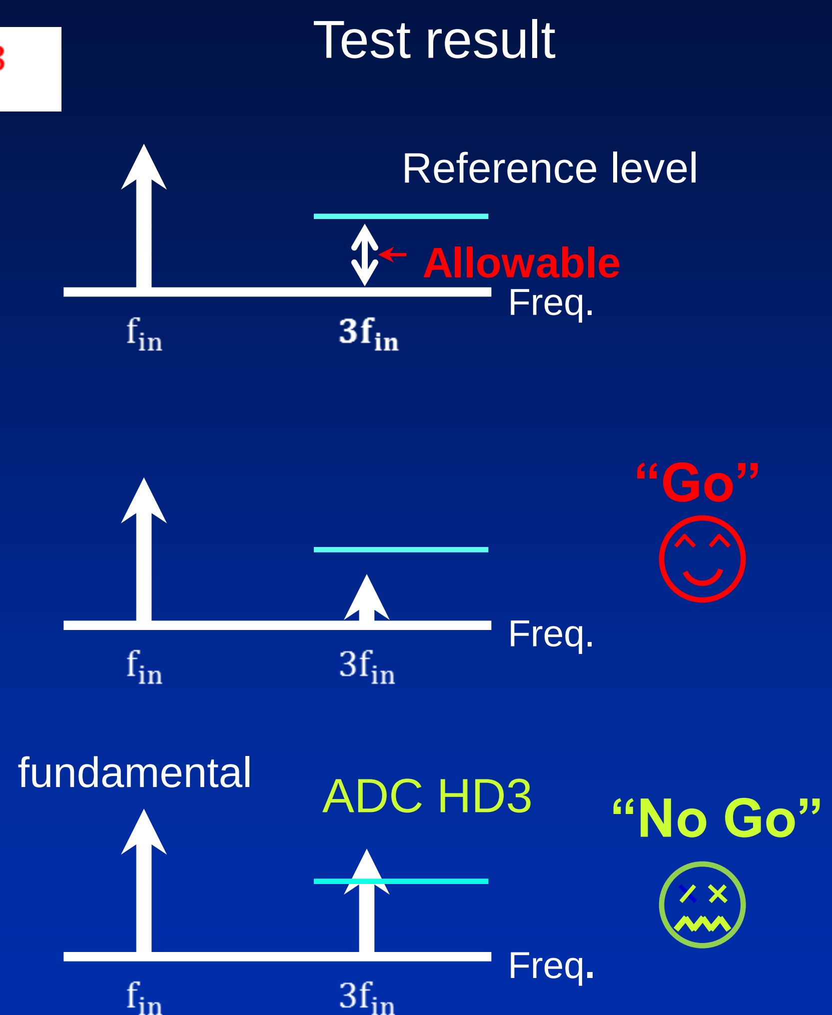
# ADC Testing with Sine Signal



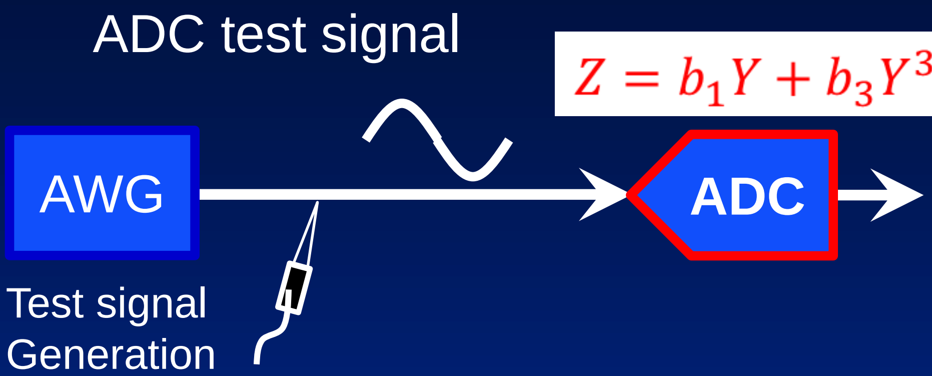




ADC linearity test

ADC HD3 measurement



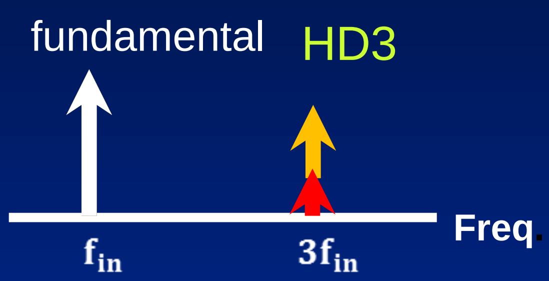
# Problem with Conventional Method



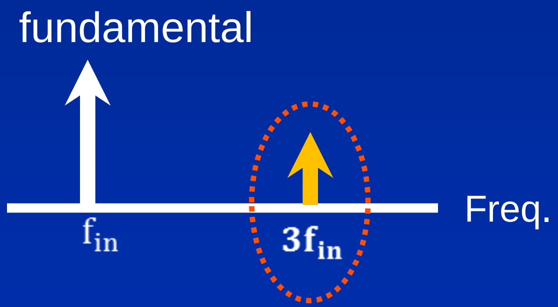

$$Z = b_1 Y + b_3 Y^3$$

$$Y = a_1 D_{in} + a_3 D_{in}.^3$$

Test result




AWG HD3+ADC HD3




AWG HD3

ADC HD3 cannot be measured accurately.

Low quality test

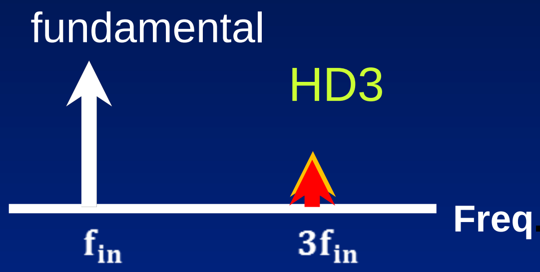
# Research Objective

ADC test signal

$$Z = b_1 Y + b_3 Y^3$$

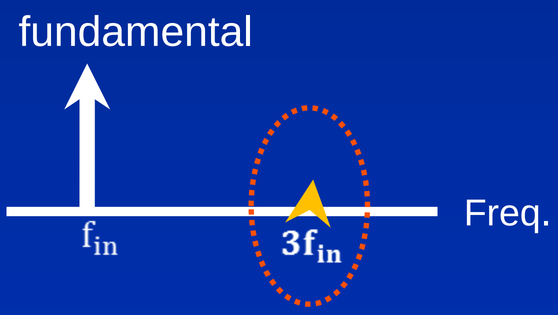

$$Y = a_1 D_{in} + a_3 D_{in}.^3$$

ADC test result




Only ADC HD3

only
program
change




High quality test

AWG HD3 reduction

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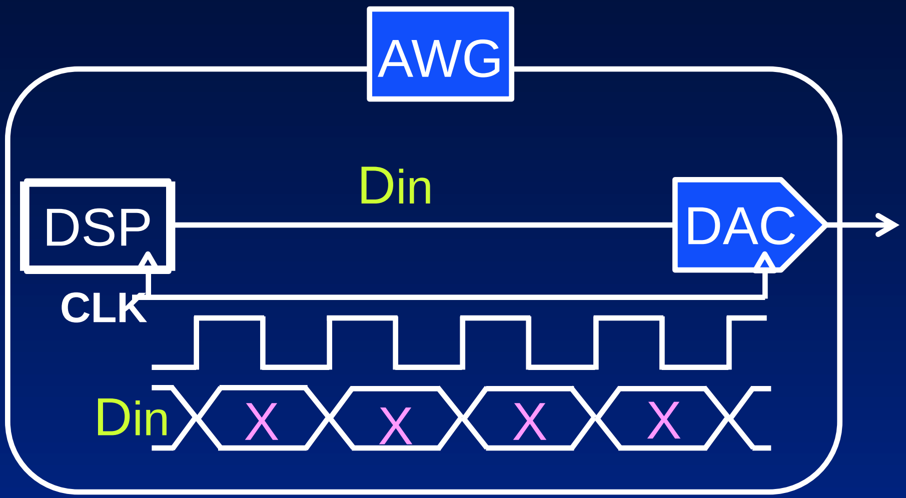
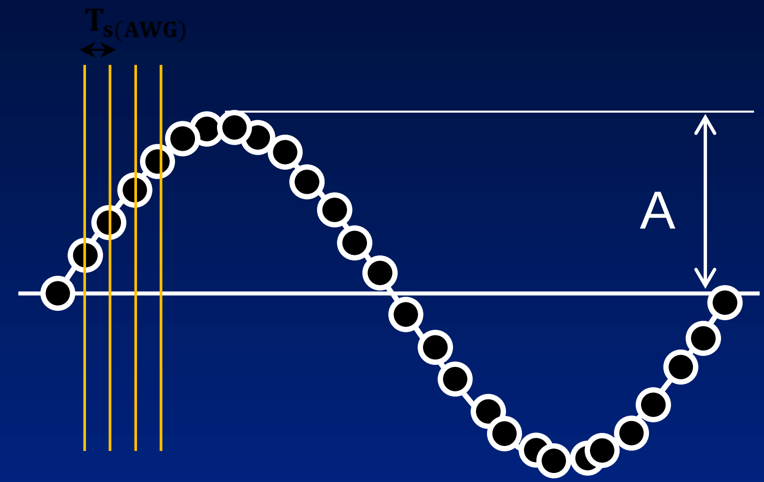
# Conventional Signal Generation with AWG

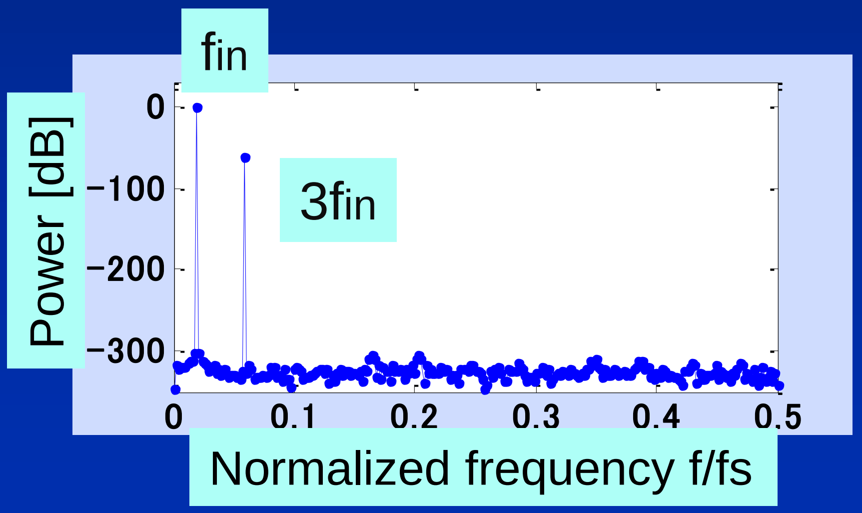


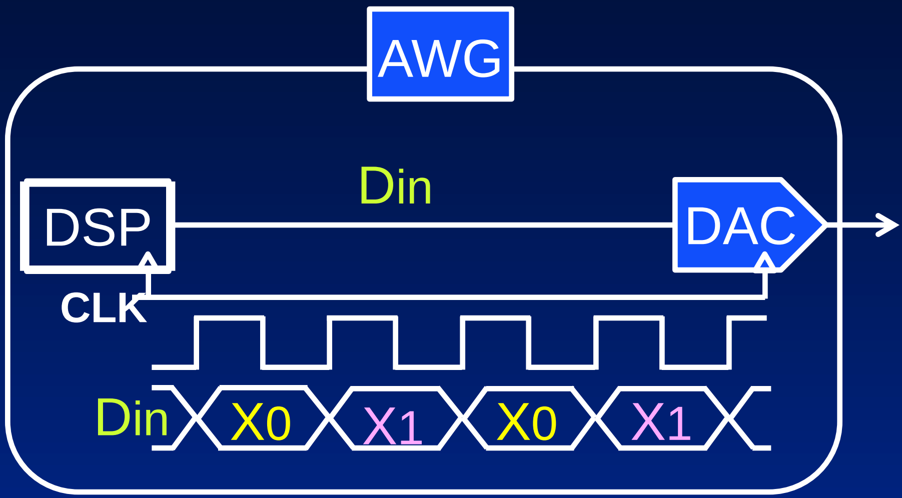

AWG sampling frequency: $f_{s(AWG)} = 1/T_s$

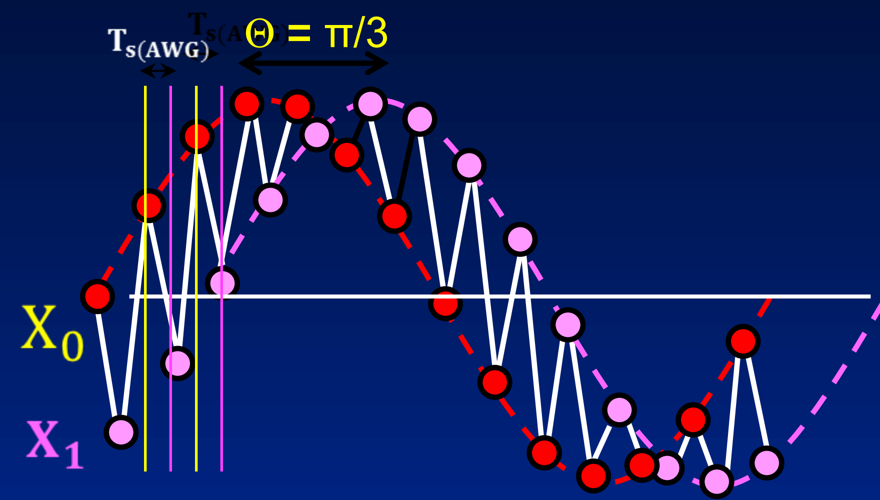
$$X = A\cos(2\pi f_{in} n T_s)$$

DAC has 3[rd] order nonlinearity



# Proposed Signal Generation with AWG



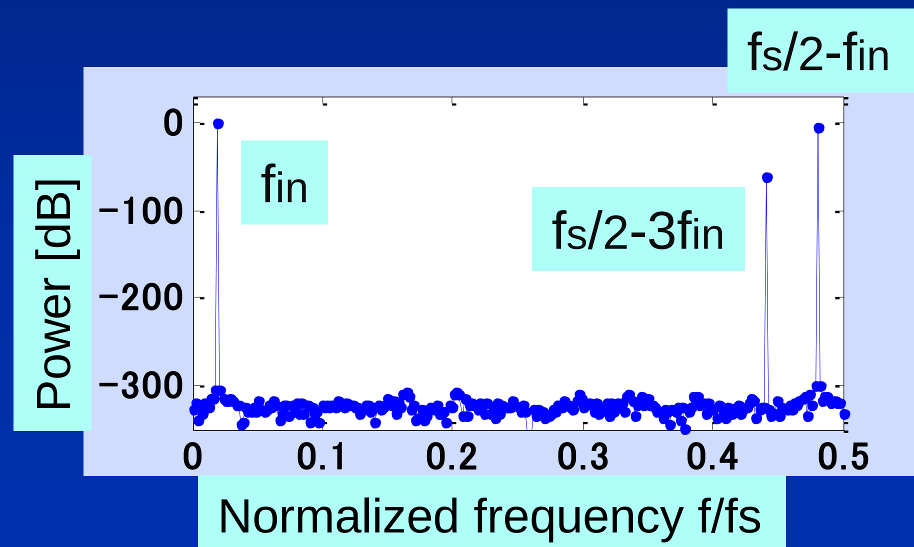




**AWG sampling frequency : $f_{s(AWG)} = 1/T_{s(AWG)}$**

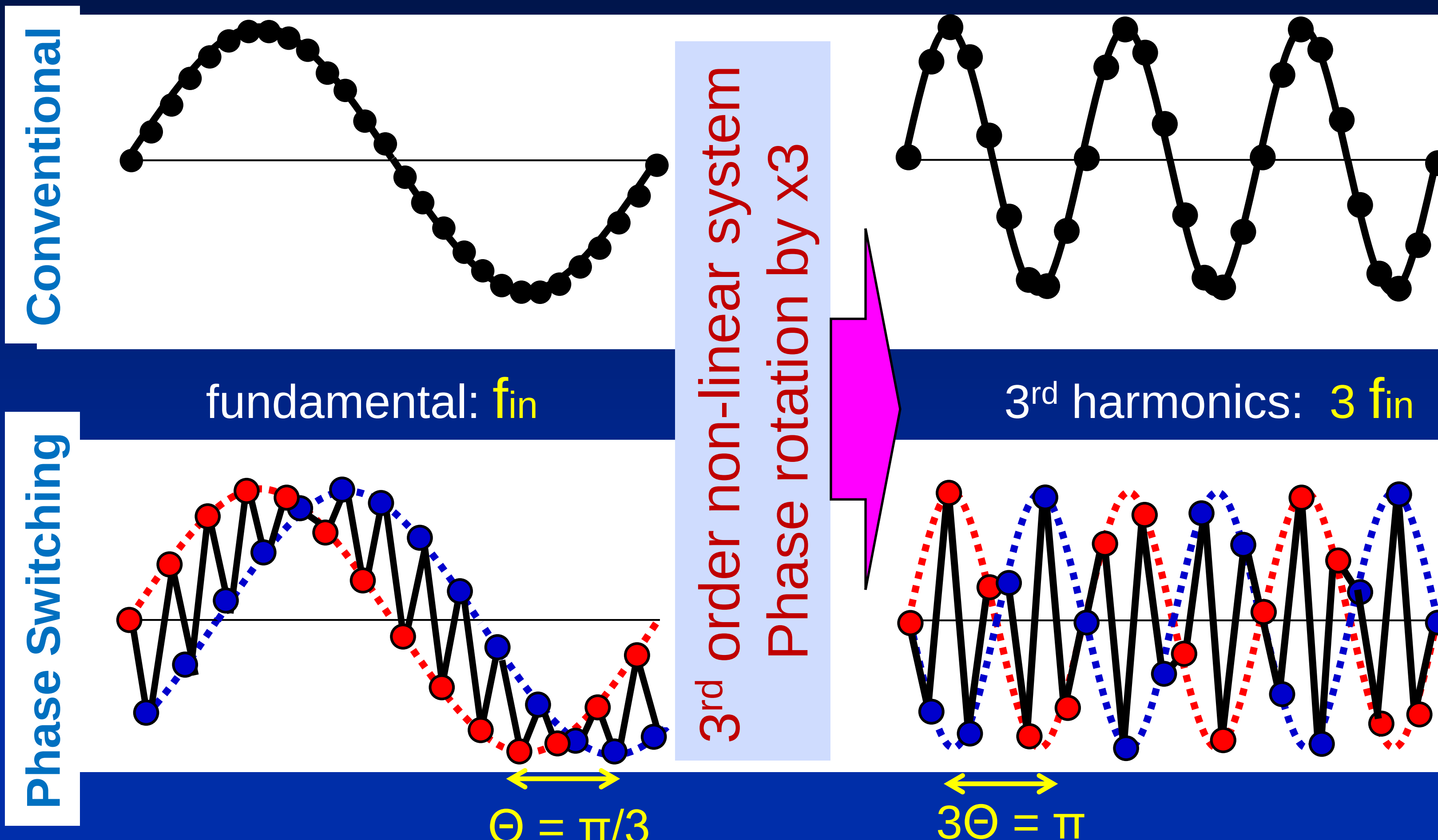
$$X_0 = 1.15A\cos(2\pi f_{in} nT_s - \pi/6)$$

$$X_1 = 1.15A\cos(2\pi f_{in} nT_s + \pi/6)$$

HD3 is cancelled



# Principle of 3rd Harmonics Cancellation

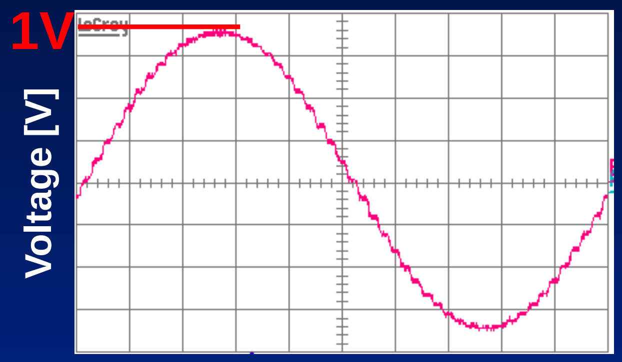



Two waves with phase difference **π** are cancelled

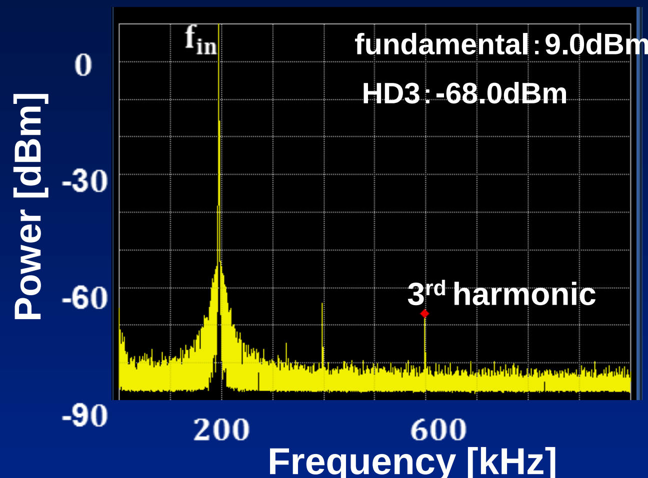
# Conventional and Phase Switching Signals

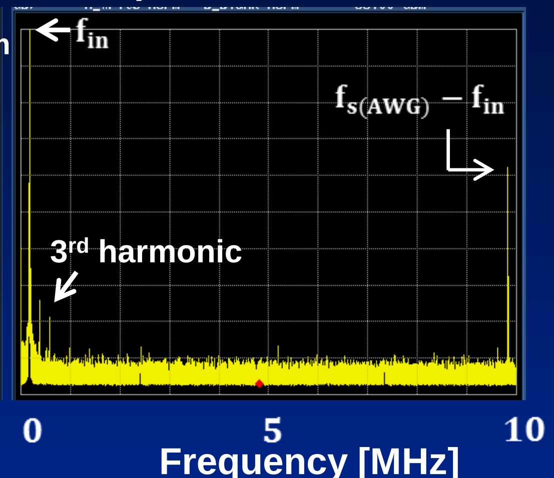
## Conventional

**Waveform**



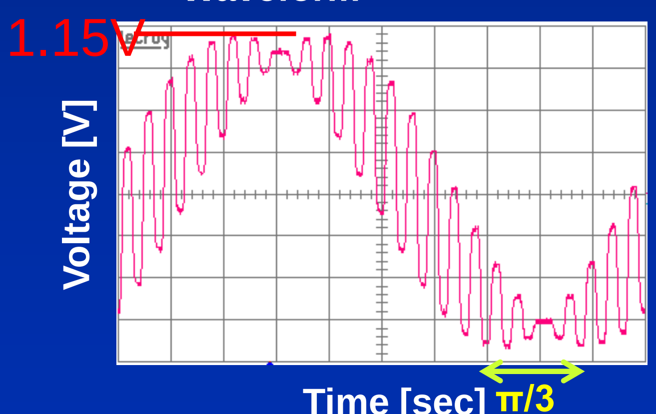

**Measured Power Spectrum**

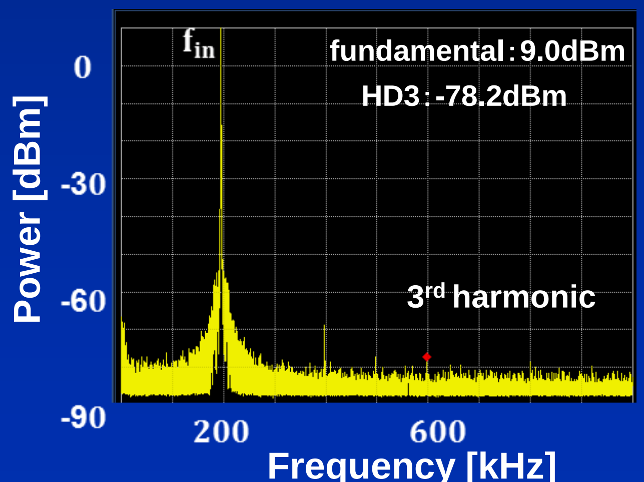


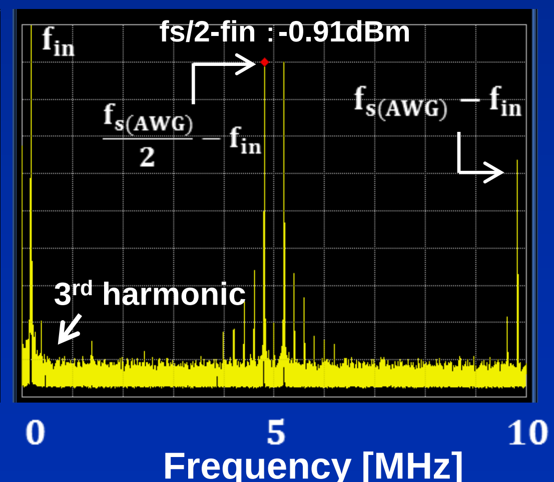




## Phase Switching

**Waveform**



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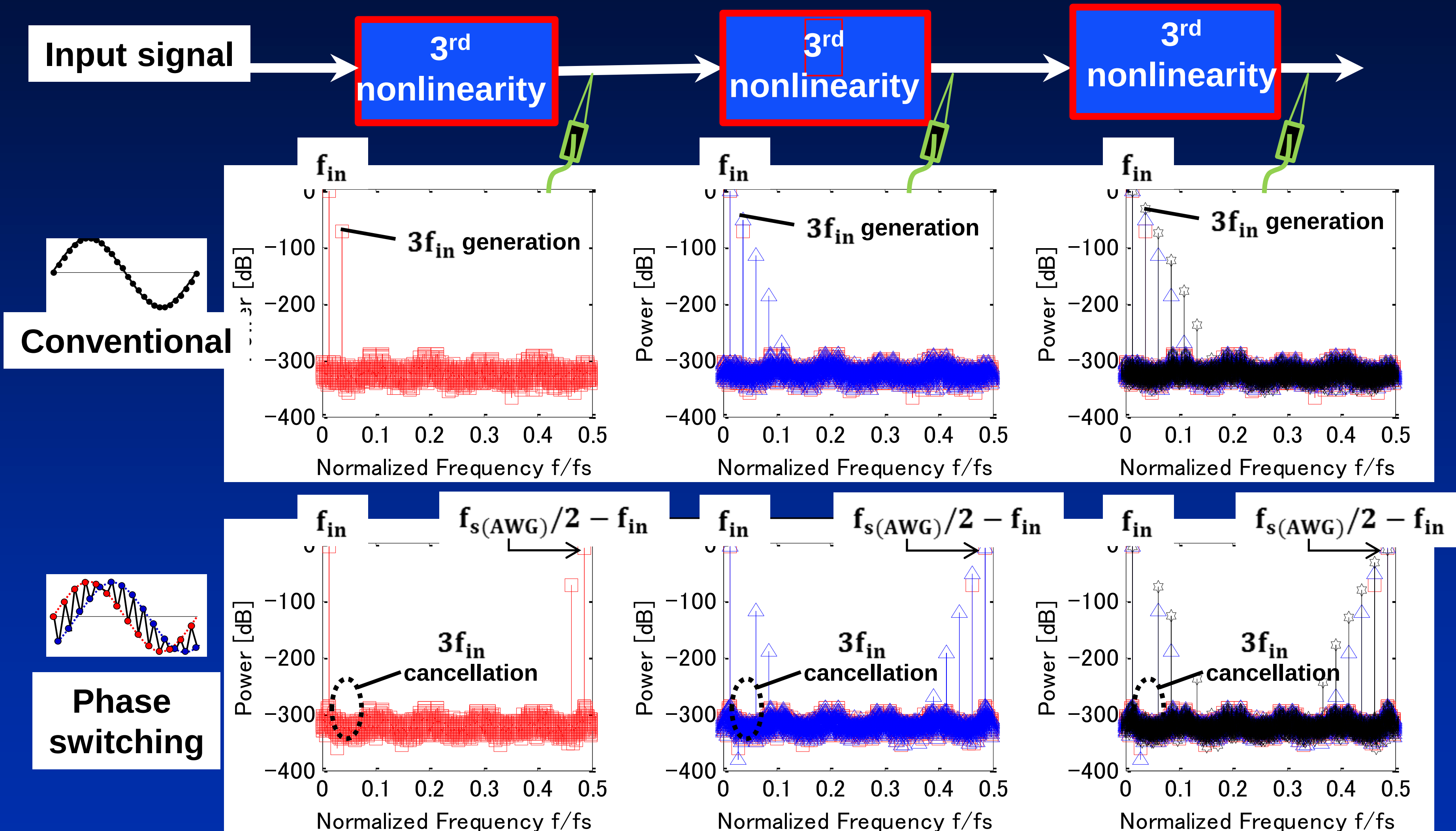
# Conditions of HD3 Cancellation in Cascaded System



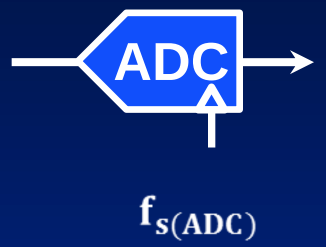

HD3's are not cancelled if attenuate spurious at $f_s/2 - f_{in}$.

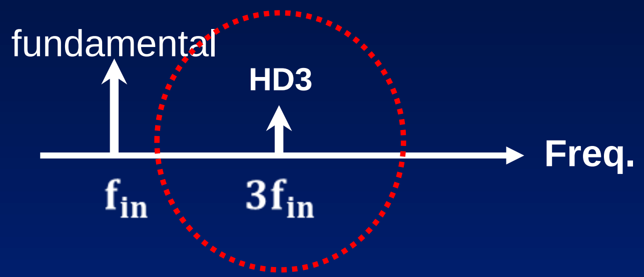
# Problem of Phase Switching Signal Generation

Ideal


**Nonlinearity Model**

$$Y = a_1X + a_3X^3$$

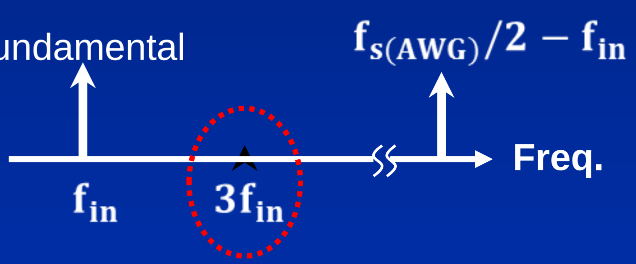


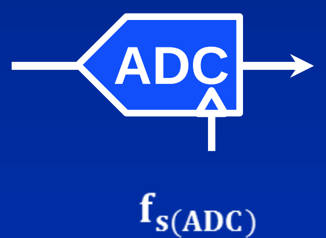

HD3 due to
ADC nonlinearity

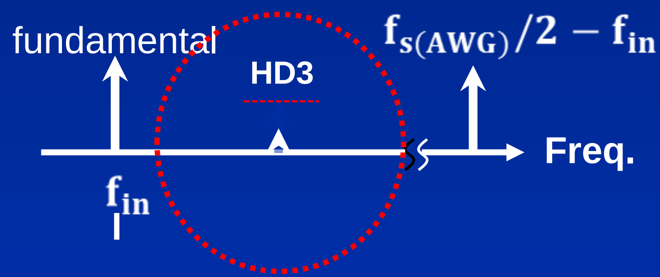
Phase
switching

Spurious
due to phase switching




$$Y = a_1X + a_3X^3$$




Reduction of HD3
due to AWG nonlinearity

Reduction of HD3
due to ADC nonlinearity

Big problem !

# Model for Theoretical Analysis

AWG Input with Phase Switching

$$D_{in}(nT_s) = \begin{cases} A \cdot \sin(2\pi f_{in} nT_s - \frac{\pi}{6}) & \text{n: odd} \\ A \cdot \sin\left(2\pi f_{in} nT_s + \frac{\pi}{6}\right) & \text{n: even} \end{cases}$$

AWG Nonlinearity Model

$$Y(nT_s) = a_1 D_{in}(n) + a_3\{D_{in}(n)\}^3$$

ADC Nonlinearity Model

$$Z(n) = b_1 Y(nT_s) + b_3\{Y(nT_s)\}^3$$

For simplicity

$f_{s(AWG)} = f_{s(ADC)}$

w/o LPF

# AWG Output

$$Y(nT_s) = a_1 D_{in}(n) + a_3\{D_{in}(n)\}^3$$

$$= \quad P\sin(2\pi f_{in} nT_s)$$ ← signal

large

$$+\, Q\cos\left(2\pi\left(\frac{f_s}{2} - f_{in}\right)nT_s\right)$$

$$+\, R\cos\left(2\pi(\frac{f_s}{2} - 3f_{in})nT_s\right)$$

small

spurious

# Direct Application of Phase Switching Signal

ADC output *Z(n)* components

| | | |
|---|---|---|
| $\alpha_0$ | $\beta_1 \sin(2\pi f_{in} n T_s)$ | ← signal |
| $\alpha_{-1} \cos\left(2\pi(\frac{f_s}{2} - f_{in}) n T_s\right)$ | $\beta_3 \sin(2\pi 3 f_{in} n T_s)$ | ← HD3 |
| $\alpha_1 \cos\left(2\pi(\frac{f_s}{2} + f_{in}) n T_s\right)$ | $\beta_{-1} \sin(2\pi(f_s - f_{in}) n T_s)$ | |
| $\alpha_{-3} \cos\left(2\pi(\frac{f_s}{2} - 3 f_{in}) n T_s\right)$ | $\beta_{-3} \sin(2\pi(f_s - 3 f_{in}) n T_s)$ | ← HD3 |
| | $\beta_{-5} \sin(2\pi(f_s - 5 f_{in}) n T_s)$ | |
| ⋮ | ⋮ | |

By calculation $\beta_3 = \beta_{-3}$

$3f_{in}$ and $f_s - 3f_{in}$ components are cancelled

⇓

CANNOT measure ADC HD3.

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# AWG Output and Low Pass Filtering

$$\mathrm{Y}'(\mathrm{n}T_s) = a_1 D_{in}(n) + a_3\{D_{in}(n)\}^3$$

$$= \quad \mathrm{P}\sin(2\pi f_{in} n T_s)$$

$$+\ \mathrm{q}\ \mathrm{Q}\cos\left(2\pi\left(\frac{f_s}{2} - f_{in}\right)nT_s\right)$$

$$+\ \mathrm{r}\ \mathrm{R}\cos\left(2\pi(\frac{f_s}{2} - 3f_{in})nT_s\right)$$

$0 < \mathrm{q} < 1,\ 0 < \mathrm{r} < 1$ : spurious attenuation

w/ LPF

# Application of Phase Switching and LPF

## ADC output *Z(n)* components

$\alpha'_0$

$\boldsymbol{\alpha'_{-1}}\cos\left(2\pi(\frac{f_s}{2} - f_{in})nT_s\right)$

$\boldsymbol{\alpha'_{1}}\cos\left(2\pi(\frac{f_s}{2} + f_{in})nT_s\right)$

$\boldsymbol{\alpha'_{-3}}\cos\left(2\pi(\frac{f_s}{2} - 3f_{in})nT_s\right)$

⋮

$\boldsymbol{\beta'_1}\sin(2\pi f_{in}nT_s)$ ← signal

$\boldsymbol{\beta'_3}\sin(2\pi 3f_{in}nT_s)$ ← HD3

$\boldsymbol{\beta'_{-1}}\sin(2\pi(f_s - f_{in})nT_s)$

$\boldsymbol{\beta'_{-3}}\sin(2\pi(f_s - 3f_{in})nT_s)$ ← HD3

$\boldsymbol{\beta'_{-5}}\sin(2\pi(f_s - 5f_{in})nT_s)$

⋮

By calculation $|\beta'_3| \gg |\beta'_{-3}|$

$3f_{in}$ and $f_s - 3f_{in}$ components are NOT cancelled

⇓

ADC HD3 can be measured.

# Spurious Attenuation Effect

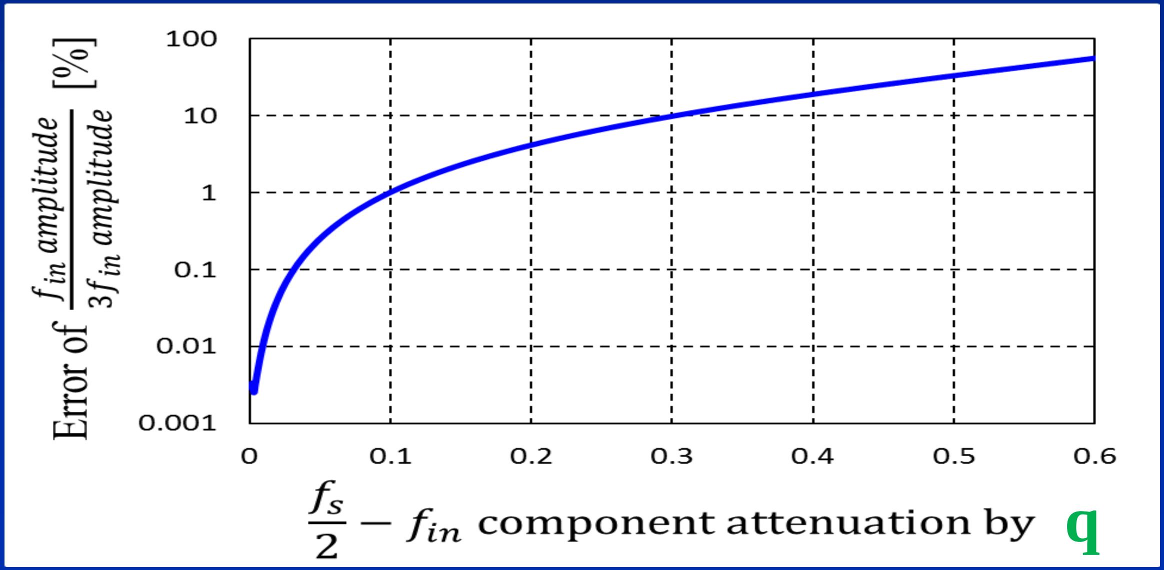
## AWG output and low pass filtering

$$Y(nTs) = P\sin(2\pi f_{in} nT_s) + \mathbf{q}\, Q\cos\left(2\pi\left(\frac{f_s}{2} - f_{in}\right)nT_s\right) + \mathbf{r}\, R\cos\left(2\pi\left(\frac{f_s}{2} - 3f_{in}\right)nT_s\right)$$

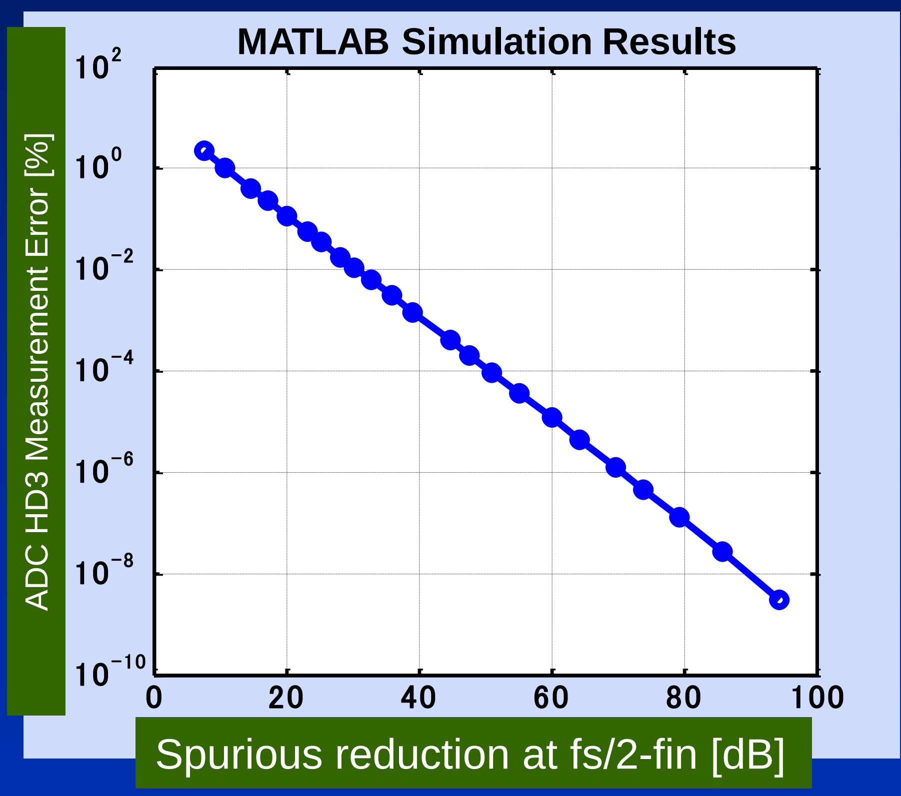
$\mathbf{f_{s(AWG)}/2 - f_{in}}$

spurious reduction

Accurate HD3 measurement



# Spurious Reduction at $f_{s(AWG)}/2 - f_{in}$


| Spurious reduction at fs/2-fin | | HD3 measurement Error |
|---|---|---|
| 10dB | ➡ | 1% |
| 20dB | ➡ | 0.1% |

For accurate ADC HD3 measurement attenuate the spurious at $\frac{f_{s(AWG)}}{2} - f_{in}$

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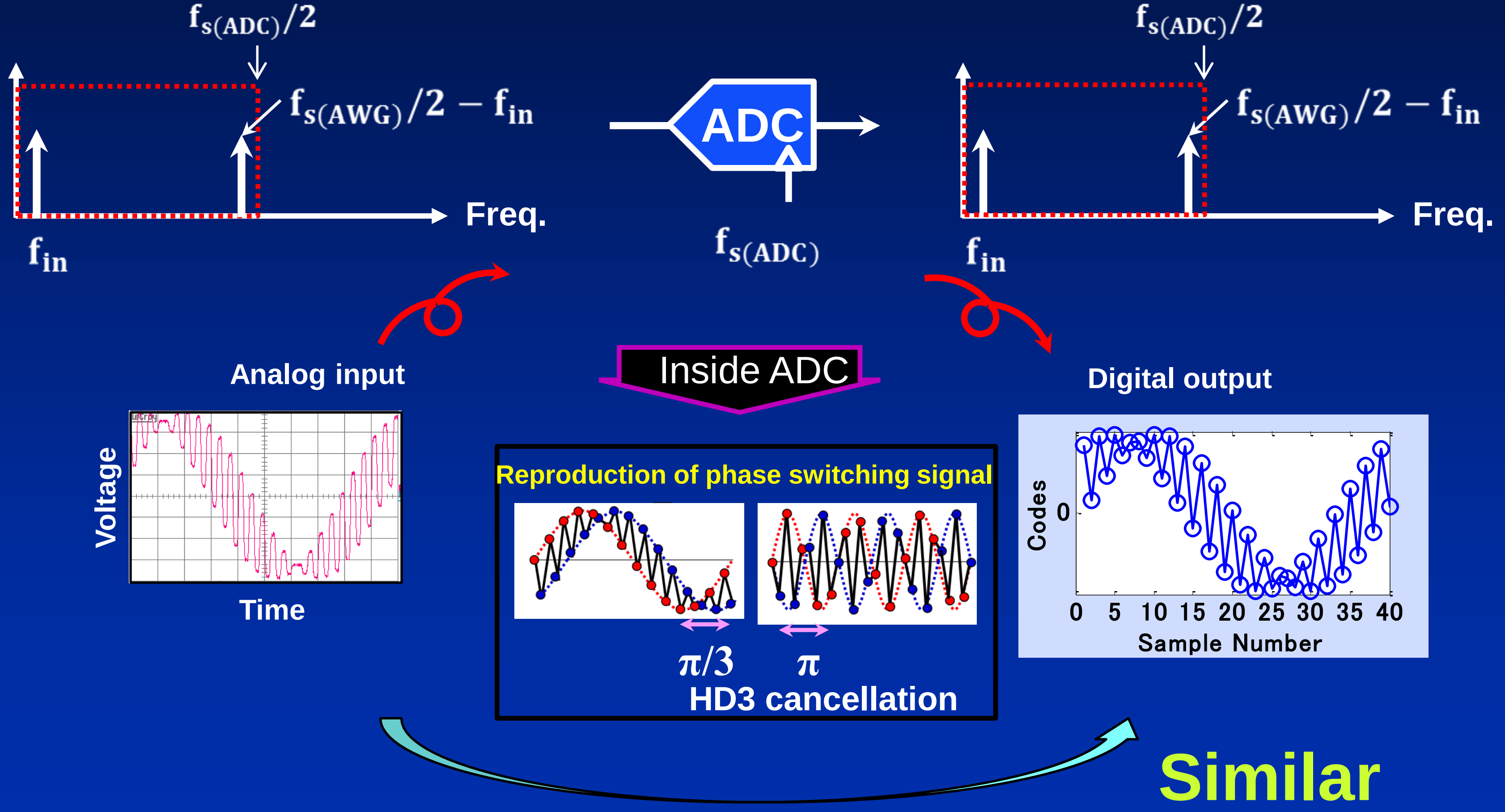
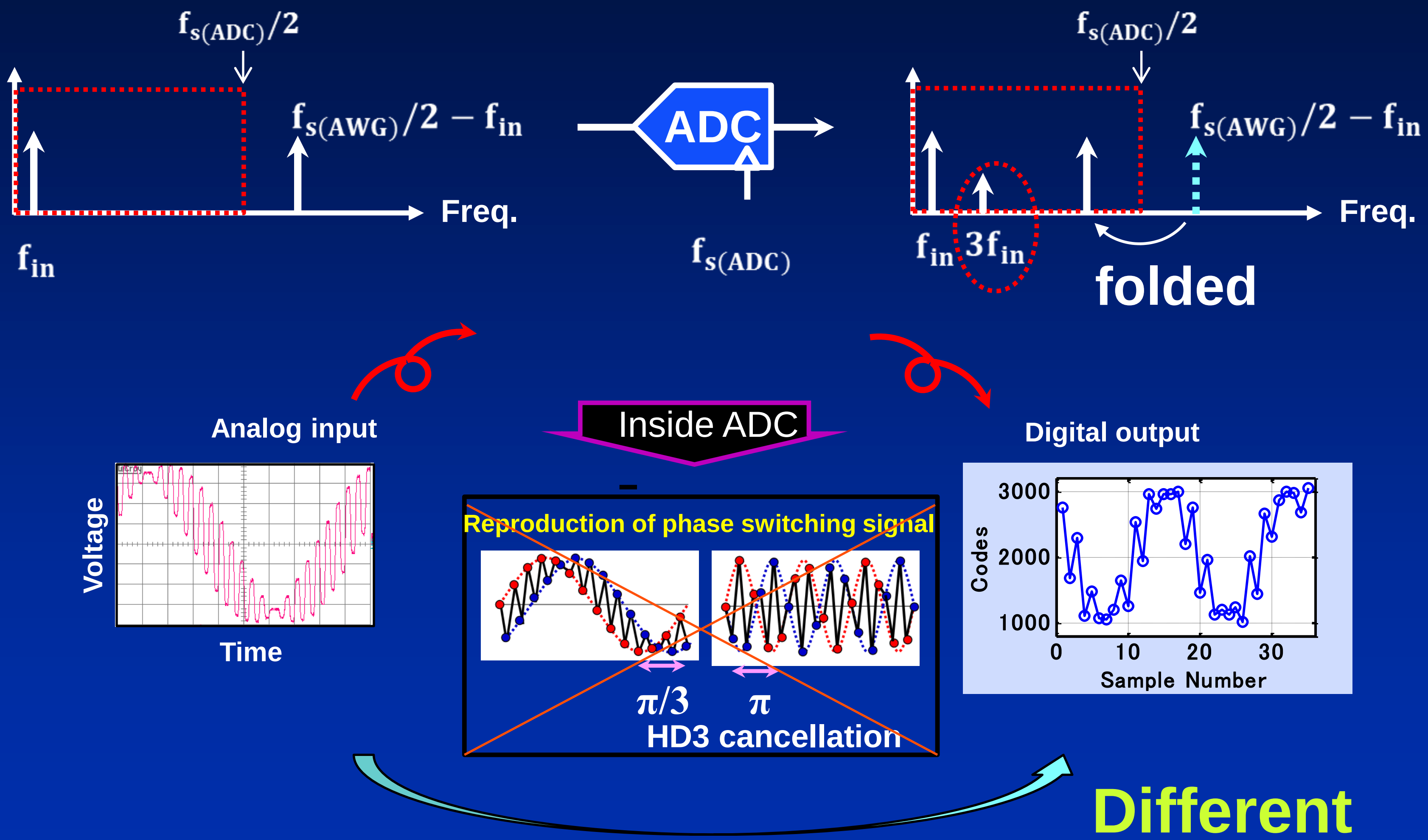
# When Spurious @ $f_{s(AWG)}/2 - f_{in}$ is Within $f_{s(ADC)}/2$




**ADC HD3 can NOT be measured accurately**

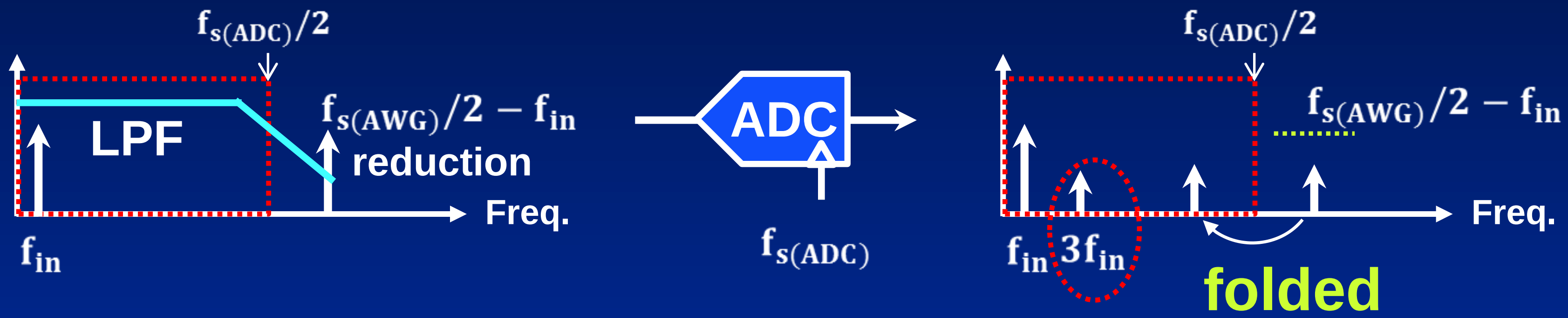
# When Spurious @ $f_{s(AWG)}/2 - f_{in}$ is Beyond $f_{s(ADC)}/2$




**ADC HD3 can be measured accurately**

# Conditions for Accurate ADC HD3 Measurement

$\frac{f_{s(AWG)}}{2} - f_{in} > \frac{f_{S(ADC)}}{2}$, and/or Spurious Reduction at $\frac{f_{s(AWG)}}{2} - f_{in}$




① Spurious power reduction at $f_{s(AWG)}/2 - f_{in}$

② $\frac{f_{s(AWG)}}{2} - f_{in} > \frac{f_{S(ADC)}}{2}$ Change sampling frequency by folding

**Accurate measurement of ADC output HD3 with phase switching signal**

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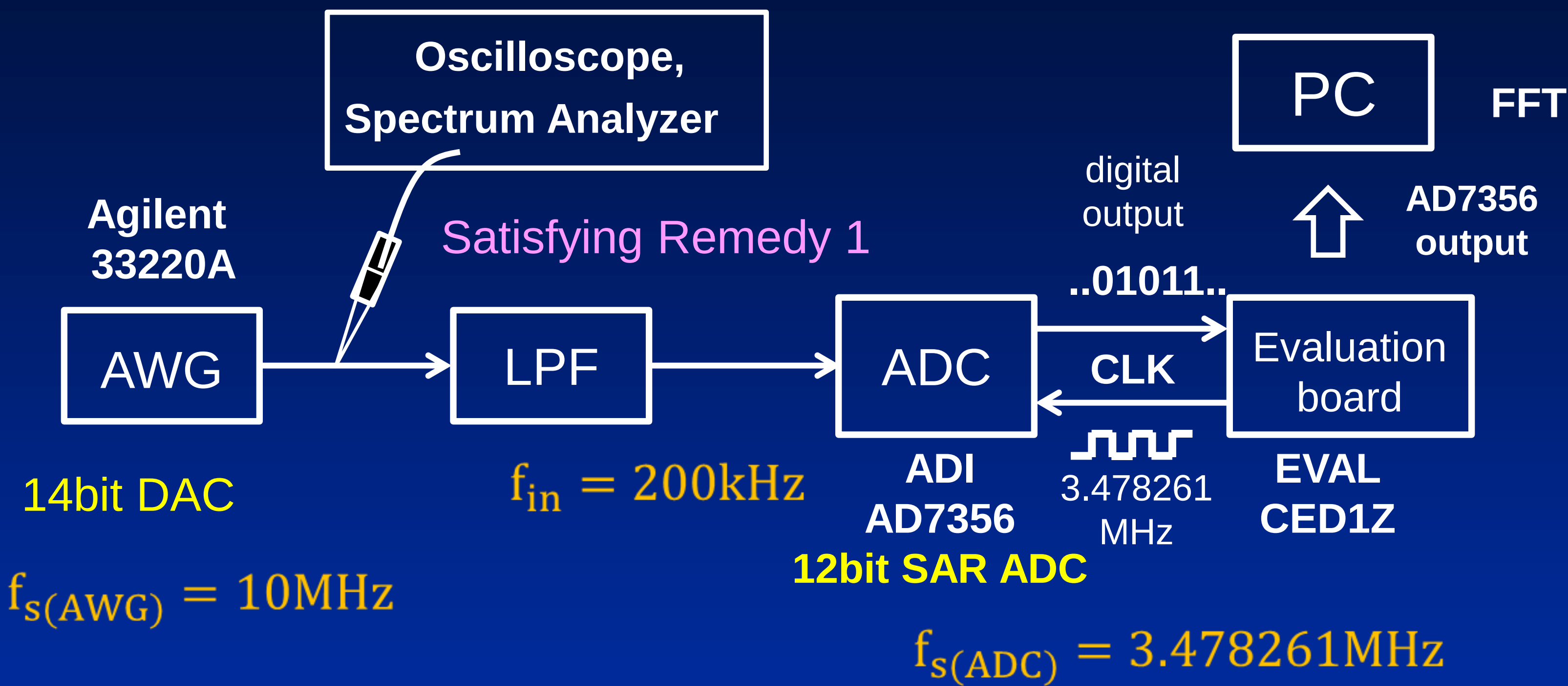
# ADC 3rd Harmonic Measurement Diagram



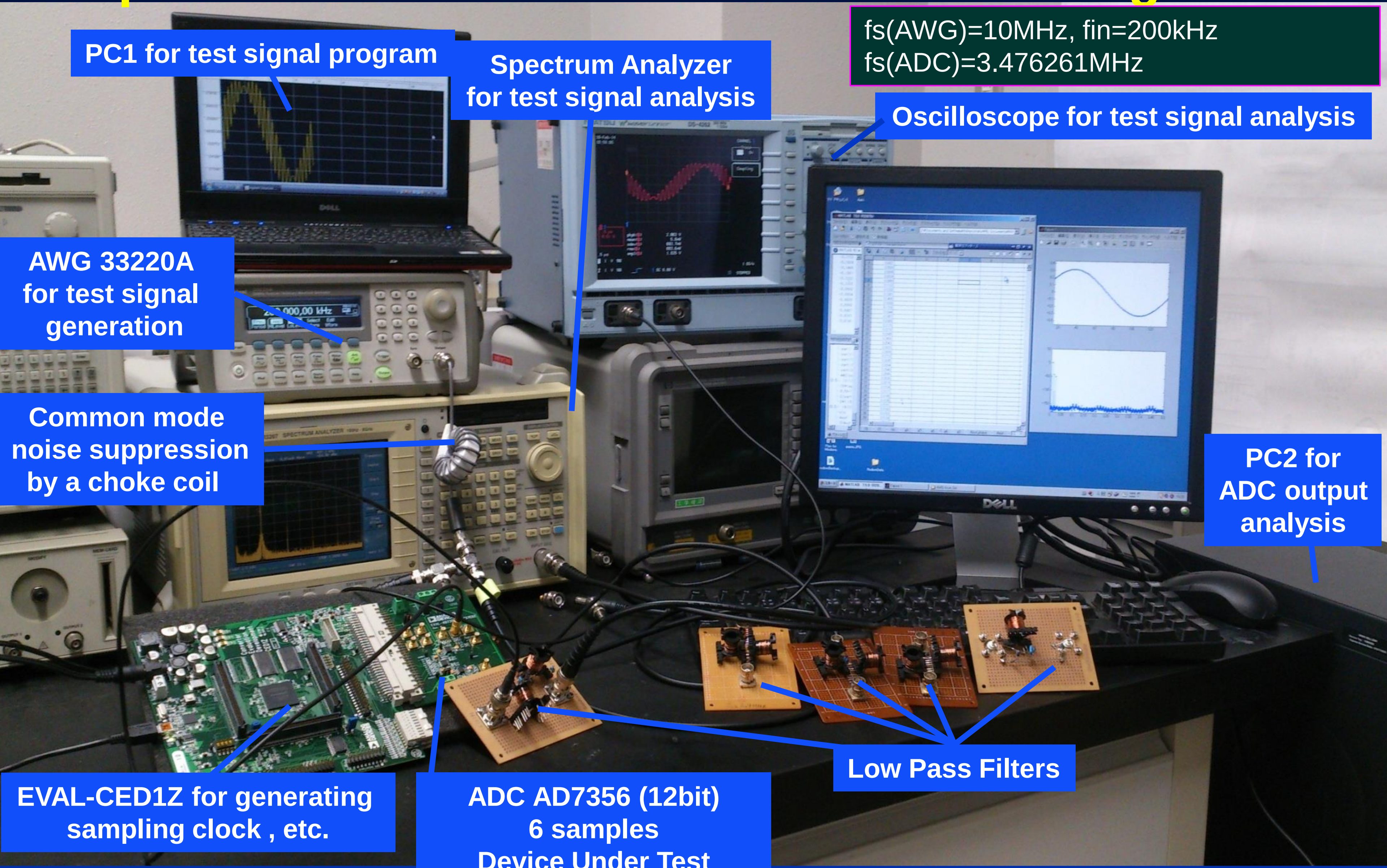

ADC test signal generation

- Conventional
- Phase switching

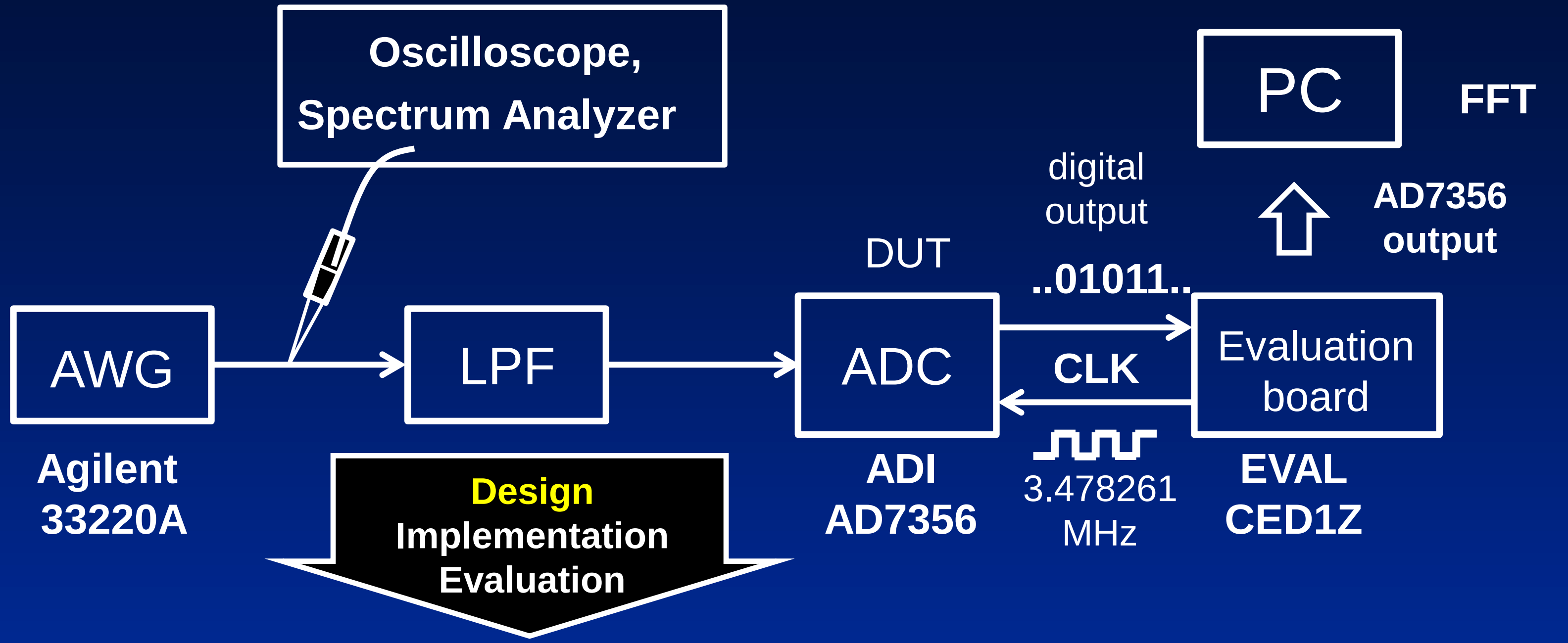
Satisfying Remedy 2

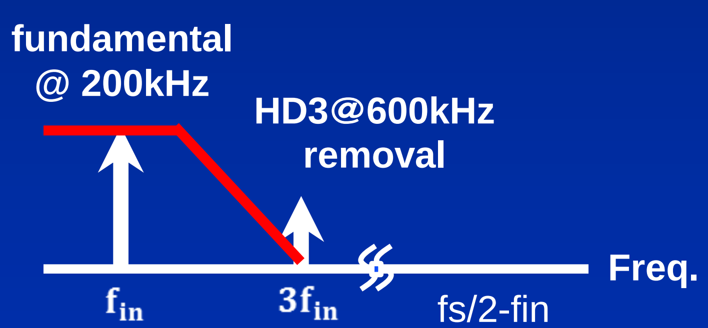
$$\frac{f_{s(AWG)}}{2} - f_{in} > \frac{f_{s(ADC)}}{2}$$

# Experimental Environment for ADC Testing

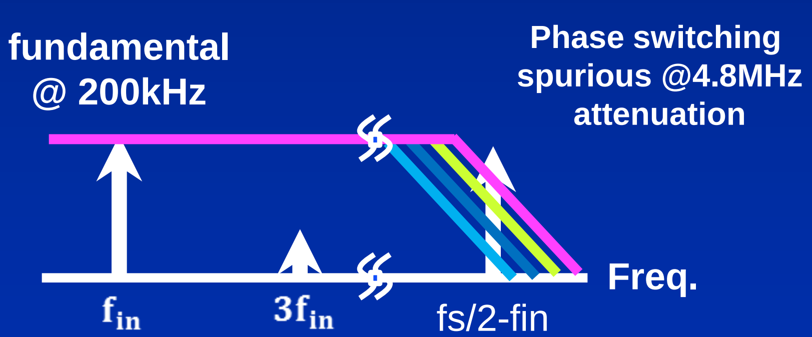


# Analog LPF Design for ADC Testing



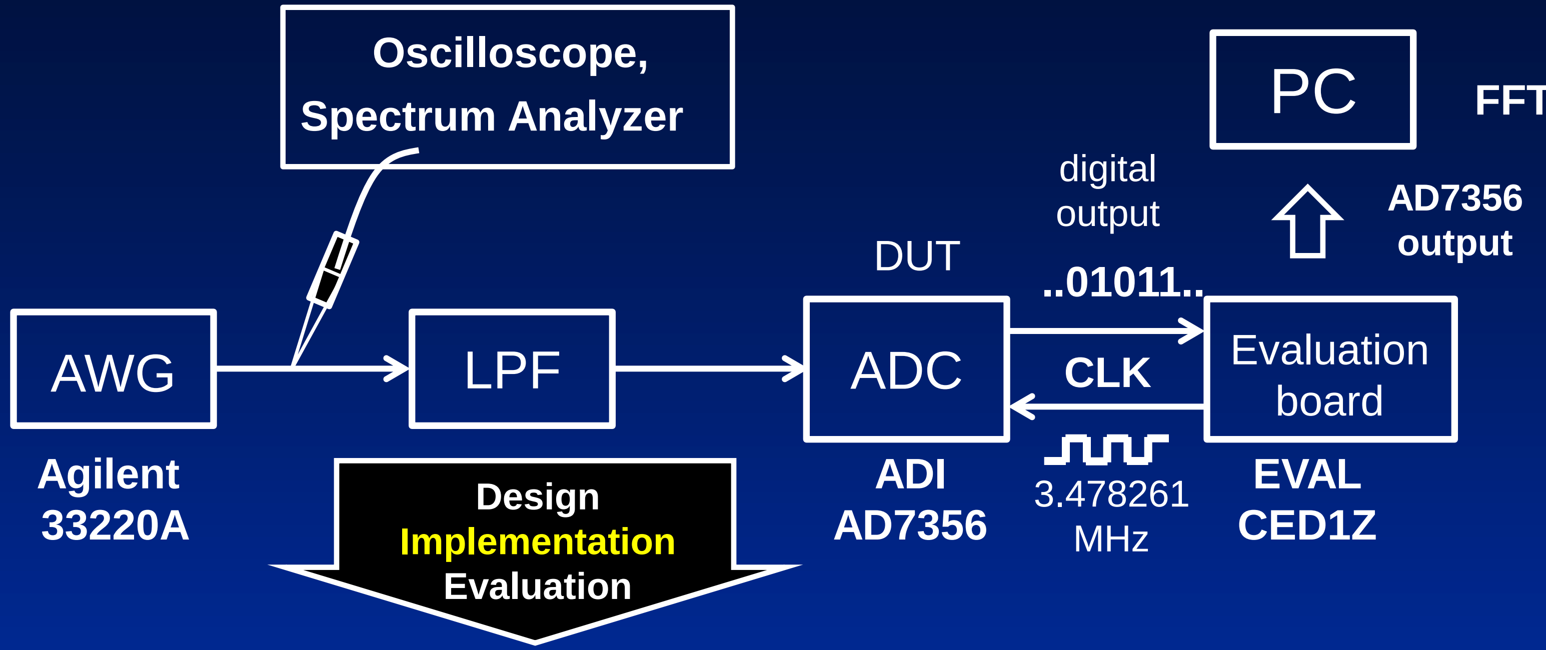

fc=250kHz
$5^{th}$ order LC Butterworth LPF



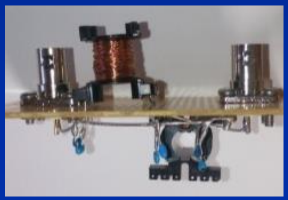

fc= 1MHz, 2MHz, 2.7MHz, 3.7MHz

$4^{th}$ order LC Butterworth LPF

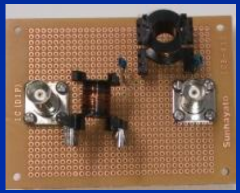
# LPF Implementation



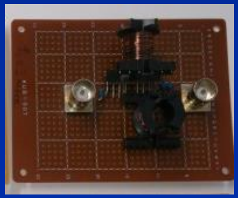

fc=250kHz



fc=1MHz

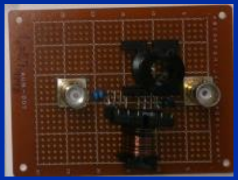


fc=2MHz



fc=2.7MHz

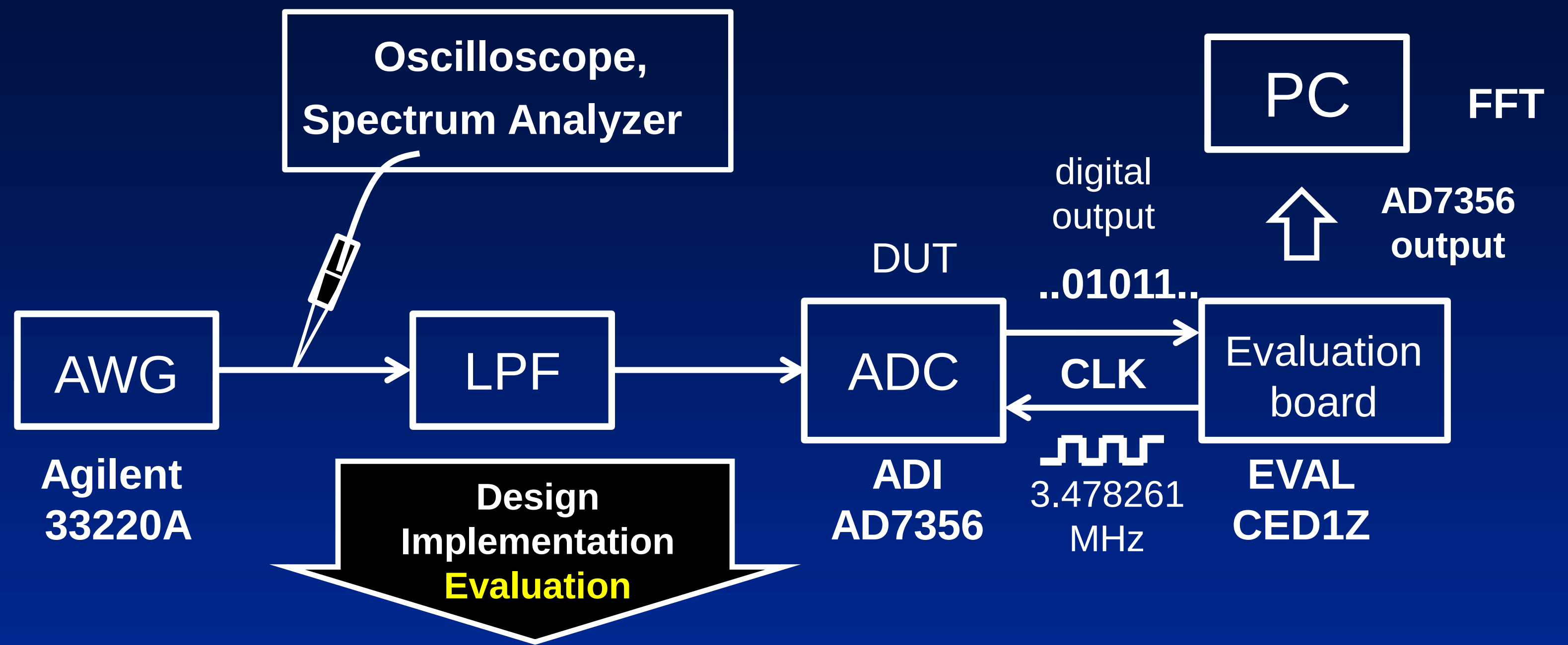
fc=3.7MHz

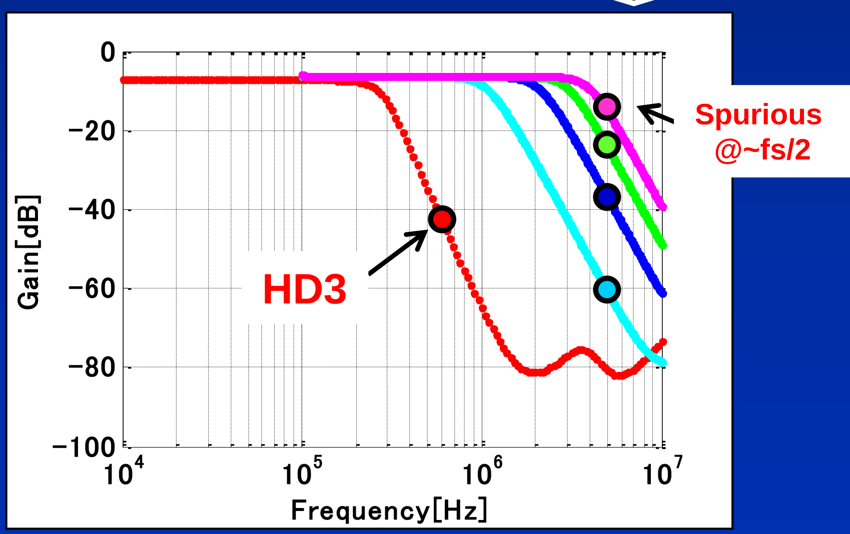


for HD3 reduction

for fs/2-fin spurious reduction

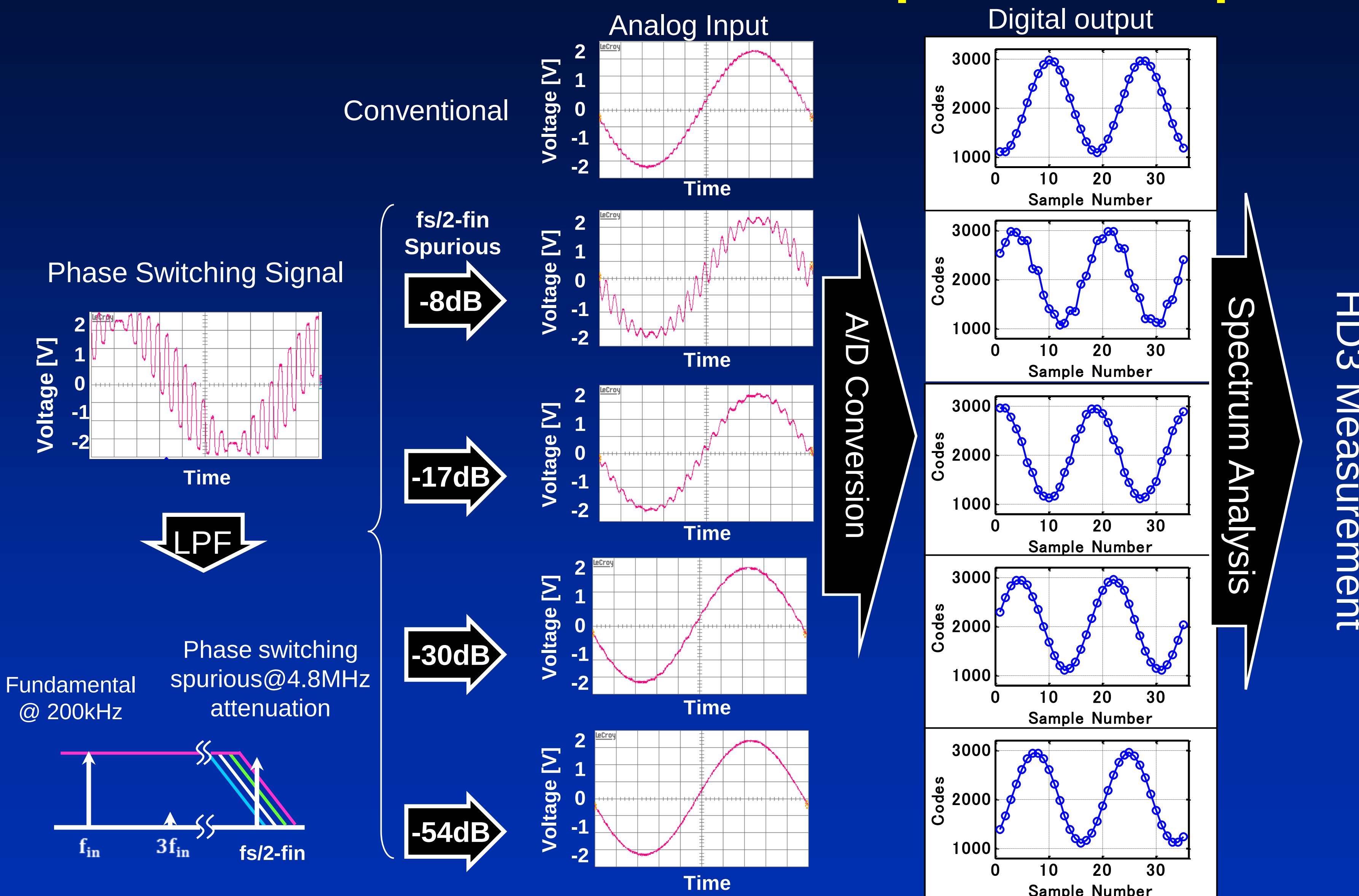
# LPF Evaluation with Frequency Response Analysis



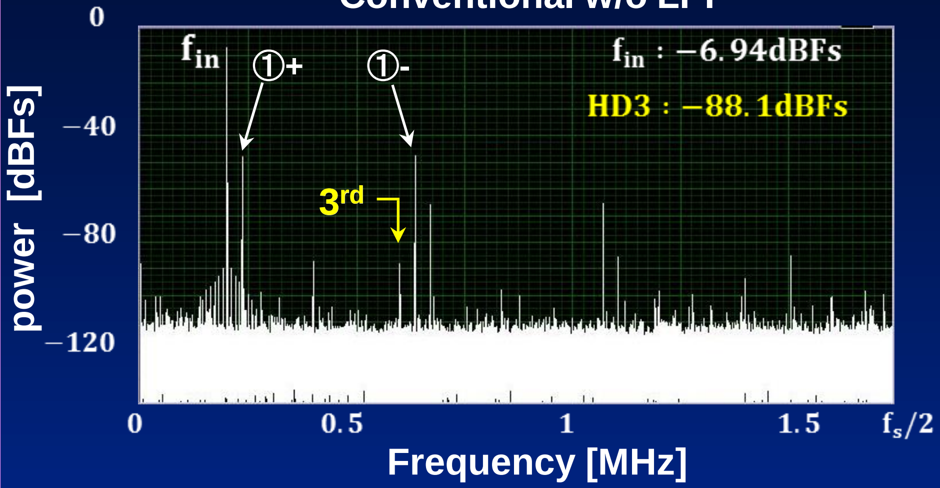

- fc=250kHz→ - 40dB @ 600kHz
- fc=1MHz → - 54 dB@4.8MHz
- fc=2MHz → - 30 dB@4.8MHz
- fc=2.7MHz→ - 17 dB@4.8MHz
- fc=3.7MHz→ - 8.0 dB@4.8MHz

# Measured Waveforms of ADC Input and Output

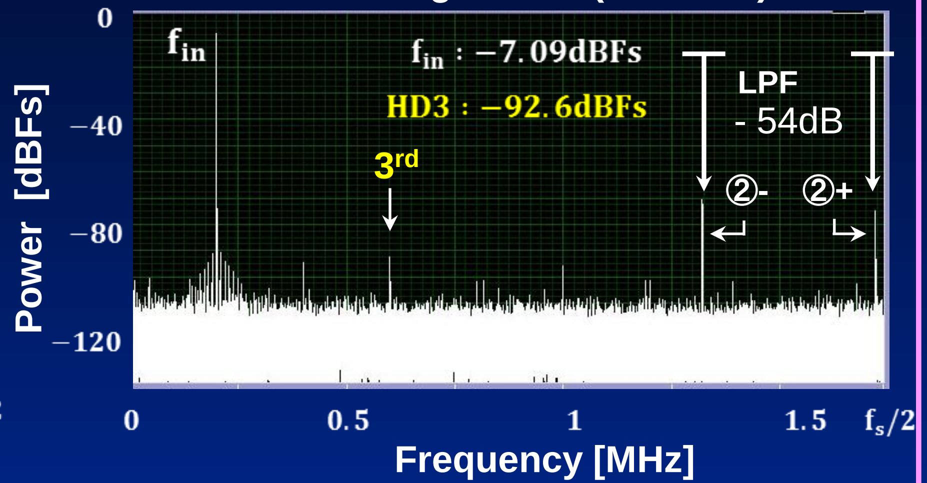


# Comparison of Conventional and Proposed Methods

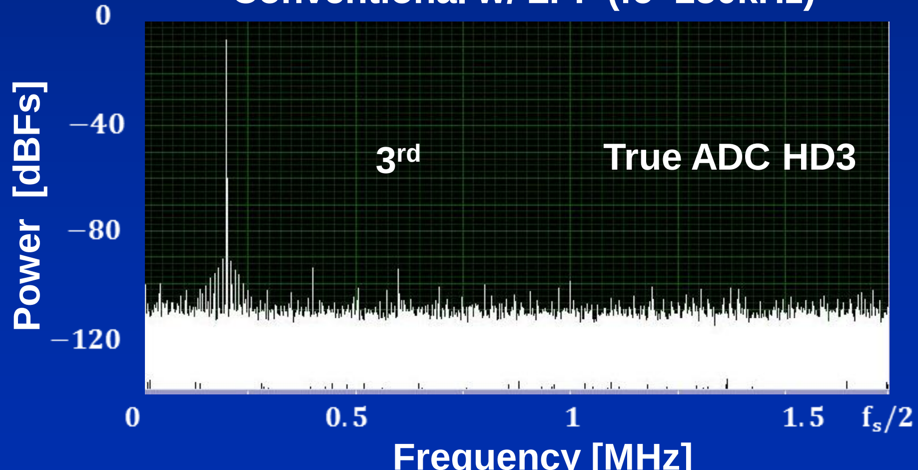
Conventional w/o LPF




Phase switching w/ LPF (fc=1MHz)




Conventional w/ LPF (fc=250kHz)




True ADC HD3: -94.6dBFs

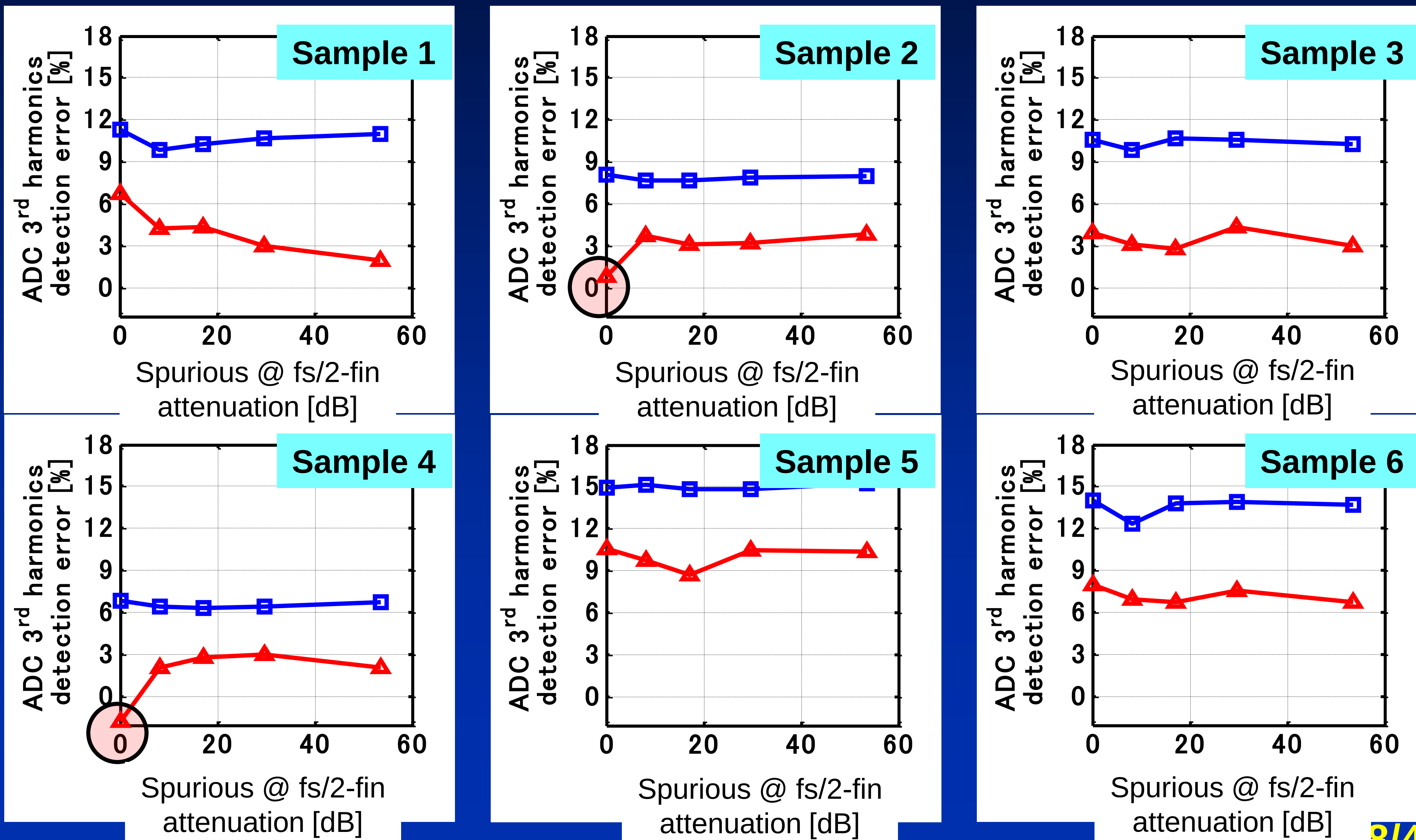
Conventional method
Measured HD3: -88.1dBFs
Error 6.8%

Proposed method
Measured HD3: -92.6dBFs
Error 2.1%

①± : $f_{s(AWG)} \pm f_{in}$　　②± : $\frac{f_s}{2} \pm f_{in}$

# ADC HD3 Measurement Results


ADC (AD7356) HD3 measurement error reduction is verified



# Outline

- Research background
- Proposed solution
- Problems of proposed solution
- Remedy 1
- Remedy 2
- Experimental results
- Conclusion

## Conclusions

- Low distortion sine signal generation
- Without AWG hardware modification
- Just AWG program change
  and a simple analog LPF
- Verified with
  AWG (Agilent 33220)
  6 samples of 12bit SAR ADC (AD7356)

↓

Greatly improved quality of ADC Linearity testing
at virtually no extra cost.

# Future Work

- Generalization to other types of low distortion sinusoidal signal generation
  - HD2, HD2&HD3 cancellation for 1-tone
  - IMD3 cancellation for 2-tone

↓

- We have partially verified these.
- Detailed theoretical analysis, simulations, and experiments are underway.